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Comparison of the Fatigue Characteristics of Recycled Asphalt Pavements

Lara Smith

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Comparison of the Fatigue Characteristics of Recycled Asphalt Pavements

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

in partial fulfillment of the requirements for the degree of

Master of Science in
Civil Engineering

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Morgantown, West Virginia

2015

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ABSTRACT

Comparison of the Fatigue Characteristics of Recycled Asphalt Pavements

Lara Smith

When the service life of asphalt pavement has expired, it can be reclaimed and reused as a percentage of new pavement. This recycled asphalt pavement (RAP) usually is exposed to years of environmental conditioning and oxidation, which stiffens the asphalt binder. As the binder stiffens, certain engineering properties change, such as dynamic modulus, and the pavement begins to experience distresses.

The asphalt mixture performance tester (AMPT) is a new performance testing machine that applies load cycles within a cell that also acts as an environmental conditioning chamber. This research focused on the using the AMPT to determine dynamic modulus and fatigue characteristics of mix designs with three RAP levels and two binder grades. Asphalt Pavement Hierarchical Analysis Toolbox – Fatigue Program was the analysis software utilized that generated the three fatigue coefficients in the traditional fatigue equation. Kenpave, developed by Yang Huang, was used to develop strain-modulus curves so that the mix designs could be compared at a designated loading frequency and the respective dynamic modulus and strain level.

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Chapter 1: Introduction

Background

As recycling asphalt pavement becomes a more common practice, it is essential to ensure that the performance of the material meets current standards. After asphalt concrete has been exposed to several years of environmental conditions and repeated loads, it experiences distresses. Fatigue and rutting are two major distresses which should be evaluated in asphalt concrete pavements. Recycled asphalt pavement (RAP) may experience distresses at a different rate and magnitude than virgin asphalt pavement due to the aging of the recycled binder. In order for RAP to be a feasible option, it must be able to endure as many, if not more, loading cycles as a virgin mixture. Having a higher number of cycles to failure can increase the service life and reduce the financial cost of repairs and replacements.

The Asphalt Mixture Performance Tester (AMPT) is a dynamic testing machine that encloses an asphalt specimen in an environmental conditioning chamber that can also apply confining pressure for triaxial testing. Dynamic modulus, flow number, and flow time are three main tests that the machine is used for which can be used to predict the rutting potential of the pavement. However, a new uniaxial fatigue test was standardized in 2014 which allows damage characteristics to be evaluated using Simplified Continuum Damage Uniaxial Fatigue (SCDUF) or Simplified Viscoelastic Continuum Damage (S-VECD) models¹. This test requires three specimens to be tested at three micro strain levels after performing a fingerprint dynamic modulus test on each. Exported data from the AMPT can be analyzed using the ALPHA Fatigue software developed by Drs. Richard Kim and Shane Underwood.

Problem Statement

This research was performed to compare four mix designs using the Uniaxial Fatigue Test (UTS 032) and Dynamic Modulus Test (UTS 006), and three mix designs using the Flow Number Test (UTS

005). In total, 54 AMPT specimens were produced; 36 tested using the uniaxial fatigue test, 12 tested using the dynamic modulus test, and 6 tested using both the dynamic modulus and flow number tests. Results from the AMPT were analyzed with the Asphalt Pavement Hierarchical Analysis Toolbox – Fatigue Program (ALPHA-F) and the MasterSolver developed by Dr. Ramon Bonaquist.

Superpave job mix formulas for three RAP levels and two binder grades were provided by West Virginia Paving. Virgin aggregate, RAP, and binder were obtained from West Virginia Paving's asphalt plant in Beaver, West Virginia.

Objectives

The first objective of this experiment was to provide a comparison of fatigue characteristics between mix designs using PG 70 – 22 with 0%, 15%, and 25% RAP, analyzed using the ALPHA-F software. The second objective was to provide a comparison of fatigue characteristics between two binders PG 70 – 22 and PG 64 – 22 with 25% RAP, analyzed using the ALPHA-F software. Finally, the third objective was to provide a comparison of the flow number and fatigue characteristics between mix designs using PG 70 – 22 with 0%, 15%, and 25% RAP.

Achieving these objectives is important, because if the addition of RAP proves to be detrimental to the pavement's fatigue performance it will need to be reevaluated as a usable material. In contrast, if it proves to be beneficial to the performance, RAP should be considered in more applications.

Report Outline

This report is split into five chapters with the first chapter being the introduction. The second chapter provides a literature review of RAP, the AMPT, Dynamic Modulus, Flow Number, and the Uniaxial Fatigue Test. Chapter three describes the experimental design and methodology. Chapter four presents a summary of the raw data, as well as the analysis using the MasterSolver and ALPHA-F

software. The fifth chapter summarizes the findings and provides recommendations for future research. Lastly, the appendix provides supplemental tables and figures.

Chapter 2: Literature Review

Background of RAP

Recycling not only is beneficial environmentally, it can also be more cost effective than using virgin material. RAP is asphalt pavement that has been milled, or ripped up, from a roadway. Since RAP is taken from the roadway, it can contain the original pavement as well as any repairs or maintenance treatments². RAP stockpiles are subject to segregation similar to aggregate stockpiles; making them susceptible to variations in gradation. In addition, RAP stockpiles may also be made up of several roadways with assorted gradations, asphalt contents, and binder grades².

Previous studies have shown that in Hveem and Marshall Mix designs, the performance of RAP mixes can surpass virgin mixes². From those studies, it can be predicted that Superpave mix designs with high RAP will also outperform virgin mixtures. An appendix to AASHTO M 323 provides the Superpave mix design process for mixes with RAP. This appendix is based on the National Cooperative Highway Research Program (NCHRP) Report 452². The AASHTO specification allows up to 15 percent RAP without modifying the binder, use of a lower temperature grade binder if the RAP content is between 15 and 25 percent, and the use of a viscosity blending procedure if the RAP content is more than 25 percent. The WVDOH has largely incorporated AASHTO M 323 into their material procedure for designing Superpave mixes, including the provision for designing mixes with RAP.

Concerns

To accommodate RAP in new mixes, some things need to be considered. First, one must determine what the RAP contributes to the mix in terms of aggregates and asphalt content. Stockpiles may contain different roadway segments, which vary in aggregate gradation, asphalt content, et cetera. Stockpile sampling and testing must be performed for binder content and gradation. To do this, samples

should be taken from at least 10 random places and at a minimum depth of 150 mm from the surface of the stockpile². Superpave mix designs also have strict regulations on source and consensus properties, which the RAP will need to meet in order to be used.

There have been concerns over the issue of RAP acting like black rock. This means that the asphalt in the RAP does not blend at all with the virgin binder. NCHRP performed studies on this in Project D9 – 12, and concluded that low RAP pavements act as if total blending has occurred, and high RAP pavements act as if partial blending has occurred. Assuming total blending occurs, asphalt content can be determined by using an ignition furnace or extraction via chemical solvent.

When the pavement is removed from the roadway, it can vary in size from very fine to large chunks greater than five inches. A characteristic of RAP is that it contains a greater number of fines than larger chunks⁷. Removing the RAP material smaller than the number 30 sieve can improve the gradation by reducing the amount of dust in the material⁷. Another method for is to split the material on the number 4 sieve and determine asphalt contents and gradations for each.

Current Use in WV

AASHTO M 323 requires reducing the binder grade when the amount of RAP between 15 and 25 percent. In 2014, the West Virginia Department of Transportation (WVDOT) issued a memo allowing increased the allowable RAP content to 25% in Marshall Base 1 and 2 and Superpave 19.0, 25, and 37.5 mm mixes³ without the requirement to modify the binder grade. All mix designs are still subject to meeting the guidelines set in MP 401.02.24, with the exception of Section 5, Line 5.4; the requirement that a softer binder grade for mix designs using greater than 15% RAP³.

RAP Asphalt Contribution

RAP must undergo some testing prior to use, such as asphalt content. Asphalt content can be determined by following the method in American Society for Testing and Materials (ASTM) designation D6307: Standard Test Method for Asphalt Content of Hot-Mix Asphalt by Ignition Method. The fine fraction of the RAP, passing the 4.75 mm sieve, generally has a higher asphalt content than the coarse fraction. The asphalt contents of both fractions can be determined by splitting the RAP on the 4.75 mm sieve and running a burn-off for both, then performing a weighted average. The binder contained in the RAP can also contribute to the mix as a stiffer binder than the original performance grade used, but recent research has shown the effect is not significant in mixtures containing less than 25% RAP⁴.

Background of the Asphalt Mixture Performance Tester

The Asphalt Mixture Performance Tester (AMPT) is a machine designed to test engineering properties of hot-mix asphalt specimens by applying dynamic loading within a temperature controlled triaxial cell. It was developed through National Cooperative Highway Research Program (NCHRP) as a simple performance tester for the hot-mix asphalt mix design⁵. The AMPT can be used for tests such as Dynamic Modulus, Uniaxial Fatigue, Flow Number, and Overlay Testing.

The loading is applied using a hydraulic servomechanism that can be controlled using a computer equipped with Universal Testing Software (UTS) designed for the AMPT. The bottom plate in the cell is mounted on the actuator, the movable fixture, while the top plate is fixed. For tests requiring direct tension, specimens are glued to end platens and then bolted to both the top and bottom plates.

As well as dynamic loading, the AMPT also can condition the asphalt specimens to a desired temperature prior to and during testing. This is achieved using heated or cooled air circulated through

the cell and controlled using the temperature controller. Samples can be conditioned using stand-alone chambers as well, to facilitate sequential testing of multiple samples.

AMPT Dynamic Modulus Test

For this test and related analysis, referenced AASHTO documents are:

- PP 60 – 14, Standard Practice for Preparation of Cylindrical Performance Test Specimens Using the Superpave Gyratory Compactor (SGC),
- TP 79 – 13, Standard Method of Test for Determining the Dynamic Modulus and Flow Number for Asphalt Mixture Performance Tester (AMPT), and
- PP 61 – 13, Standard Practice for Developing Dynamic Modulus Master Curves for Asphalt Mixtures using the Asphalt Mixture Performance Tester (AMPT).
- TP 107-14, Standard Method of Test for Determining the Damage Characteristic Curve of Asphalt Mixtures from Direct Tension Cyclic Fatigue Tests

Sample Specifications

For the AMPT, cylindrical performance test specimens must be acquired from Superpave Gyratory Compactor (SGC) specimens that have a diameter of 150 mm and a minimum height of 160 mm⁶. Cored and sawn samples must meet the tolerance specified by AASHTO PP 60 – 14, shown in Table 1.

Table 1 - Test Specimen Dimensional Tolerances⁶

Item	Specification
Average diameter	98 to 104 mm
Standard deviation of diameter	≤0.5 mm
Height	147.5 to 152.5 mm
End flatness	≤0.5 mm
End perpendicularity	≤1.0 mm

Test Parameters

Since the AMPT can test at various temperatures and loading frequencies, recommended settings are based on the performance grade, shown in Table 2.

Table 2 - Recommended Testing Temperatures and Loading Frequencies¹⁰

PG 58 – XX and softer		PG 64 – XX and PG 70 – XX		PG 76 – XX and stiffer	
Temperature °C	Loading Frequencies, Hz	Temperature °C	Loading Frequencies, Hz	Temperature °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

Inputs for Control Software

Information required for the UTS006 (Dynamic Modulus Test) includes¹⁰:

- diameter measured at the top, middle, and bottom of the sample
- height measured at four points 90° from each other
- sample identity
- test temperature
- test frequency

Outputs

The Dynamic Modulus Test reports the following in a summary .csv file for the three test temperatures:

- dynamic modulus
- phase angle
- average temperature
- average confining pressure

- average micro strain
- load drift
- load standard error
- average deformation standard error
- deformation uniformity
- phase uniformity

Master Curve Analysis

Development of MasterSolver

In April of 2009, NCHRP released an excel workbook, with Ramon Bonaquist being the principal investigator, that allowed users of the AMPT to generate dynamic modulus master curves. This workbook, known as MasterSolver, utilizes a modified version of the Mechanistic-Empirical Design Guide (MEPDG) master curve equation, the Arrhenius equation, and the Hirsch model⁸.

Dynamic Modulus

Historically, the stiffness of the asphalt mixture has been described by the dynamic modulus determined by compressive testing. The modified equation that the MasterSolver utilizes to generate the dynamic modulus master curve is as follows:

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

Where:

$|E^*|$ = dynamic modulus

ω_r = reduced frequency, Hz

Max = limiting maximum modulus, ksi

Min = limiting minimum modulus, ksi

β , and γ = fitting parameters

Reduced Frequency

In order to incorporate dynamic modulus data tested at various temperatures and frequencies to a master curve, it must be fitted to a reduced frequency curve. The reduced frequency can be determined using Equation 2, known as the Arrhenius equation.

$$\log \omega_r = \log \omega + \frac{\Delta E_a}{19.14714} \left(\frac{1}{T} - \frac{1}{T_r} \right) \quad (2)$$

Where:

ω_r = reduced frequency at the reference temperature

ω = loading frequency at the test temperature

T_r = reference temperature, °K

T = test temperature, °K

ΔE_a = activation energy (treated as a fitting parameter), J/mol

MasterSolver Analysis

The MasterSolver workbook requires users to extract certain data points from the .csv files the AMPT produces as well as determine other information that is not utilized within the UTS006 (Dynamic Modulus Test) software such as voids in the mineral aggregate (VMA). The required inputs and are summarized in the list below⁸.

Inputs

- voids in the mineral aggregate (VMA)
- voids filled with asphalt (VFA)

- test temperature
- loading frequency
- modulus
- phase angle

Once the data has been entered, the Excel add-on known as Solver can be used to minimize the sum of squares (error squared) between the predicted and actual log of the average modulus⁸. This allows the data to be “fit” to the reduced frequency explained previously. The outputs from the analysis are summarized in the list below⁸.

Outputs

- average modulus
- modulus covariance
- average phase angle
- phase angle standard deviation
- fitted modulus
- goodness of fit (R^2)
- β (parameter)
- γ (parameter)
- E^* versus reduced frequency master curve
- phase angle versus reduced frequency master curve

Uses of Analysis

The master curves generated from the MasterSolver analysis can be used for various applications. The curves predict how the asphalt’s dynamic modulus and phase angle will behave at

various test temperatures and loading frequencies. This allows mix designs to be compared across those parameters.

AMPT Flow Number Test

For this test and related analysis, referenced AASHTO documents are:

- PP 60 – 14: the Standard Practice for Preparation of Cylindrical Performance Test Specimens Using the Superpave Gyratory Compactor (SGC)
- TP 79 – 13: Standard Method of Test for Determining the Dynamic Modulus and Flow Number for Asphalt Mixture Performance Tester (AMPT).

Sample Specifications

For the AMPT, cylindrical performance test specimens must be acquired from Superpave Gyratory Compactor (SGC) specimens that have a diameter of 150 mm and a minimum height of 160 mm⁶. Cored and sawn samples must meet the tolerance specified by AASHTO PP 60 – 14, shown in Table 1.

Test Parameters

The testing temperature for the flow number test is the high adjusted PG temperature that can be determined using the (Long Term Pavement Performance) LTPP Bind program (<http://www.fhwa.dot.gov/research/tfhrc/programs/infrastructure/pavements/ltpb/download.cfm>). This program is based on project location and the respective climate. The evaluation parameters for using the LTPP Bind are presented in Table 3.

Table 3 - LTPP Bind Evaluation Parameters¹⁴

Evaluation Parameter		HMA and WMA
Desired Reliability, %		50
Target Rut Depth, mm		12.5
Adjustment for Traffic Loading and Speed		0.0
Depth of Layer, mm	Surface Layers	20
	Intermediated and Base Layers	Depth at the top of surface of the layer

The testing parameters for the flow number test are presented in Table 4.

Table 4 - Test Parameters¹⁴

Test Parameter	Value
Test Temperature	Determined from LTPP Bind
Repeated Axial Stress	600 kPa
Contact Stress	30 kPa
Confining Stress	0 kPa

Inputs for Control Software

Information required for the AMPT's control software UTS005 (Flow Number Test) includes¹⁵:

- diameter measured at the top, middle, and bottom of the sample
- height measured at four points 90° from each other
- sample identity
- test temperature
- axial stress
- contact stress
- termination micro strain
- termination cycles

Outputs

The Flow Number Test reports the following in a summary .csv file for each specimen:

- deviator stress
- micro strain
- confining stress
- load standard error
- temperature
- contact stress
- flow number

Uses of Analysis

The reported flow number is essentially the number of test cycles that correspond to the minimum point in the “Rate of Change in Axial Strain versus the Number of Loading Cycles” curve¹⁹. The test is destructive due to a loading pulse of 0.1 seconds and a rest time of 0.9 seconds. This test is important in determining rutting resistance of the mixture. The Table 5 shows the requirements for different design ESALs.

Table 5 - Flow Number Criteria (FHWA)

Design Traffic, Million ESAL	Flow Number
<3	N/A
3 to 10	50
10 to 30	190
>30	740

AMPT Uniaxial Fatigue Test

Sample Specifications

For the AMPT, cylindrical performance test specimens must be compacted using the Superpave Gyratory Compactor (SGC) to a diameter of 150 mm and a minimum height of 180 mm¹. The

compacted samples are cored and sawn samples and must meet the tolerance specified by AASHTO TP 107 – 14, shown in Table 6.

Table 6 - Test Specimen Dimensional Tolerances¹

Item	Specification
Average diameter	100 to 104 mm
Standard deviation of diameter	≤ 0.5 mm
Height	127.5 to 132.5 mm
End flatness	≤ 0.5 mm
End perpendicularity	≤ 1.0 mm

Test Parameters

AASHTO's PP 107-14 designates that the test temperature for fatigue testing shall be the average of the high and low temperatures minus three based on the 98% reliability climactic PG determined by LTPPBind¹. TP 107-14 recommends performing the test on the first sample at a strain level of 300 micro strain and the second and third strain levels are based on the performance of the first specimen per Table 7.

Table 7 - On-Specimen Strain Levels¹

Case	ϵ_{OS2}	ϵ_{OS3}
$500 < N_{fl} < 1,000$	$\epsilon_{OS1} - 100$	$\epsilon_{OS1} - 150$
$1,000 < N_{fl} < 5,000$	$\epsilon_{OS1} - 50$	$\epsilon_{OS1} - 100$
$5,000 < N_{fl} < 20,000$	$\epsilon_{OS1} + 50$	$\epsilon_{OS1} - 50$
$20,000 < N_{fl} < 100,000$	$\epsilon_{OS1} + 100$	$\epsilon_{OS1} + 50$
$100,000 < N_{fl} < 5,000$	$\epsilon_{OS1} + 150$	$\epsilon_{OS1} + 100$

Inputs for Control Software

Information required for the UTS032 (S-VECD Fatigue Test) includes¹:

- test temperature
- gauge length

- diameter measured at the top, middle, and bottom of the sample
- height measured at four points 90° from each other
- sample identity
- target peak-to-peak axial micro strain

Outputs

The UTS032 (S-VECD Fatigue Test) software reports the following in .csv files from the final five cycles of the dynamic modulus fingerprint test, initial five cycles of the S-VECD test, and the final five cycles of the S-VECD test:

- time
- axial stress
- actuator strain
- axial micro strain (for each LVDT)
- temperature
- load
- actuator displacement
- displacement (for each LVDT)

The UTS032 (S-VECD Fatigue Test) software reports the following analyzed data in a .csv file from the S-VECD test:

- dynamic modulus
- cycle count
- phase angle
- peak-to-peak stress

- peak-to-peak average axial micro strain
- peak-to-peak actuator micro strain
- temperature
- machine compliance factor
- load standard error
- minimum and maximum actuator strain
- minimum and maximum strain (for each LVDT)
- peak-to-peak load
- minimum and maximum load
- peak-to-peak actuator displacement
- peak-to-peak displacement (for each LVDT)
- minimum and maximum actuator displacement
- minimum and maximum displacement (for each LVDT)

Asphalt Pavement Hierarchical Analysis Toolbox – Fatigue Program

Development of Simplified Viscoelastic Continuum Damage Model

Continuum damage theory (CDT) has been used to predict damage within materials since the 1960's¹². Damage can be tested by applying a load with a constant rate of strain or by cyclic loading. For asphalt, the loading level to cause failure is higher than what most testing apparatuses can apply¹². The cyclic loading can be applied by a controlled stress test, push-pull test, pull-pull test, or controlled strain test. Simplified viscoelastic continuum damage (S-VECD) is a recent development that can be used for predicting fatigue in asphalt pavements¹².

S-VECD produces a damage characteristic curve that relates the damage parameter (S) to the pseudo-secant modulus (C). To generate this curve, the damage caused by the first loading cycle is included, but the few cycles after are excluded¹³. It has also been found that push-pull can be used as long as the tensile strain does not fall below 25 and does not exceed 37.5 micro strains¹³. Software has been developed to allow users to analyze S-VECD data more easily than with other iterative methods.

ALPHA-F Analysis

ALPHA-F was developed by Drs. Richard Kim and Shane Underwood to facilitate data analysis of fatigue testing using the AMPT. This software produces a model prediction report which can be used to compare characteristics of asphalt mixtures.

Analysis steps

Upon launching the ALPHA-F program the user is asked for a series of inputs, including the location of the data files for use during the analysis, including:

UTS006 (Dynamic Modulus Test) summary .csv files of three test temperatures (for three $|E^*|$ samples)

- VFA
- VMA
- UTS032 (S-VECD Fatigue Test) initial five cycles .csv files (for at least three Fatigue samples)
- UTS032 (S-VECD Fatigue Test) final five cycles .csv files (for at least three Fatigue samples)

ALPHA-F computes the phase angle versus cycle number and displays the results on a plot as shown on Figure xx. The user is allowed to adjust the point used for the fatigue analysis, but the

recommendation is to select the point where there is a sudden drop in the phase angle as shown on Figure 1. However, the figure included with the ALPHA-F user guide does not display this behavior as shown on Figure 2; no guidance is given for the selection of the failure cycle when there is no sudden drop in the phase angle. The “OK” button is selected and the program computes the damage models.

Figure 1 - ALPHA-F Phase Angle and Failure Cycle (With Sudden Drop in Phase Angle)

Figure 2 - ALPHA-F Phase Angle Phase Angle and Failure Cycle (Without Sudden Drop in Phase Angle)

Figure 3 - Best Fit Selection Dialogue Box

ALPHA-F does a best fit analysis of the damage using both a power-law model and an exponential model as shown on Figure 3. The user can select either of the models but the recommendation is to use the model with the lowest mean square error, MSE. After selecting the damage model the program completes the analysis and displays a summary screen as shown in Figure 3 and an output file of the analysis is created, including:

- K_1 , K_2 , and K_3 for traditional strain fatigue relationship
- endurance limit at 5, 10, 15, 20, and 25°C
- damage model coefficients: a , b , y , z , α
- parameter r and s in failure criterion
- shift factor coefficients: T_r and E_a
- master curve parameters: κ , β , δ , and γ

Uses of Analysis

The main use of fatigue analysis is to predict the k -values using the traditional strain fatigue relationship as defined by Equation 3.

$$N_f = K_1 \left(\frac{1}{\varepsilon_t} \right)^{K_2} (|E^*|)^{K_3} \quad (3)$$

Where:

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

$\varepsilon_t = \text{strain}$

$|E^*| = \text{dynamic modulus}$

The K-values are constants that can be determined from damage models produced by performing regression analyses on laboratory fatigue test data to correlate to field performance. The formulas used in the damage models of ALPHA-F are defined in Equations 4, 5, and 6.

$$C = e^{aS^b} \quad (4)$$

$$C = 1 - yS^z \quad (5)$$

$$N_f = r(G^r)^S \quad (6)$$

Where:

C = psuedo modulus

r, S = damage parameters

G^r = rate of average released pseudo strain

y, z = fitting coefficients for the power model

a, b = fitting coefficients for the exponential model

The Asphalt Institute used 0.0796, 3.291, and 0.854 and Shell used 0.0685, 2.363, and 5.671 for K_1 , K_2 , and K_3 , respectively¹⁶. Rauhut, as cited by Hass et. al (1994) showed there is a large difference in the fatigue curves produced by different researchers, Figure 4.

Figure 4 - Various Fatigue Equations²⁰

When evaluating a material for fatigue properties, an endurance limit may exist. Strains less than the endurance limit do not damage the fatigue properties of the material so in effect an infinite number of load applications can be applied to the pavement without causing fatigue damage. This concept is used for perpetual pavement design. The Texas Department of Transportation uses a strain limit of $<70 \mu$ -strain in their perpetual pavement design manual²⁰.

Chapter 3: Methodology

Experimental Design

The first factor of this experiment is RAP content, which has three levels: 0%, 15%, and 25%.

The second factor of this experiment is binder grade, which has two levels: PG 70-22 and PG 64-22.

Objective one was accomplished by preparing twenty seven samples with PG 70-22 with 0%, 15%, and 25% RAP contents and testing for dynamic modulus and fatigue characteristics. Objective two was accomplished by preparing nine additional samples with PG 64-22 and 25% RAP content and testing for dynamic modulus and fatigue characteristics. Objective three was accomplished by preparing six samples with PG 70-22 and 0%, 15%, and 25% RAP contents and testing for dynamic modulus and flow number.

For simplicity, the samples prepared to achieve objectives one and two are hereinafter referred to as DM and FT samples and the samples prepared to achieve objective three are hereinafter referred to as DM and FN samples. It shall be noted that the DM and FN samples were prepared and tested over a year before the DM and FT samples.

Material Preparation

For this experiment all aggregate samples were obtained from West Virginia Paving's plant in Beaver, WV. Limestone stockpiles used were 67's, 8's, F-Sand, and W-Sand. Processed RAP was also obtained from this location. Aggregate material properties are presented in Appendix A, following the job mix formulas. Upon arrival at West Virginia University's Asphalt Technology Lab, the virgin aggregate went through the following steps

1. Initial drying at 110°C for 6 hours
2. Initial sieving for 9 minutes

3. Separated by sieve size
4. Washing using drum washer
5. Final drying at 110°C for 10 hours
6. Final sieving until no additional aggregate passed
7. Stored in sealed plastic buckets

The gradation for each stockpile as documented in the West Virginia Paving mix design submission was used to compute a weigh-out table of the amount of aggregate needed for each stockpile and for each sieve. The aggregates for each mix were weighed out and stored in sealed plastic bags until mixing.

Upon arrival at West Virginia University's Asphalt Technology Lab, RAP underwent the following steps:

1. Initial drying at 100°C for 4 hours
2. Split on the #4 (4.75 mm) sieve and separated
3. Stored in sealed plastic buckets

The RAP was separated on the #4 sieve to determine proportions of “coarse” and “fine” material. These proportions were kept consistent between mixes to promote uniformity between specimens. The asphalt content of the fine and coarse RAP were determined using an NCAT oven and assuming a correction factor of zero.

Asphalt binder was delivered in gallon cans, so it was necessary to split the binder, at a temperature of 100°C, into quart cans. The amount of asphalt in each can was targeted to be slightly

more than what was needed for each specimen. This method prevented excessive heating and cooling of the asphalt. Unused asphalt binder from mixing was discarded to maintain consistency between mixes.

Superpave® Specimen Verification

Mix designs were initially verified in the spring of 2014, for the dynamic modulus and flow number tests. All of the job mix formulas were able to produce Superpave bulk and Rice samples that met the specification. Due to the delay in testing, new material was used for the fatigue testing. In order to verify that the mix designs used could still meet an air void content (VTM) of 4.0%, Superpave® bulk and Rice samples were remade in accordance with AASHTO T 312 – 12 and T 209 – 12. It was found that not all of the mix designs could meet the standard specification, so the asphalt contents (P_b) were altered for PG 70 – 22 with 15% RAP and 25% RAP, and PG 64 – 22 with 25% RAP. Table 8 lists the asphalt contents used in all mix designs that achieved an air void content of $4.0 \pm 0.5\%$.

Table 8 - Percent Asphalt Content

Binder Grade	% RAP	P_b
DM and FT		
PG 64-22	25	4.9%
PG 70-22	0	4.9%
	15	4.6%
	25	4.9%
DM and FN		
PG 70-22	0	4.9%
	15	5.1%
	25	4.7%

With the altered asphalt contents, the theoretical maximum (G_{mm}) and bulk (G_{mb}) specific gravities were determined and used to calculate air void content (VTM). The results are summarized Table 9.

Table 9 – G_{mm} , G_{mb} and VTM of Verification Samples

Binder Grad	% RAP	G_{mb}	G_{mm}	VTM, %
DM and FT				
PG 64-22	25	2.433	2.522	3.5
PG 70-22	0	2.434	2.527	3.7
	15	2.436	2.535	3.9
	25	2.420	2.526	4.1
DM and FN				
PG 70-22	0	2.416	2.515	3.9
	15	2.422	2.512	3.6
	25	2.427	2.538	4.4

AMPT Specimen Preparation

Using the theoretical maximum specific gravities from the verification samples, the mass required to produce a specimen with a target height was calculated. Knowing that this equation does not fully represent the relationship between whole sample and cored specimen air void contents, it was assumed that multiple iterations would be required to achieve target VTM. Equation 7, given in AASHTO PP 60 – 14, was the first step in calculating target sample mass and is restated below for convenience.

$$Mass = \left[\frac{100 - (V_{at} + F)}{100} \right] * G_{mm} * 176.7147 * H \quad (7)$$

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

Using $V_{at} = 7.0\%$, $F = 1.5$, $H = 18$ cm, and respective G_{mm} values, the preliminary desired masses of the samples were calculated. After cooling overnight, the samples were then cored to a

diameter of 100 mm and approximately 15 mm sawed off each end. The cored specimens were dried and tested for bulk specific gravity in accordance with T 331 – 13 and the air void results are listed in Table 10.

Table 10 - AMPT Trial Specimen Properties

Binder Grade	% RAP	G _{mm}	Mass, g	G _{mb}	VTM, %
DM and FT					
PG 64-22	25	2.527	7354.8	2.428	3.9
PG 70-22	0	2.535	7378.1	2.445	3.6
	15	2.526	7351.9	2.446	3.2
	25	2.522	7340.2	2.409	4.5
DM and FN					
PG 70-22	0	2.515	7320	2.423	3.7
	15	2.512	7311	2.433	3.1
	25	2.538	7387	2.402	5.4

The mass and air voids (VTM) of the samples is used to compute an adjusted mass per Equation 8⁶. Since the mass of the trial samples was less than the 7 percent target, the mass for the test samples was reduced.

$$Mass_{adj} = \left(\frac{100 - V_{at}}{100 - V_{am}} \right) * Mass \quad (8)$$

Where:

$Mass_{adj}$ = adjusted mass

V_{at} = target air void content

V_{am} = measured air void content

$Mass$ = mass used for trial specimen

The cored specimens were evaluated in the same manner as previously stated and the final masses determined to be used for AMPT sample fabrication are stated in the Table 11.

Table 11 - Final Adjusted Mass of AMPT Samples

Binder Grade	% RAP	G _{mm}	Final Adjusted Mass, g	G _{mb}	VTM (%)
DM and FT					
PG 64-22	25	2.527	7080.0	2.350	6.8
PG 70-22	0	2.535	7085.0	2.349	7.0
	15	2.526	7100.0	2.363	6.8
	25	2.522	7090.0	2.359	6.6
DM and FN					
PG 70-22	0	2.515	7085.0	2.330	7.3
	15	2.512	7100.0	2.342	6.8
	25	2.538	7090.0	2.349	7.4

Samples were made with the final adjusted masses in Table 11. All samples were compacted to a height of 180 mm and the dynamic modulus and flow number samples had 15 mm removed from each end, while the fatigue samples had 25 mm was removed from each end. As the samples were cut it was observed that near the completion of the cutting the weight of the waste piece caused it to fall away before the cut was complete. This resulted in some tearing away of the material on the sample side of the cut. The process for cutting the samples should be refined in future research. The samples were sawn and cored and the dimensional requirements of PP 60-13 (DM and FN samples) or TP 107-14 (DM and FT) were measured and the compliance of the samples to the requirements was verified.

Dynamic Modulus Test

Pre-Testing Setup

To perform the dynamic modulus test, AMPT specimens were produced in accordance with PP 61 – 13 and TP 79 – 13. Devcon 5-minute epoxy was used to attach the gauge points to the specimen and allowed to cure for at least one hour prior to being placed into the environmental conditioning unit. A dummy sample with an internal thermometer was also placed in the conditioning unit to verify that the specimens would be at the target test temperature after conditioning.

Dynamic Modulus Testing

Once a specimen reached test temperature, it was placed into the AMPT testing chamber between two end platens separated by Teflon spacers and LVDT's were attached to the gauge points with the fixtures provided by InstronTek. The LVDT's were adjusted to zero displacement according to the "levels" tool within the software. The cell was lowered and the temperature was monitored also using the "levels" tool within the software until all testing specifications were met. During equalization, the required inputs were entered into the testing software to conserve time. Testing was initiated using the hydraulic manifold system and performed using the "start" function of the UTS006 software that automatically applies the load at the designated frequency. After the test was completed, the specimen was placed back in the environmental conditioning unit at the next test temperature. At the conclusion of all tests, gauge points were removed and soaked in acetone to remove the epoxy for future use.

Flow Number Test

Pre-Testing Setup

To perform the flow number test, AMPT specimens were produced in accordance with PP 61 – 13 and TP 79 – 13. A dummy sample with an internal thermometer was placed in the conditioning unit with the specimens to be tested, to verify that the specimens would be at the target test temperature after conditioning.

Testing

Once a specimen reached test temperature, it was placed into the AMPT testing chamber between two end platens separated by greased latex friction reducing spacers. The cell was lowered and the temperature monitored using the "levels" tool within the software until the desired testing temperature was reached. During equalization, the inputs listed in Chapter 2 were entered into the

testing software to conserve time. Testing was initiated using the hydraulic manifold system and performed using the “start” function of the UTS005 software that automatically applied the required loading and stopped the test when a failure criterion was reached.

S-VECD Fatigue Test

Testing Setup

To perform the S-VECD fatigue test, AMPT specimens were produced in accordance with PP 60-14 and TP 107-14. Devcon 5-minute epoxy was used to attach the gauge points to the specimen prior to end platen gluing. Devcon 10110 (steel putty) was used to attach the steel end platens required for tensile testing with the AMPT. Each specimen remained in the end platen gluing jig for a minimum of four hours to allow the steel putty to set. After the four hours, the specimen was able to be removed from the jig and allowed to cure for an additional twelve hours before being placed in the environmental conditioning unit. A dummy sample with an internal thermometer was also placed in the conditioning unit to verify that the specimens would be at the target test temperature after conditioning.

Testing

Once a specimen reached test temperature, it was placed into the AMPT testing chamber and the end platens were bolted to the bottom plate. To bolt the specimen to the top plate, the actuator was raised and a seating load of 0.09 kN was applied. To improve consistency in testing, the bolts were tightened to 6.00 foot-pounds using a torque wrench. After tightening all bolts, the seating load was removed so the specimen was not experiencing any compressive or tensile loading. The LVDT's were attached to the gauge points and adjusted to slightly above the minimum displacement according to the “levels” tool within the software. This was done to allow the LVDT to displace a greater distance since the fatigue test elongates the specimen. The cell was lowered and the temperature was monitored using

the “levels” tool within the software until all testing specifications were met. During equalization, the required inputs were entered into the testing software to conserve time.

Fatigue testing requires that successive specimens be tested at varying strain levels. Although TP 107-14 recommends a strain level of 300 micro strains for the first sample, the InstroTek technician that assisted with setting up the AMPT in the WVU Asphalt Technology Lab recommended using an initial strain of 150 micro strains. Based on this value and Table 6 the strain levels used during this research are presented in Table 11. The N_f values found during the testing of the first sample of each of the factors and level combinations was always greater than 100,000 so only the last line of Table 12 applied to this research.

Table 12 - On-Specimen Strain Levels for the Second and Third Specimens

Case	ϵ_{os2}	ϵ_{os3}
$500 < N_f < 1,000$	50	---
$1,000 < N_f < 5,000$	100	50
$5,000 < N_f < 20,000$	200	100
$20,000 < N_f < 100,000$	250	200
$100,000 < N_f$	300	250

After the test was complete, the gauge points were removed and soaked in acetone to remove the epoxy for future use. The specimen was then placed into an oven at 150°C for one hour to soften the steel putty for easier removal. End platens were cleaned with WD-40, then ethyl alcohol, and finally acetone to ensure no residue was left behind.

Chapter 4: Results and Analysis

DM and FN Sample Analysis

Dynamic Modulus

All samples used for dynamic modulus testing met the standards set in PP 60-14 and were at an air void content of $7.0 \pm 0.5\%$. Data from the dynamic modulus tests is presented in Appendix B and summarized in Table 13.

Table 13 - Dynamic Modulus (MPa) of DM and FN Samples

%RAP	Replicate	Test Temp									
		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
0	1	13,004	9,646	6,529	4,130	3,516	1,786	1,365	579	248	131
	2	14,610	10,756	7,081	6,109	3,330	1,648	1,282	545	248	152
15	1	16,396	12,679	8,977	8,108	4,902	2,627	1,848	793	345	179
	2	14,713	11,073	7,715	12,969	7,922	4,371	2,275	1,027	462	234
25	1	16,085	12,362	8,756	8,508	5,150	2,785	2,399	1,076	469	221
	2	15,513	12,266	8,639	9,205	5,743	3,199	2,572	1,151	496	241

The average dynamic modulus for each combination of mix type, loading frequency, and temperature was determined and is presented in Figures 5, 6 and 7.

Figure 5 - Average Dynamic Modulus at 4°C of DM and FN Samples

Figure 6 - Average Dynamic Modulus at 20°C of DM and FN Samples

Figure 7 - Average Dynamic Modulus at 40°C of DM and FN Samples

KENPAVE Analysis of Dynamic Modulus

To analyze the dynamic modulus, the frequency was first determined using Equation 9.

$$d = \frac{12a}{s} \quad (9)$$

Where:

d = duration (sec)

a = contact radius (in)

s = speed (ft/sec)

For a 4500 load and 110 psi tire pressure the contact radius is 3.61 in. At 55 mph the duration was calculated to be 0.54 seconds, yielding a frequency of 1.866 Hz. Using the master curves, the dynamic moduli at 1.866 Hz and 20° were determined and are presented in Table 14

Table 14 - KENPAVE Dynamic Modulus Values

Binder Grade	% RAP	Dynamic Modulus (psi)	Dynamic Modulus (MPa)
PG 70-22	0	550,000	3,792
	15	790,000	5,447
	25	800,000	5,516

Using KENPAVE, fatigue and rutting modulus vs. strain graphs were created for a range of modulus for both a full-depth pavement and conventional pavement, Figure 8, and are shown in Figures 9 and 10.

Figure 8 - Pavement Structure Cross Section

Figure 9 - Conventional Pavement - Strain Based Fatigue

Figure 10 - Full Depth Pavement - Strain Based Fatigue

Using the strains corresponding to the various moduli, the N_f values were calculated to compare the mix designs. The Asphalt Institutes values for f_1 , f_2 , and f_3 were used in Equation 3 to define Equation 10. The results of using this equation are presented in Table 15.

$$N_f = 0.0796 \left(\frac{1}{\epsilon} \right)^{3.291} \left(\frac{1}{E} \right)^{0.854} \quad (10)$$

where:

N_f = number of passes until fatigue occurs

ϵ = strain

E = modulus (psi)

Table 15 - KENPAVE N_f Values

Binder Grade	% RAP	Dynamic Modulus (psi)	Full Depth		Conventional	
			ϵ	N_f	ϵ	N_f
PG 70-22	0	550,000	0.00108	56,800,000	0.00359	1,100,000
	15	790,000	0.000796	115,500,000	0.00298	1,500,000
	25	800,000	0.000786	119,000,000	0.00297	1,500,000

From Table 15, it can be seen that the full depth pavement has a higher predicted N_f value in all mix types than the conventional pavement. It also can be seen that the two RAP containing mixtures had higher N_f values than the virgin mixture. The strain values are >70 micro strains, which means that these pavements are not likely to be considered a perpetual design.

Master Curve

Using the MasterSolver workbook, the dynamic modulus master curves were generated for the three RAP contents. Note the data points on the graph are for the reduced frequency, not the test frequency.

Figure 11 - Dynamic Modulus Master Curve for PG 70 -22 with 0% RAP

Figure 12 - Dynamic Modulus Master Curve for PG 70-22 with 15% RAP

Figure 13 - Dynamic Modulus Master Curve for PG 70-22 with 25% RAP

Flow number

All samples used for flow number testing met the standards set in PP 60-14 and were at an air void content of $7.0 \pm 0.5\%$. Data from the flow number test is presented in Appendix B and summarized in Table 16.

Table 16 - Flow Number Values

Binder Grade	% RAP	Replicate	Flow Number
PG 70-22	0	1	178
		2	167
	15	1	342
		2	555
	25	1	591
		2	611

From Table 16, it can be seen that as RAP content increased, flow number increased. This can be related to the contributed binder of the RAP acting as a stiffer binder and less susceptible to rutting than a softer binder.

DM and FT Sample Analysis

Dynamic Modulus

All samples used for dynamic modulus testing met the standards set in PP 60-14 and were at an air void content of $7.0 \pm 0.5\%$. Data from the dynamic modulus test is presented in Appendix B and summarized in Table 17.

Table 17 - Dynamic Modulus (MPa) of DM and FT Samples

Binder	% RAP	Replicate	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	0.01Hz
PG 70-22	0	1	13,146	9,399	5,993	6,144	3,343	1,603	1,108	448	199	111
		2	12,906	9,385	6,192	5,310	2,875	1,400	1,281	541	242	137
		3	13,255	9,362	5,983	5,620	2,923	1,371	1,137	467	204	113
	15	1	14,857	10,845	7,336	8,470	5,079	2,723	2,019	866	368	182
		2	15,626	12,241	8,878	7,944	4,830	2,610	2,099	934	409	207
		3	18,992	14,610	10,403	10,068	6,113	3,344	2,622	1,162	510	253
	25	1	16,180	12,846	9,592	8,839	5,773	3,422	2,551	1,252	609	327
		2	17,033	13,621	10,046	8,965	5,605	3,148	2,448	1,145	529	272
		3	15,941	12,770	9,434	8,170	5,078	2,864	2,615	1,257	590	298
PG 64-22	25	1	16,145	12,422	8,845	8,334	5,105	2,793	2,070	910	395	195
		2	16,745	13,282	9,804	7,979	4,974	2,803	2,253	1,059	491	252
		3	17,517	13,892	10,138	9,674	6,162	3,549	2,615	1,230	569	290

The average dynamic modulus for each combination of mix type, loading frequency, and temperature was calculated and is presented in Figures 14, 15 and 16.

Figure 14 - Average Dynamic Modulus Values at 4°C

Figure 15 - Average Dynamic Modulus Values at 20°C

Figure 16 - Average Dynamic Modulus Values at 40°C

Master Curve

Using the MasterSolver workbook, the following dynamic modulus master curves were generated.

Figure 17 - Dynamic Modulus Master Curve for PG 70-22 with 0% RAP

Figure 18 - Dynamic Modulus Master Curve for PG 70-22 with 15% RAP

Figure 19 - Dynamic Modulus Master Curve for PG 70-22 with 25% RAP

Figure 20 - Dynamic Modulus Master Curve for PG 64-22 with 25% RAP

S-VECD Fatigue

The Dynamic Modulus Fingerprint Test is a required preliminary test prior to running the S-VECD Fatigue Test. Due to mechanical complications, not all results were usable for analysis; tests that

encountered errors were omitted from this chapter. The errorless results from this test are summarized in Table 18, while all fatigue test data is presented in Appendix B.

Table 18 - Fingerprint Dynamic Modulus and Fatigue Test Data

Binder	% RAP	Replicate	Micro strain	Initial E* (MPa)	Final E* (MPa)	N _f
PG 70-22	0	1a	150	8,368	8,270	>100,000
		1c	250	1,0131	10,042	11,620
		2b	175	8,414	8,310	>100,000
		2c	200	8,647	8,541	>100,000
		3a	150	9,216	9,082	>100,000
		3b	300	8,647	8,535	15,070
	15	1a	150	11,119	10,990	>100,000
		1b	300	12,485	12,363	1,720
		1c	250	11,695	11,569	21,430
		2a	150	10,560	10,460	>100,000
		3a	150	11,776	11,648	>100,000
		3c	250	10,478	10,421	52,490
	25	1a	150	11,491	11,402	>100,000
		2a	150	11,328	11,194	>100,000
		2b	300	11,304	11,164	2,750
		3a	150	11,529	11,468	>100,000
		3b	300	11,192	11,082	1,810
PG 64-22	25	1a	150	11,141	11,019	>100,000
		1b	300	10,214	10,124	16,590
		1c	250	9,974	9,894	11,060
		2a	150	11,251	11,117	>100,000
		3a	150	11,263	11,156	>100,000
		3c	250	11,507	11,406	3,190

ALPHA-Fatigue

The ALPHA-F software produces a model report for a set of samples. For this analysis, each mix type makes up an entire set. Since the “Identify Failure Cycle” screen did not always show the sudden drop in phase angle, it was assumed that the failure cycle was at the highest point on the graph, as shown in Figures 21 and 22.

Figure 21 - ALPHA-F Phase Angle and Failure Cycle Dialogue Box

Figure 22 - ALPHA-F Phase Angle and Failure Cycle Dialogue Box

The damage model coefficients, shift factor coefficients, master curve function coefficients, and K-values from Equations 3 – 6 in Chapter 2, are summarized in Tables 19, 20, and 21. To visually compare the damage coefficient and k-values across RAP levels, they are presented in Figures 23 – 27, respectively.

Table 19 - Damage Model Coefficients

Binder Grade	% RAP	a	b	α	r	s
PG 70-22	0	-4.83E-05	8.78E-01	3.716	1.09E+05	-4.67E-01
	15	-2.15E-05	9.19E-01	3.789	1.35E+05	-5.41E-01
	25	-1.96E-05	9.21E-01	4.084	1.26E+05	-5.43E-01
PG 64-22	25	-3.27E-05	8.74E-01	3.93	1.52E+05	-5.22E-01

Figure 23 - % RAP vs. Damage Coefficient "a"

Figure 24 - % RAP vs. Damage Coefficient "b"

Figure 25 - % RAP vs. Damage Coefficient "α"

Figure 26 - % RAP vs. Damage Parameter "r"

Figure 27 - %RAP vs. Damage Parameter "s"

Table 20 - Shift Factor Coefficients and Mastercurve Function Coefficients

Binder Grade	% RAP	Shift Factor Coefficients		Mastercurve Function			
		T_r	E_a	$\log(\text{Min})$	β	$\log(\text{Max}) - \log(\text{Min})$	γ
PG 70-22	0	21.1	199.84	1.48	2.86	-3.82E-01	-5.16E-01
	15	21.1	202.02	1.59	2.75	-7.58E-01	-5.26E-01
	25	21.1	205.68	1.79	2.55	-7.35E-01	-5.10E-01
PG 64-22	25	21.1	209.66	1.70	2.65	-7.58E-01	-5.19E-01

Table 21 - Traditional Strain Fatigue Relationship Coefficients

Binder Grade	% RAP	K_1 (kpa)	K_2 (kpa)	K_3 (kpa)	K_1 (psi)	K_2 (psi)	K_3 (psi)
PG 70-22	0	2.58E+08	2.434	-1.894	6.65E+06	2.434	-1.894
	15	1.29E+07	3.146	-2.095	2.26E+05	3.146	-2.096
	25	9.42E+06	3.213	-2.124	1.56E+05	3.213	-2.124
PG 64-22	25	1.96E+07	2.915	-1.975	4.32E+05	2.915	-1.975
Asphalt Institute		N/A	N/A	N/A	0.0796	3.291	-0.854

The fatigue coefficients measured for the samples in this research are considerably different than the values used by the Asphalt Institute¹⁶. In order to verify that the fatigue equations behaved like the equations used in Figure 4, they were plotted in Figure 28 using consistent dynamic modulus and strain levels with the AI equation using units of psi.

Visual Analysis of Fatigue Equations

Figure 28 - Visual Analysis of Fatigue Equations

The endurance limits reported by ALPHA-F are presented in Table 22. As RAP content increased, so did the endurance limit, for all reported temperatures. However, the softer binder grade performed worse than the stiffer binder grade with 0% RAP.

Table 22 - Endurance Limits

Binder Grade	% Rap	Endurance Limit (micro strain)				
		5°C	10°C	15°C	20°C	25°C
PG 70-22	0	8	8	9	9	12
	15	11	11	12	13	16
	25	15	15	15	16	19
PG 64-22	25	6	5	5	5	6

Kenpave Analysis of Dynamic Modulus

The DM and FT samples were analyzed using Kenpave in the same manner as the DM and FN samples, with the exception of using the k-values produced by ALPHA-F and the respective dynamic modulus and strain values. The results of this analysis are shown in Table 23.

Table 23 - Kenpave Analysis of DM and FT Samples

Binder Grade	% RAP	Modulus (kpa)	Full Depth		Conventional	
			ϵ	N_f	ϵ	N_f
PG 70-22	0	2,241,000	1.05E-04	1,170,000	2.73E-04	114,000
	15	6,378,000	4.25E-05	4,054,000	1.69E-04	53,000
	25	6,619,000	4.10E-05	3,827,000	1.64E-04	45,000
PG 64-22	25	6,550,000	4.15E-05	4,014,000	1.65E-04	72,000

The same trend noted for the DM and FN samples, with respect to the full depth analysis having greater N_f than conventional pavement, also appears to be true for the DM and FT samples. The strain levels are >70 micro strains, the TXDOT criteria for perpetual pavements²¹.

Master Curve Comparison

The Equation 1 regression coefficients for the master curves are given in Table 24.

Table 24 - Master Curve Coefficients

Binder	% RAP	Max E	Min E	β	γ
PG 70-22	0	3187.3	4.3	-0.86295	-0.51545
	15	3223.0	5.7	-1.24852	-0.52620
	25	3198.1	5.0	-1.33533	-0.44922
PG 64-22	25	3185.7	7.2	-1.24512	-0.51845

Despite previous research¹⁸ showing that the β term is highly sensitive to binder differentiation, between PG 70-22 and PG 64-22 with 25% RAP the difference is only 0.09021. However, the difference in the β terms between 0% RAP and 25% RAP with PG 70-22, is 0.47238. More research should be performed to determine if the addition of RAP has a correlation to the β term. It should be noted that despite using the same equation as MasterSolver, ALPHA-F uses SI units, and therefore the master curve coefficients in Table 20 look very different from Table 24.

In order to determine if DM and FN and DM and FT specimens are significantly different, their respective master curves will be compared by plotting them on the same graph. The master curves will also be compared by the RAP content for both DM and FN samples and DM and FT samples. The results are shown below:

Figure 29 - Comparison of 0% RAP Between DM and FN and DM and FT

Figure 30 - Comparison of 15% RAP Between DM and FN and DM and FT

Figure 31 - Comparison of 25% RAP Between DM and FN and DM and FT

DM and FN Comparison

Figure 32 - DM and FN Master Curve Comparison by % RAP

Figure 33- DM and FT Master Curve Comparison by %RAP

Chapter 5: Conclusions and Recommendations

Dynamic Modulus Conclusions

From the analyzed data presented in Chapter 4, it can be concluded that mixes with a 15% and 25% RAP content had a higher dynamic modulus value at the tested temperatures and frequencies than the virgin mix. The data shows when comparing RAP containing mixtures, the greater RAP content does not mean that the dynamic modulus will also be greater. For example, Figure 6 shows 15% RAP has a higher dynamic modulus than 25% RAP. More research is recommended to determine if RAP mixes react differently, compared to virgin mixtures, at other testing temperatures.

Showing RAP mixes have a higher dynamic modulus is important because dynamic modulus is generally described as the stiffness of the mix. If the mix is stiffer, then it may have a higher susceptibility to fatigue cracking, but lower susceptibility to permanent deformation. Further research is suggested to see if there is an optimum RAP content based on dynamic modulus values.

Flow Number Conclusions

From the analyzed data presented in Chapter 4, it can be concluded that mixes with 15% and 25% RAP content had a higher flow number than the virgin mix. In comparing the laboratory test results to the FHWA Criteria (Table 4), it was found that the virgin mix design did not meet the flow number required for the design traffic designated on the job mix formula sheet. However, both the 15% and 25% RAP mixes exceeded the minimum. Higher flow numbers mean that the mix is less susceptible to permanent deformation which was also reflected by the dynamic modulus analysis.

ALPHA-Fatigue Conclusions

From the analyzed data presented in Chapter 4, it can be concluded that the fatigue equations produced by ALHPA-F are reasonable. It was found that there is a large range of variation for these coefficients depending on the type of mix, asphalt content, and units used during testing and analysis.

The damage coefficients used in the ALPHA-F analysis were also compared across RAP levels. The absolute value of damage coefficients “b” and “ α ” and damage parameters “r” and “s”, all increase with an increase in RAP, while the absolute value of damage coefficient “a” decreases. The absolute value of damage coefficient “ α ” and damage parameters “r” and “s”, all increase with a softer binder, while the absolute value of damage coefficients “a” and “b” decrease with a softer binder. These coefficients are used in the modeling of the damage characteristic curve. If there is a relationship between the damage coefficients and RAP content, then there may also be a relationship in the damage characteristics and the K-values used in the traditional fatigue equation.

Kenpave Conclusions

According to the results of Kenpave analysis of the DM and FN samples, as RAP content increased, so did the number of cycles to failure in both full-depth and conventional pavement structures. This can be explained by the RAP mixtures experiencing lower strain since their dynamic modulus values were greater than the virgin mixture.

The Kenpave analysis of the DM and FT samples showed a greater number of cycles to failure for the RAP containing mixtures in the full-depth pavement structure. However, the

virgin mix performed significantly better in a conventional pavement structure than the RAP containing mixtures.

In comparing the N_f values based off of the k -values determined by ALPHA-F and Asphalt Institute, it was seen that there is a significant difference between them. The DM and FN samples were only evaluated based on the dynamic modulus, while the DM and FT used both the dynamic modulus and damage characteristic equations. More research is recommended to evaluate if using Kenpave with ALPHA-F is a viable option.

Recommendations

There are several recommendations to the experimental design. The first recommendation is that more replicates be prepared to continue the dynamic modulus and flow number research performed in the spring of 2014 (DM and FN samples). This research only used two replicates due to time and material constraints. Second, not all 36 S-VECD Fatigue specimens were able to be analyzed using the ALPHA-F software. It is recommended to prepare additional specimens to replace the ones that experience errors during testing to achieve complete triplicates of each mix design. Third, in order to reduce the number of specimens lost, the cause of errors during testing should be eliminated. It is suspected that the errors encountered were from the LVDT jiggling out of the gauge fixtures after the fingerprint test. Further research is recommended to develop a way to keep the LVDTs from experiencing errors. Finally, 0% and 15% RAP contents with PG 64-22 should also be tested using the same method as the 25% RAP. These mix designs were not able to be prepared and tested due to time and material constraints.

Additional research topics were mentioned throughout this paper, in summary:

- Determining if there is an optimum RAP content that produces a peak dynamic modulus
- AMPT sample preparation method that reduces edge breaking
- Determine if correlation exists between RAP content and β term in master curve equation
- Determine if correlation exists between RAP content and damage coefficients and K-values
- Determine if ALPHA-F equations can be used with strains reported using Kenpave analysis

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Appendix A

Job Mix Formulas

T400

04-10

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

Report Number: 1421924		Date Accepted: June 14, 2011	
HMA Type: 19.0 mm w/RAP		HMA Code: 13242	
Producer: Southern WV Asphalt		Plant Location: Beaver, WV	
Designed By: Mark Isaacs		Design Lab: Southern WV Asphalt-Alta, WV	
Plant Type: Drum		Plant Make: ASTEC	
Plant Code: A0770		Design ESALs 3 to 30 million (3)	

MIX COMPOSITION						
Coarse Aggregate Source			Code	Fine Aggregate Source		Code
CA ₁	Boxley Aggregates, Lewisburg WV		G079A	FA ₂	Boxley Aggregates, Lewisburg WV	
CA ₂	Boxley Aggregates, Lewisburg WV		G079A	FA ₃	Boxley Aggregates, Lewisburg WV	
FA ₁				FA ₄		
	CA ₁	CA ₂	CA ₃	FA ₁	FA ₂	FA ₃
Agg. Type	#67 Limestone	#8 Limestone		Limestone	Limestone (w/)	
Agg. Code	1131	1135		1116	1116	
% Total Agg.	35	15		15	10	
% RAP Total Agg.:	25		Blended Binder G*/sin delta if > 25% RAP:			
% Binder In RAP Design:	3.1		Binder Type:	PG 70-22	Binder Code:	1091
Binder Source:	Shelly Liquid Division-Kanauga, OH				Binder Source Code:	M001A

Sieve Fraction								Fines/Effective Asphalt Ratio	Tensile Strn. Ratio
Sieve Size	Target	Allowable		Sieve Size	Target	Allowable		1.2	86.6
		Min.	Max.			Min.	Max.		
2" (50 mm)				#4 (4.75 mm)	48			Temperature Range Completed Mixture (°F)	
1.5" (37.5 mm)				#8 (2.36 mm)	34	28	40		
1" (25 mm)	100	100	100	#16 (1.18 mm)	22			Desirable Mean Temp.	Temp. Range Min. Max.
3/4" (19 mm)	98	90	100	#30 (600 µm)	15				
1/2" (12.5 mm)	87		90	#50 (300 µm)	10			311	286 336
3/8" (9.5 mm)	75			#200 (75 µm)	5.1	2.0	8.0		

JOB MIX FORMULA VALUES				
		Job Mix Formula	Job Mix Formula Tolerances	
Specific gravity stone bulk (Gsb):	Design Property	Design Targets	Minimum	Maximum
2.695	Asphalt (%)	4.7	4.3	5.1
	Air Voids (%)	4.0	2.8	5.2
	VMA (%)	14.1	13.1	15.1
	VFA (%)	72	70	78
Maximum Density (kg/m ³)				
2526				
Gyrations @ N _{design}	80	Desirable Mean Temp. for Lab. Specimens (°F):		Comp. Temp.: 306 Mixing Temp.: 312

Remarks: This JMF was designed for use on the West Virginia Parkway Authority as per Change Order #1 and Supplemental Agreement #1 dated 3/28/2011.

This agreement allows the substitution of WMA for HMA pavement and the use of RAP up to 25 percent (see change order for specific details). When used as WMA the following will apply: 1) target mix temperature will be 281°F with a range of 256 to 306°F 2) 1% to 3% water (by weight of PG binder) will be added.

Figure 34 - Job Mix Formula for PG 70-22 0% RAP

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RAP-1515

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

Report Number:	1394738	Date Accepted:	April 5, 2010
HMA Type:	19 mm w/RAP	HMA Code:	13242
Producer:	Southern WV Asphalt	Plant Location:	Beaver, WV
Designed By:	Wayne Ingram & Dallas Roggess	Design Lab:	Southern WV Asphalt, Ingleside, WV
Plant Type:	Drum	Plant Make:	Astec
Plant Code:	A0770	Design ESALs:	3 to < 30 million (3)

MIX COMPOSITION						
Coarse Aggregate Source		Code	Fine Agg. / Mineral Filler Source		Code	
CA ₁	Boxley Aggregates, Lewisburg, WV	G079A	FA ₁	Boxley Aggregates, Lewisburg, WV	G079A	
CA ₂	Boxley Aggregates, Lewisburg, WV	G079A	FA ₂	Boxley Aggregates, Lewisburg, WV	G079A	
CA ₃			FA ₃			
	CA ₁	CA ₂	CA ₃	FA ₁	FA ₂	FA ₃
Agg. Type	#67 Limestone	#8 Limestone		Limestone	(No Washed)	
Agg. Code	1131	1135		1116		
% Total Agg.	35	20		(31) 30		
% RAP Total Agg.:	(14) 15		Blended Binder G*/in delta if > 25% RAP:			
% Binder in RAP Design:	4.2		Binder Type:	PG 70-22	Binder Code:	1091
Binder Source:	Shelly Liquid Division, Kanawga, Oh.			Binder Source Code: M001A		

Sieve Fraction							Fines / Effective Asphalt Ratio	Tensile Strn. Ratio	
Sieve Size	Target	Allowable		Sieve Size	Target	Allowable		1.2	88.1
		Min.	Max.			Min.	Max.		
2" (50 mm)				#4 (4.75 mm)	45			Temperature Range Completed Mixture (°F)	
1.5" (37.5mm)				#8 (2.36 mm)	30	24	36		
1" (25 mm)	100	100	100	#16 (1.18 mm)	20				
3/4" (19 mm)	96	90	100	#30 (600 µm)	14				
1/2" (12.5mm)	83		90	#50 (300 µm)	10				
3/8" (9.5 mm)	69			#200 (75 µm)	5.2	2.0	8.0	311	286 336

JOB MIX FORMULA VALUES				
Job Mix Formula Targets			Job Mix Formula Tolerances	
Specific gravity stone bulk (G _{sb}): 2.676	Design Property	Accepted Target	Minimum	Maximum
Maximum	Asphalt (%)	5.1	4.7	5.5
Density (kg/m ³)	Air Voids (%)	4.0	2.8	5.2
2523	VMA (%)	14.4	13.4	15.4
	VFA (%)	72	70	78
Gyrations @ N _{target} :		Gyrations @ N _{design} :	80	Gyrations @ N _{max} :

Remarks: This design was formulated in accordance with memorandum dated 1/21/2010 "Superpave Mix Design Gyrations Level Changes". Additional mix design data for this JMF can be found under T-400# 1356096 and 1394738.

100 #6 mix - 5

Figure 35 - Job Mix Formula for PG 70-22 15% RAP

T400 SP
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WEST VIRGINIA DIVISION OF HIGHWAYS JOB MIX FORMULA FOR SUPERPAVE HOT-MIX ASPHALT

Report Number: 1421927				Date Accepted: June 16, 2011			
HMA Type: 19 mm				HMA Code: 13242			
Producer: Southern WV Asphalt				Plant Location: Beaver, WV			
Designed By: Mark Isaacs & Dallas Boggess				Design Lab: Southern WV Asphalt - Lewisburg, WV			
Plant Type: Drum				Plant Make: ASTEC			
Plant Code: A0770				Design ESALs: 3 to < 30 million (3)			
MIX COMPOSITION							
Coarse Aggregate Source			Code	Fine Aggregate Source			Code
CA ₁	Boxley Aggregates - Lewisburg, WV		G079A	FA ₁	Boxley Aggregates - Lewisburg, WV		G079A
CA ₂	Boxley Aggregates - Lewisburg, WV		G079A	FA ₂	Boxley Aggregates - Lewisburg, WV		G079A
CA ₃				FA ₃			
	CA ₁	CA ₂	CA ₃	FA ₁	FA ₂	FA ₃	
Agg. Type	# 67 Limestone	# 8 Limestone		Limestone	Limestone (u)		
Agg. Code	1131	1135		1116	1116		
% Total Agg.	38	22		25	15		
% RAP Total Agg.:			Blended Binder G*/sin delta if > 25% RAP:				
% Binder In RAP Design:			Binder Type:	PG 70-22	Binder Code:	1091	
Binder Source:			Shelly Liquid Division - Kanauga, Oh.			Binder Source Code:	M001A
Sieve Fraction							
Sieve Size	Target	Allowable		Sieve Size	Target	Allowable	
		Min.	Max.			Min.	Max.
2" (50 mm)				#4 (4.75 mm)	46		
1.5" (37.5 mm)				#8 (2.36 mm)	29	23	35
1" (25 mm)	100	100	100	#16 (1.18 mm)	19		
3/4" (19 mm)	99	90	100	#30 (600 µm)	12		
1/2" (12.5 mm)	83		90	#50 (300 µm)	8		
3/8" (9.5 mm)	73			#200 (75 µm)	5.0	2.0	8.0
						Fines / Effective Asphalt Ratio	Tensile Strn. Ratio
						0.8	96.0
Temperature Range Completed Mixture (°F)							
						Desirable Mean Temp.	Temp. Range Min. Max.
						311	286 336
JOB MIX FORMULA VALUES							
		Job Mix Formula		Job Mix Formula Tolerances			
Specific gravity stone bulk (Gsb): 2.679	Design Property	Design Targets		Minimum		Maximum	
	Asphalt (%)	4.9		4.5		5.3	
	Air Voids (%)	4.0		2.8		5.2	
Maximum Density (kg/m³)	VMA (%)	15.0		14.0		16.0	
2501	VFA (%)	72		70		78	
Gyrations @ N_{design}:	80	Desirable Mean Temp. for Lab. Specimens (°F):		Comp. Temp.:	309	Mixing Temp.:	330

Remarks: Mix design data for this JMF can be found under T-400# 1420971 (Alta plant).

Figure 36 - Job Mix Formula for PG 70-22 25% RAP

Aggregate Properties

Design Package
Attachment #8

WEST VIRGINIA DIVISION OF HIGHWAYS
WORKSHEET FOR CALCULATING BULK SPECIFIC
GRAVITY AND ABSORPTION OF COARSE AGGREGATE

Source	<u>Boxley</u>	<u>G079A</u>
Type	<u>L/S 67s</u>	
Tested by	<u>Mark Isaacs</u>	
Date	<u>1/7/14</u>	

COARSE AGGREGATE (RECORD WEIGHTS TO THE NEAREST 0.1 GRAMS)			
A = Weight of oven-dry sample in air		<u>4033.6</u>	
B = Weight of saturated-surface-dry sample in air		<u>4061.3</u>	
C = Weight of saturated sample in water		<u>2570.1</u>	
Bulk Specific Gravity (Oven-dry Basis) =			
	$\frac{A}{B - C}$	=	<u>2.705</u>
	(SSD)		<u>2.724</u>
Apparent Specific Gravity =	$\frac{A}{A - C}$	=	<u>2.756</u>
Absorption, percent =	$\frac{B - A}{A} \times 100$	=	<u>0.69</u>
<p><i>Note: Report the following values to the nearest thousandth (0.001):</i> <i>Bulk and Apparent Specific Gravities</i> <i>Report % Absorption to the nearest hundredth (0.01)</i></p>			

Figure 37 - Aggregate Properties of L/S 67's

WEST VIRGINIA DIVISION OF HIGHWAYS

WASHED SIEVE ANALYSIS (AASHTO T-11 AND T-27)

Producer Boxley Aggregate Source G079A
 Type of Mix _____ Aggregate Type L/S 67s
 Technician Mark Isaacs Date 1/7/14

Sieve Size	Weight Retained	Percent Loss	Percent Passing
2 1/2" (63mm)		0.0	100.0
2" (50mm)	0.0	0.0	100.0
1 1/2" (37.5mm)	0.0	0.0	100.0
1" (25mm)	0.0	0.0	100.0
3/4" (19mm)	188.6	7.3	92.7
1/2" (12.5mm)	889.6	34.2	58.5
3/8" (9.5mm)	622.3	23.9	34.6
#4 (4.75mm)	798.9	30.7	3.8
#8 (2.36mm)	55.3	2.1	1.7
#16 (1.18mm)	1.0	0.0	1.7
#30 (600um)	1.6	0.1	1.6
#50 (300um)	0.9	0.0	1.6
#100 (150um)	1.9	0.1	1.5
#200 (75um)	3.0	0.1	1.4
- #200	35.6	1.4	
Total	2598.7		
<div> <div>(A) Weight of original sample</div> <div>2599.6</div> </div> <div> <div>(B) Weight after wash</div> <div>2566.3</div> </div> <div> <div>(C) Loss of - #200 after wash</div> <div>33.3</div> </div> <div> <div>(D) - #200 from sieving (Pan Weight)</div> <div>2.3</div> </div> <div> <div>(T) Total passing #200 (C + D)</div> <div>35.6</div> </div>			

Note: Report all values to the nearest tenth (0.1)

Figure 38 - Aggregate Gradation 1 L/S 67's

WEST VIRGINIA DIVISION OF HIGHWAYS

WASHED SIEVE ANALYSIS (AASHTO T-11 AND T-27)

Producer Boxley Aggregate Source G079A
 Type of Mix _____ Aggregate Type L/S 67s
 Technician Mark Isaacs Date 1/7/14

Sieve Size	Weight Retained	Percent Loss	Percent Passing
2 1/2" (63mm)		0.0	100.0
2" (50mm)		0.0	100.0
1 1/2" (37.5mm)	0.0	0.0	100.0
1" (25mm)	0.0	0.0	100.0
3/4" (19mm)	335.9	12.7	87.3
1/2" (12.5mm)	1023.6	38.5	48.8
3/8" (9.5mm)	540.6	20.4	28.4
#4 (4.75mm)	650.2	24.5	3.9
#8 (2.36mm)	66.3	2.5	1.4
#16 (1.18mm)	0.5	0.0	1.4
#30 (600um)	0.6	0.0	1.4
#50 (300um)	0.6	0.0	1.4
#100 (150um)	3.2	0.1	1.2
#200 (75um)	2.1	0.1	1.2
- #200	30.9	1.2	
Total	2654.5		
<div> <div>(A) Weight of original sample</div> <div>2655.3</div> </div> <div> <div>(B) Weight after wash</div> <div>2626.3</div> </div> <div> <div>(C) Loss of - #200 after wash</div> <div>29.0</div> </div> <div> <div>(D) - #200 from sieving (Pan Weight)</div> <div>1.9</div> </div> <div> <div>(T) Total passing #200 (C + D)</div> <div>30.9</div> </div>			

Note: Report all values to the nearest tenth (0.1)

WEST VIRGINIA DIVISION OF HIGHWAYS

WASHED SIEVE ANALYSIS

Figure 39 - Aggregate Gradation 2 L/S 67's

(AASHTO T-11 AND T-27)

Producer Boxley Aggregate Source G079A
 Type of Mix _____ Aggregate Type L/S 67s
 Technician Mark Isaacs Date 1/7/14

Sieve Size	Weight Retained	Percent Loss	Percent Passing
2 1/2" (63mm)		0.0	100.0
2" (50mm)		0.0	100.0
1 1/2" (37.5mm)	0.0	0.0	100.0
1" (25mm)	0.0	0.0	100.0
3/4" (19mm)	251.6	9.8	90.2
1/2" (12.5mm)	812.3	31.7	58.5
3/8" (9.5mm)	733.9	28.6	29.9
#4 (4.75mm)	663.3	25.8	4.1
#8 (2.36mm)	55.3	2.2	1.9
#16 (1.18mm)	2.0	0.1	1.9
#30 (600um)	0.4	0.0	1.8
#50 (300um)	0.9	0.0	1.8
#100 (150um)	1.2	0.0	1.8
#200 (75um)	1.6	0.1	1.7
- #200	43.5	1.7	
Total	2566.0		
(A) Weight of original sample			
			2566.3
(B) Weight after wash			
			2525.9
(C) Loss of - #200 after wash			
			40.4
(D) - #200 from sieving (Pan Weight)			
			3.1
(T) Total passing #200 (C + D)			
			43.5

Note: Report all values to the nearest tenth (0.1)

Figure 40 - Aggregate Gradation 3 L/S 67's

Design Package
Attachment #8

WEST VIRGINIA DIVISION OF HIGHWAYS
WORKSHEET FOR CALCULATING BULK SPECIFIC
GRAVITY AND ABSORPTION OF COARSE AGGREGATE

Source	Boxley	G079A
Type	L/S 8s	
Tested by	Mark Isaacs	
Date	1/7/14	

COARSE AGGREGATE (RECORD WEIGHTS TO THE NEAREST 0.1 GRAMS)		
A = Weight of oven-dry sample in air		2588.6
B = Weight of saturated-surface-dry sample in air		2602.3
C = Weight of saturated sample in water		1644.3
Bulk Specific Gravity (Oven-dry Basis) =	$\frac{A}{B - C}$	2.702
	(SSD)	2.716
Apparent Specific Gravity =	$\frac{A}{A - C}$	2.741
Absorption, percent =	$\frac{B - A}{A} \times 100$	0.53
<i>Note: Report the following values to the nearest thousandth (0.001): Bulk and Apparent Specific Gravities Report % Absorption to the nearest hundredth (0.01)</i>		

Figure 41 - Aggregate Properties L/S 8's

WEST VIRGINIA DIVISION OF HIGHWAYS

WASHED SIEVE ANALYSIS
(AASHTO T-11 AND T-27)

Producer Boxley Aggregate Source G079A
 Type of Mix _____ Aggregate Type L/S 8s
 Technician Mark Isaacs Date 1/7/14

Sieve Size	Weight Retained	Percent Loss	Percent Passing
2 1/2" (63mm)		0.0	100.0
2" (50mm)	0.0	0.0	100.0
1 1/2" (37.5mm)	0.0	0.0	100.0
1" (25mm)	0.0	0.0	100.0
3/4" (19mm)	0.0	0.0	100.0
1/2" (12.5mm)	0.0	0.0	100.0
3/8" (9.5mm)	193.0	11.9	88.1
#4 (4.75mm)	1244.9	76.7	11.3
#8 (2.36mm)	133.2	8.2	3.1
#16 (1.18mm)	15.9	1.0	2.1
#30 (600um)	1.1	0.1	2.1
#50 (300um)	0.9	0.1	2.0
#100 (150um)	1.3	0.1	1.9
#200 (75um)	1.9	0.1	1.8
- #200	29.3	1.8	
Total	1621.5		
(A) Weight of original sample			1622.3
(B) Weight after wash			1594.9
(C) Loss of - #200 after wash			27.4
(D) - #200 from sieving (Pan Weight)			1.9
(T) Total passing #200 (C + D)			29.3

Note: Report all values to the nearest tenth (0.1)

Figure 42 - Aggregate Gradation 1 L/S 8's

WEST VIRGINIA DIVISION OF HIGHWAYS

WASHED SIEVE ANALYSIS (AASHTO T-11 AND T-27)

Producer Boxley Aggregate Source G079A
 Type of Mix _____ Aggregate Type L/S 8s
 Technician Mark Isaacs Date 1/7/14

Sieve Size	Weight Retained	Percent Loss	Percent Passing
2 1/2" (63mm)		0.0	100.0
2" (50mm)		0.0	100.0
1 1/2" (37.5mm)	0.0	0.0	100.0
1" (25mm)	0.0	0.0	100.0
3/4" (19mm)	0.0	0.0	100.0
1/2" (12.5mm)	0.0	0.0	100.0
3/8" (9.5mm)	176.3	11.4	88.6
#4 (4.75mm)	1188.6	77.0	11.6
#8 (2.36mm)	144.2	9.3	2.3
#16 (1.18mm)	11.9	0.8	1.5
#30 (600um)	0.5	0.0	1.5
#50 (300um)	0.6	0.0	1.4
#100 (150um)	1.0	0.1	1.4
#200 (75um)	1.1	0.1	1.3
- #200	20.2	1.3	
Total	1544.4		
(A) Weight of original sample			1544.6
(B) Weight after wash			1526.3
(C) Loss of - #200 after wash			18.3
(D) - #200 from sieving (Pan Weight)			1.9
(T) Total passing #200 (C + D)			20.2

Note: Report all values to the nearest tenth (0.1)

WEST VIRGINIA DIVISION OF HIGHWAYS

WASHED SIEVE ANALYSIS

Figure 43 - Aggregate Gradation 2 L/S 8's

(AASHTO T-11 AND T-27)

Producer Boxley Aggregate Source G079A
 Type of Mix _____ Aggregate Type L/S 8s
 Technician Mark Isaacs Date 1/7/14

Sieve Size	Weight Retained	Percent Loss	Percent Passing
2 1/2" (63mm)		0.0	100.0
2" (50mm)		0.0	100.0
1 1/2" (37.5mm)	0.0	0.0	100.0
1" (25mm)	0.0	0.0	100.0
3/4" (19mm)	0.0	0.0	100.0
1/2" (12.5mm)	0.0	0.0	100.0
3/8" (9.5mm)	196.3	12.4	87.5
#4 (4.75mm)	1212.6	76.8	10.7
#8 (2.36mm)	134.9	8.5	2.2
#16 (1.18mm)	6.9	0.4	1.8
#30 (600um)	1.6	0.1	1.7
#50 (300um)	0.9	0.1	1.6
#100 (150um)	1.3	0.1	1.5
#200 (75um)	2.1	0.1	1.4
- #200	22.0	1.4	
Total	1578.6		
(A) Weight of original sample			
			1579.3
(B) Weight after wash			
			1559.3
(C) Loss of - #200 after wash			
			20.0
(D) - #200 from sieving (Pan Weight)			
			2.0
(T) Total passing #200 (C + D)			
			22.0

Note: Report all values to the nearest tenth (0.1)

Figure 44 - Aggregate Gradation 3 L/S 8's

Design Package
Attachment #8A

**WORKSHEET FOR CALCULATING BULK SPECIFIC
GRAVITY AND ABSORPTION OF FINE AGGREGATE**

Source	Boxley	G079A
Type	F/Sand	
Tested by	Mark Isaacs	
Date	1/10/14	

FINE AGGREGATE (RECORD WEIGHTS TO THE NEAREST 0.1 GRAMS)		
A = Weight of oven-dry sample in air		492.8
B = Weight of flask filled to calibration mark with distilled water		1270.4
C = Weight of flask, sample, and water to calibration mark		1584.8
D = Weight of saturated-surface-dry sample in air		502.0
Bulk Specific Gravity (Oven-dry Basis) =	$\frac{A}{B + D - C}$	= 2.627
(SSD)		2.676
Apparent Specific Gravity =	$\frac{A}{B + A - C}$	= 2.762
Absorption, percent =	$\frac{D - A}{A} \times 100$	= 1.87

*Note: Report the following values to the nearest thousandth (0.001):
Bulk and Apparent Specific Gravities
Report % Absorption to the nearest hundredth (0.01)*

Figure 45 - Aggregate Properties L/S F-Sand

WEST VIRGINIA DIVISION OF HIGHWAYS

WASHED SIEVE ANALYSIS
(AASHTO T-11 AND T-27)

Producer Boxley Aggregate Source G079A
 Type of Mix _____ Aggregate Type F/Sand
 Technician Mark Isaacs Date 1/10/14

Sieve Size	Weight Retained	Percent Loss	Percent Passing
2 1/2" (63mm)		0.0	99.8
2" (50mm)		0.0	99.8
1 1/2" (37.5mm)	0.0	0.0	99.8
1" (25mm)	0.0	0.0	99.8
3/4" (19mm)	0.0	0.0	99.8
1/2" (12.5mm)	0.0	0.0	99.8
3/8" (9.5mm)	0.0	0.0	99.8
#4 (4.75mm)	5.1	1.4	98.4
#8 (2.36mm)	97.0	26.4	72.0
#16 (1.18mm)	88.6	24.1	47.9
#30 (600um)	45.9	12.5	35.4
#50 (300um)	39.6	10.8	24.6
#100 (150um)	30.2	8.2	16.4
#200 (75um)	19.9	5.4	11.0
- #200	40.4	11.0	
Total	366.7		
(A) Weight of original sample			366.9
(B) Weight after wash			329.6
(C) Loss of - #200 after wash			37.3
(D) - #200 from sieving (Pan Weight)			3.1
(T) Total passing #200 (C + D)			40.4

Note: Report all values to the nearest tenth (0.1)

Figure 46 - Aggregate Gradation 1 L/S F-Sand

WEST VIRGINIA DIVISION OF HIGHWAYS

WASHED SIEVE ANALYSIS
(AASHTO T-11 AND T-27)

Producer Boxley Aggregate Source G079A
 Type of Mix _____ Aggregate Type F/Sand
 Technician Mark Isaacs Date 1/10/14

Sieve Size	Weight Retained	Percent Loss	Percent Passing
2 1/2" (63mm)		0.0	99.9
2" (50mm)		0.0	99.9
1 1/2" (37.5mm)	0.0	0.0	99.9
1" (25mm)	0.0	0.0	99.9
3/4" (19mm)	0.0	0.0	99.9
1/2" (12.5mm)	0.0	0.0	99.9
3/8" (9.5mm)	0.0	0.0	99.9
#4 (4.75mm)	4.1	1.2	98.7
#8 (2.36mm)	80.1	23.8	74.9
#16 (1.18mm)	66.9	19.9	55.0
#30 (600um)	57.6	17.1	37.9
#50 (300um)	44.9	13.4	24.5
#100 (150um)	31.9	9.5	15.0
#200 (75um)	15.7	4.7	10.3
- #200	34.6	10.3	
Total	335.8		
(A) Weight of original sample <u>335.9</u> (B) Weight after wash <u>302.9</u> (C) Loss of - #200 after wash <u>33.0</u> (D) - #200 from sieving (Pan Weight) <u>1.6</u> (T) Total passing #200 (C + D) <u>34.6</u>			

Note: Report all values to the nearest tenth (0.1)

Figure 47 -- Aggregate Gradation 2 L/S F-Sand

WEST VIRGINIA DIVISION OF HIGHWAYS

WASHED SIEVE ANALYSIS (AASHTO T-11 AND T-27)

Producer Boxley Aggregate Source G079A
 Type of Mix _____ Aggregate Type F/Sand
 Technician Mark Isaacs Date 1/10/14

Sieve Size	Weight Retained	Percent Loss	Percent Passing
2 1/2" (63mm)		0.0	100.0
2" (50mm)		0.0	100.0
1 1/2" (37.5mm)	0.0	0.0	100.0
1" (25mm)	0.0	0.0	100.0
3/4" (19mm)	0.0	0.0	100.0
1/2" (12.5mm)	0.0	0.0	100.0
3/8" (9.5mm)	0.0	0.0	100.0
#4 (4.75mm)	1.9	0.6	99.4
#8 (2.36mm)	83.9	24.4	75.0
#16 (1.18mm)	66.8	19.4	55.6
#30 (600um)	56.1	16.3	39.3
#50 (300um)	44.9	13.0	26.3
#100 (150um)	31.6	9.2	17.1
#200 (75um)	18.9	5.5	11.6
- #200	39.8	11.6	
Total	343.9		
(A) Weight of original sample			
			344.2
(B) Weight after wash			
			305.3
(C) Loss of - #200 after wash			
			38.9
(D) - #200 from sieving (Pan Weight)			
			0.9
(T) Total passing #200 (C + D)			
			39.8

Note: Report all values to the nearest tenth (0.1)

Figure 48 - Aggregate Gradation 3 L/S F-Sand

Design Pack:
Attachment #

**WORKSHEET FOR CALCULATING BULK SPECIFIC
GRAVITY AND ABSORPTION OF FINE AGGREGATE**

Source	Boxley	G079A
Type	W/Sand	
Tested by	Mark Isaacs	
Date	1/10/14	

FINE AGGREGATE
(RECORD WEIGHTS TO THE NEAREST 0.1 GRAMS)

A = Weight of oven-dry sample in air		498.1
B = Weight of flask filled to calibration mark with distilled water		1270.4
C = Weight of flask, sample, and water to calibration mark		1586.9
D = Weight of saturated-surface-dry sample in air		502.0

Bulk Specific Gravity (Oven-dry Basis) =	$\frac{A}{B + D - C}$	=	2.685
(SSD)			2.706
Apparent Specific Gravity =	$\frac{A}{B + A - C}$	=	2.743

Absorption, percent =	$\frac{D - A}{A} \times 100$	=	0.78
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*Note: Report the following values to the nearest thousandth (0.001):
Bulk and Apparent Specific Gravities
Report % Absorption to the nearest hundredth (0.01)*

Figure 49 - Aggregate Properties L/S W-Sand

WEST VIRGINIA DIVISION OF HIGHWAYS

WASHED SIEVE ANALYSIS
(AASHTO T-11 AND T-27)

Producer Boxley Aggregate Source G079A
 Type of Mix _____ Aggregate Type W/Sand
 Technician Mark Isaacs Date 1/10/14

Sieve Size	Weight Retained	Percent Loss	Percent Passing
2 1/2" (63mm)		0.0	99.9
2" (50mm)		0.0	99.9
1 1/2" (37.5mm)	0.0	0.0	99.9
1" (25mm)	0.0	0.0	99.9
3/4" (19mm)	0.0	0.0	99.9
1/2" (12.5mm)	0.0	0.0	99.9
3/8" (9.5mm)	0.0	0.0	99.9
#4 (4.75mm)	2.1	0.6	99.3
#8 (2.36mm)	94.6	26.6	72.7
#16 (1.18mm)	85.6	24.1	48.6
#30 (600um)	65.1	18.3	30.3
#50 (300um)	49.9	14.0	16.3
#100 (150um)	33.2	9.3	7.0
#200 (75um)	15.8	4.4	2.6
- #200	9.1	2.6	
Total	355.4		
(A) Weight of original sample 355.6 (B) Weight after wash 347.2 (C) Loss of - #200 after wash 8.4 (D) - #200 from sieving (Pan Weight) 0.7 (T) Total passing #200 (C + D) 9.1			

Note: Report all values to the nearest tenth (0.1)

Figure 50 - Aggregate Gradation 1 L/S W-Sand

WEST VIRGINIA DIVISION OF HIGHWAYS

WASHED SIEVE ANALYSIS (AASHTO T-11 AND T-27)

Producer Boxley Aggregate Source G079A
 Type of Mix _____ Aggregate Type W/Sand
 Technician Mark Isaacs Date 1/10/14

Sieve Size	Weight Retained	Percent Loss	Percent Passing
2 1/2" (63mm)		0.0	99.9
2" (50mm)		0.0	99.9
1 1/2" (37.5mm)	0.0	0.0	99.9
1" (25mm)	0.0	0.0	99.9
3/4" (19mm)	0.0	0.0	99.9
1/2" (12.5mm)	0.0	0.0	99.9
3/8" (9.5mm)	0.0	0.0	99.9
#4 (4.75mm)	2.5	0.7	99.2
#8 (2.36mm)	84.9	25.3	73.9
#16 (1.18mm)	75.1	22.3	51.6
#30 (600um)	68.4	20.3	31.3
#50 (300um)	44.1	13.1	18.2
#100 (150um)	32.1	9.5	8.7
#200 (75um)	20.1	6.0	2.7
- #200	9.2	2.7	
Total	336.4		
(A) Weight of original sample 336.2 (B) Weight after wash 328.1 (C) Loss of - #200 after wash 8.1 (D) - #200 from sieving (Pan Weight) 1.1 (T) Total passing #200 (C + D) 9.2			

Note: Report all values to the nearest tenth (0.1)

WEST VIRGINIA DIVISION OF HIGHWAYS

WASHED SIEVE ANALYSIS

Figure 51 - Aggregate Gradation 2 L/S W-Sand

(AASHTO T-11 AND T-27)

Producer Boxley Aggregate Source G079A
 Type of Mix _____ Aggregate Type W/Sand
 Technician Mark Isaacs Date 1/10/14

Sieve Size	Weight Retained	Percent Loss	Percent Passing
2 1/2" (63mm)		0.0	99.8
2" (50mm)		0.0	99.8
1 1/2" (37.5mm)	0.0	0.0	99.8
1" (25mm)	0.0	0.0	99.8
3/4" (19mm)	0.0	0.0	99.8
1/2" (12.5mm)	0.0	0.0	99.8
3/8" (9.5mm)	0.0	0.0	99.8
#4 (4.75mm)	2.2	0.7	99.1
#8 (2.36mm)	77.9	23.9	75.2
#16 (1.18mm)	85.6	26.3	48.9
#30 (600um)	64.2	19.7	29.2
#50 (300um)	48.9	15.0	14.2
#100 (150um)	21.9	6.7	7.5
#200 (75um)	16.2	5.0	2.5
- #200	8.3	2.5	
Total	325.2		
(A) Weight of original sample <u>325.9</u> (B) Weight after wash <u>318.6</u> (C) Loss of - #200 after wash <u>7.3</u> (D) - #200 from sieving (Pan Weight) <u>1.0</u> (T) Total passing #200 (C + D) <u>8.3</u>			

Note: Report all values to the nearest tenth (0.1)

Figure 52 - Aggregate Gradation 3 L/S W-Sand

RAP Properties

T417
Rev. 01-01

Burnoff #1

West Virginia Division of Highways

**Asphalt Content By Ignition Method (AASHTO T308, Test Method A) And
Mechanical Analysis Of Extracted Aggregate - AASHTO T30**

Lab Number: _____ Material: *Burnoff #1* Field Sample #: *1A*
Technician: *LKS* T400 #: _____ Cal. Factor: *1* Date: *3/24/15*

Data Before Ignition		Test Temp: <i>538</i> °C	Data After Ignition	
(A) Weight of Basket + Sample	<i>447.2</i>		(D) Weight of Basket + Aggregate	<i>4369.5</i>
(B) Weight of Basket	<i>3408.7</i>		(E) Weight of Basket	<i>3408.8</i>
(C) Sample Weight (A - B)	<i>1008.5</i>		(F) Aggregate Weight (D - E)	<i>960.7</i>
(K) Percent Asphalt Check: $\{ [(C - F) / C] \times 100 - (\text{Calibration Factor}) \}$			<i>4.74</i>	
Asphalt Content From Ignition Oven Printout Shall Be Used As Actual % Asphalt			<i>4.74</i>	
Minus 75 µm Material			Washed Grading	
(L) Weight In Pan After Gradation			(N) Weight Before Wash	
Loss On Wash (Q)			(O) Weight After Wash	
(M) Total - 200 (75 µm) Material (L + Q)			(Q) Loss (N - O)	
(S) Total Aggregate In Sample For Gradation Calculations :			(Line (F) Above)	

Gradation Analysis					
Sieve Size	Weight Retained	Percent Retained	Percent Passing	Reported Percent Passing	Tolerance Limits
2 in (50 mm)					
1 1/2 in (37.5 mm)					
1 in (25 mm)					
3/4 in (19 mm)					
1/2 in (12.5 mm)					
3/8 in (9.5 mm)					
No. 4 (4.75 mm)					
No. 8 (2.36 mm)					
No. 16 (1.18 mm)					
No. 30 (600 µm)					
No. 50 (300 µm)					
No. 200 (75 µm)					
- 200 (75 µm) (M)					
Total Wt. (W)					
0.2% Check: W - Q		100 (O - X) / O			
= Total Weight (X) _____		_____ %			

The Summation Of The Retained Weights Of All Of The Sieves Plus The Pan Weight Must Check The Dry Weight After Wash (O) Within 0.2% Of The Total Weight (X).

Attach all asphalt content oven printouts to this report.

Figure 53 - RAP Burnoff 1A

T417
Rev. 01-01

West Virginia Division of Highways
Asphalt Content By Ignition Method (AASHTO T308, Test Method A) And
Mechanical Analysis Of Extracted Aggregate - AASHTO T30

Lab Number: _____ Material: Poss. #4 Field Sample #: 1B
Technician: LVS T400 #: _____ Cal. Factor: 1 Date: 3/24/15

Data Before Ignition		Test Temp: <u>540</u> °C	Data After Ignition	
(A) Weight of Basket + Sample		<u>4296.5</u>	(D) Weight of Basket + Aggregate	<u>4229.7</u>
(B) Weight of Basket		<u>3351.9</u>	(E) Weight of Basket	<u>3351.9</u>
(C) Sample Weight (A - B)		<u>944.6</u>	(F) Aggregate Weight (D - E)	<u>877.8</u>
(K) Percent Asphalt Check: $\{ [(C - F) / C] \times 100 - (\text{Calibration Factor}) \}$				<u>4.07</u>
Asphalt Content From Ignition Oven Printout Shall Be Used As Actual % Asphalt				<u>7.00</u>
Minus 75 µm Material			Washed Grading	
(L) Weight In Pan After Gradation			(N) Weight Before Wash	
Loss On Wash (Q)			(O) Weight After Wash	
(M) Total - 200 (75 µm) Material (L + Q)			(Q) Loss (N - O)	
(S) Total Aggregate In Sample For Gradation Calculations :				(Line (F) Above)

Gradation Analysis					
Sieve Size	Weight Retained	Percent Retained	Percent Passing	Reported Percent Passing	Tolerance Limits
2 in (50 mm)					
1 1/2 in (37.5 mm)					
1 in (25 mm)					
3/4 in (19 mm)					
1/2 in (12.5 mm)					
3/8 in (9.5 mm)					
No. 4 (4.75 mm)					
No. 8 (2.36 mm)					
No. 16 (1.18 mm)					
No. 30 (600 µm)					
No. 50 (300 µm)					
No. 200 (75 µm)					
- 200 (75 µm) (M)					
Total Wt. (W)					
0.2% Check: W - Q		100 (O - X) / O			
= Total Weight (X) _____		_____ %			

The Summation Of The Retained Weights Of All Of The Sieves Plus The Pan Weight Must Check The Dry Weight After Wash (O) Within 0.2% Of The Total Weight (X).

Attach all asphalt content oven printouts to this report.

Figure 54 - RAP Burnoff 1B

T417
Rev. 01-01

West Virginia Division of Highways
Asphalt Content By Ignition Method (AASHTO T308, Test Method A) And
Mechanical Analysis Of Extracted Aggregate - AASHTO T30

Lab Number: _____ Material: Burnoff 1 Field Sample #: _____
Technician: L.K.S. T400 #: _____ Cal. Factor: _____ Date: 4/2/15

Data Before Ignition	Test Temp:	°C	Data After Ignition
(A) Weight of Basket + Sample			(D) Weight of Basket + Aggregate
(B) Weight of Basket			(E) Weight of Basket
(C) Sample Weight (A - B)			(F) Aggregate Weight (D - E)
(K) Percent Asphalt Check: $\{ [(C - F) / C] \times 100 - (\text{Calibration Factor}) \}$			
Asphalt Content From Ignition Oven Printout Shall Be Used As Actual % Asphalt			
Minus 75 µm Material		Washed Grading	
(L) Weight In Pan After Gradation	<u>1.2</u>		(N) Weight Before Wash
Loss On Wash (Q)	<u>138.3</u>		(O) Weight After Wash
(M) Total - 200 (75 µm) Material (L + Q)	<u>139.5</u>		(Q) Loss (N - O)
(S) Total Aggregate In Sample For Gradation Calculations :			(Line (F) Above)

Gradation Analysis					
Sieve Size	Weight Retained	Percent Retained	Percent Passing	Reported Percent Passing	Tolerance Limits
2 in (50 mm)	0	0			
1 1/2 in (37.5 mm)	0	0			
1 in (25 mm)	0	0			
3/4 in (19 mm)	0	0			
1/2 in (12.5 mm)	0	0			
3/8 in (9.5 mm)	<u>60.0</u>	<u>3.4</u>			
No. 4 (4.75 mm)	<u>442.5</u>	<u>25.3</u>			
No. 8 (2.36 mm)	<u>392.2</u>	<u>22.4</u>			
No. 16 (1.18 mm)	<u>300.8</u>	<u>17.2</u>			
No. 30 (600 µm)	<u>184.4</u>	<u>10.5</u>			
No. 50 (300 µm)	<u>124.5</u>	<u>7.1</u>			
No. 200 (75 µm)	<u>80.9</u>	<u>4.9</u>			
No. 200 (75 µm)	<u>23.4</u>	<u>1.3</u>			
- 200 (75 µm) (M)	<u>139.5</u>	<u>8.0</u>			
Total Wt. (W)	<u>1748.2</u>				
0.2% Check:	W - Q	100 (O - X) / O			
= Total Weight	(X) <u>1609.9</u>	_____ %			

The Summation Of The Retained Weights Of All Of The Sieves Plus The Pan Weight Must Check The Dry Weight After Wash (O) Within 0.2% Of The Total Weight (X).

Attach all asphalt content oven printouts to this report.

Figure 55 - RAP Burnoff Average 1

-----	-----
Elapsed Time: 24:24	Elapsed Time: 27:32
Sample Weight: 1009g	Sample Weight: 945g
Weight Loss: 50.8g	Weight Loss: 69.1g
Percent Loss: 5.03%	Percent Loss: 7.31%
Temp Comp: 0.29%	Temp Comp: 0.31%
Calib. Factor: 0.00%	Calib. Factor: 0.00%
=====	=====
Calibrated Asphalt Cnt	Calibrated Asphalt Cnt
4.74%	7.00%
=====	=====
Filter Set Pt: 850°C	Filter Set Pt: 850°C
Chamber Set Pt: 540°C	Chamber Set Pt: 540°C
Tested By: LKS	Tested By: LKS
Mix Type: Act on #4	Mix Type: Poss. #4
Sample ID: 1-A	Sample ID: 1-B
Time: 13:18:10	Time: 13:46:46
Date: 3-24-15	Date: 3-24-15
-----	-----

Figure 56 - RAP Burnoff 1 Printouts

T417
Rev. 01-01

West Virginia Division of Highways
Asphalt Content By Ignition Method (AASHTO T308, Test Method A) And
Mechanical Analysis Of Extracted Aggregate - AASHTO T30

Lab Number: _____ Material: Ret on #4 Field Sample #: 2A
Technician: LVS T400 #: _____ Cal. Factor: 1 Date: 3/23/15

Data Before Ignition	Test Temp: <u>540</u> °C	Data After Ignition
(A) Weight of Basket + Sample	<u>4495.8</u>	(D) Weight of Basket + Aggregate <u>4444.8</u>
(B) Weight of Basket	<u>3408.7</u>	(E) Weight of Basket <u>3408.7</u>
(C) Sample Weight (A - B)	<u>1087.1</u>	(F) Aggregate Weight (D - E) <u>1036.1</u>
(K) Percent Asphalt Check: $\{ [(C - F) / C] \times 100 - (\text{Calibration Factor}) \}$		<u>4.69</u>
Asphalt Content From Ignition Oven Printout Shall Be Used As Actual % Asphalt		<u>4.79</u>
Minus 75 µm Material		Washed Grading
(L) Weight In Pan After Gradation		(N) Weight Before Wash
Loss On Wash (Q)		(O) Weight After Wash
(M) Total - 200 (75 µm) Material (L + Q)		(Q) Loss (N - O)
(S) Total Aggregate In Sample For Gradation Calculations :		(Line (F) Above)

Gradation Analysis					
Sieve Size	Weight Retained	Percent Retained	Percent Passing	Reported Percent Passing	Tolerance Limits
2 in (50 mm)					
1 1/2 in (37.5 mm)					
1 in (25 mm)					
3/4 in (19 mm)					
1/2 in (12.5 mm)					
3/8 in (9.5 mm)					
No. 4 (4.75 mm)					
No. 8 (2.36 mm)					
No. 16 (1.18 mm)					
No. 30 (600 µm)					
No. 50 (300 µm)					
No. 200 (75 µm)					
- 200 (75 µm) (M)					
Total Wt. (W)					
0.2% Check:	W - Q	100 (O - X) / O			
= Total Weight (X)		%			

The Summation Of The Retained Weights Of All Of The Sieves Plus The Pan Weight Must Check The Dry Weight After Wash (O) Within 0.2% Of The Total Weight (X).

Attach all asphalt content oven printouts to this report.

Figure 57 - RAP Burnoff 2A

T417
Rev. 01-01

West Virginia Division of Highways
Asphalt Content By Ignition Method (AASHTO T308, Test Method A) And
Mechanical Analysis Of Extracted Aggregate - AASHTO T30

Lab Number: _____ Material: Pass.#4 Field Sample #: 2B
Technician: WLS T400 #: _____ Cal. Factor: 1 Date: 3/28/15

Data Before Ignition		Test Temp: <u>540</u> °C	Data After Ignition	
(A) Weight of Basket + Sample	<u>4403.9</u>		(D) Weight of Basket + Aggregate	<u>4329.0</u>
(B) Weight of Basket	<u>3352.0</u>		(E) Weight of Basket	<u>3352.0</u>
(C) Sample Weight (A - B)	<u>1051.9</u>		(F) Aggregate Weight (D - E)	<u>977.0</u>
(K) Percent Asphalt Check: $\{ [(C - F) / C] \times 100 - (\text{Calibration Factor}) \}$				<u>7.12</u>
Asphalt Content From Ignition Oven Printout Shall Be Used As Actual % Asphalt				<u>7.18</u>
Minus 75 µm Material			Washed Grading	
(L) Weight In Pan After Gradation			(N) Weight Before Wash	
Loss On Wash (Q)			(O) Weight After Wash	
(M) Total - 200 (75 µm) Material (L + Q)			(Q) Loss (N - O)	
(S) Total Aggregate In Sample For Gradation Calculations :			(Line (F) Above)	

Gradation Analysis					
Sieve Size	Weight Retained	Percent Retained	Percent Passing	Reported Percent Passing	Tolerance Limits
2 in (50 mm)					
1 1/2 in (37.5 mm)					
1 in (25 mm)					
3/4 in (19 mm)					
1/2 in (12.5 mm)					
3/8 in (9.5 mm)					
No. 4 (4.75 mm)					
No. 8 (2.36 mm)					
No. 16 (1.18 mm)					
No. 30 (600 µm)					
No. 50 (300 µm)					
No. 200 (75 µm)					
- 200 (75 µm) (M)					
Total Wt. (W)					
0.2% Check: W - Q		100 (O - X) / O			
= Total Weight (X) _____		_____ %			

The Summation Of The Retained Weights Of All Of The Sieves Plus The Pan Weight Must Check The Dry Weight After Wash (O) Within 0.2% Of The Total Weight (X).

Attach all asphalt content oven printouts to this report.

Figure 58 - RAP Burnoff 2B

T417
Rev. 01-01

West Virginia Division of Highways
Asphalt Content By Ignition Method (AASHTO T308, Test Method A) And
Mechanical Analysis Of Extracted Aggregate - AASHTO T30

Lab Number: _____ Material: Burnoff 2 Field Sample #: _____
Technician: L.V.S. T400 #: _____ Cal. Factor: _____ Date: 4/21/15

Data Before Ignition	Test Temp:	°C	Data After Ignition
(A) Weight of Basket + Sample			(D) Weight of Basket + Aggregate
(B) Weight of Basket			(E) Weight of Basket
(C) Sample Weight (A - B)			(F) Aggregate Weight (D - E)
(K) Percent Asphalt Check: $\{ [(C - F) / C] \times 100 - (\text{Calibration Factor}) \}$			
Asphalt Content From Ignition Oven Printout Shall Be Used As Actual % Asphalt			
Minus 75 µm Material		Washed Grading	
(L) Weight In Pan After Gradation	<u>0.7</u>	(N) Weight Before Wash	<u>2013.3</u>
Loss On Wash (Q)	<u>257.7</u>	(O) Weight After Wash	<u>1755.6</u>
(M) Total - 200 (75 µm) Material (L + Q)	<u>258.4</u>	(Q) Loss (N - O)	<u>257.7</u>
(S) Total Aggregate In Sample For Gradation Calculations : (Line (F) Above)			

Gradation Analysis					
Sieve Size	Weight Retained	Percent Retained	Percent Passing	Reported Percent Passing	Tolerance Limits
2 in (50 mm)	0	0			
1 1/2 in (37.5 mm)	0	0			
1 in (25 mm)	0	0			
3/4 in (19 mm)	0	0			
1/2 in (12.5 mm)	0	0			
3/8 in (9.5 mm)	<u>70.9</u>	<u>3.5</u>			
No. 4 (4.75 mm)	<u>494.4</u>	<u>24.5</u>			
No. 8 (2.36 mm)	<u>426.5</u>	<u>21.2</u>			
No. 16 (1.18 mm)	<u>328.7</u>	<u>16.3</u>			
No. 30 (600 µm)	<u>197.3</u>	<u>9.8</u>			
No. 50 (300 µm)	<u>131.7</u>	<u>6.5</u>			
No. 200 (75 µm)	<u>86.3</u> <u>19.8</u>	<u>4.3</u> <u>1.0</u>			
- 200 (75 µm) (M)	<u>258.4</u>	<u>12.8</u>			
Total Wt. (W)	<u>2014.0</u>				
0.2% Check: W - Q		100 (O - X) / O			
= Total Weight (X) _____		_____ %			

The Summation Of The Retained Weights Of All Of The Sieves Plus The Pan Weight Must Check The Dry Weight After Wash (O) Within 0.2% Of The Total Weight (X).

Attach all asphalt content oven printouts to this report.

Figure 59 - RAP Burnoff Average 2

 Elapsed Time: 26:13
 Sample Weight: 1052g
 Weight Loss: 78.5g
 Percent Loss: 7.46%
 Temp Comp: 0.28%
 Calib. Factor: 0.00%
 =====
 Calibrated Asphalt Cnt
 7.18%
 =====
 Filter Set Pt: 850°C
 Chamber Set Pt: 540°C
 Tested By: **LKS**
 Mix Type: **Pass #4**
 Sample ID: **2-B**
 Time: 14:25:56
 Date: 3-25-15

 Elapsed Time: 23:08
 Sample Weight: 1087g
 Weight Loss: 55.1g
 Percent Loss: 5.06%
 Temp Comp: 0.27%
 Calib. Factor: 0.00%
 =====
 Calibrated Asphalt Cnt
 4.79%
 =====
 Filter Set Pt: 850°C
 Chamber Set Pt: 540°C
 Tested By: **LKS**
 Mix Type: **Ret. on #4**
 Sample ID: **2-A**
 Time: 13:35:19
 Date: 3-25-15

Figure 60 - RAP Burnoff 2 Printouts

Appendix B

Flow Number Data (Spring 2014)

Table 25 - 0% RAP Replicate 1 Flow Number Data

PG 70-22 0% RAP Replicate 1	
Specimen Avg Diameter (mm)	100.32
Specimen Avg Height (mm)	148.685
Target Temperature (degC)	50
Target Confining Stress (kPa)	0
Target Contact Stress (kPa)	30
Target Deviator Stress (kPa)	600
Termination micro strain	50000
Termination cycles	10000
Sampling Interval (cycles)	1
Flow number (cycles)	178
Avg contact stress (kPa)	30
Max load Std Error (%)	8.5
Average Temperature (degC)	50
Average Confining Stress (kPa)	0
Average Deviator Stress (kPa)	599.3
Micro strain at flow point	31167

Table 26 - 0% RAP Replicate 2 Flow Number Data

PG 70-22 0% RAP Replicate 2	
Specimen Avg Diameter (mm)	100.397
Specimen Avg Height (mm)	148.765
Target Temperature (degC)	50
Target Confining Stress (kPa)	0
Target Contact Stress (kPa)	30
Target Deviator Stress (kPa)	600
Termination micro strain	50000
Termination cycles	10000
Sampling Interval (cycles)	1
Flow number (cycles)	167
Avg contact stress (kPa)	30
Max load Std Error (%)	7.6
Average Temperature (degC)	50
Average Confining Stress (kPa)	0
Average Deviator Stress (kPa)	599.3
Micro strain at flow point	29006

Table 27 - 15% RAP Replicate 1 Flow Number Data

PG 70-22 15% RAP Replicate 1	
Specimen Avg Diameter (mm)	100.453
Specimen Avg Height (mm)	148.66
Target Temperature (degC)	50
Target Confining Stress (kPa)	0
Target Contact Stress (kPa)	30
Target Deviator Stress (kPa)	600
Termination micro strain	50000
Termination cycles	10000
Sampling Interval (cycles)	1
Flow number (cycles)	342
Avg contact stress (kPa)	30
Max load Std Error (%)	9.8
Average Temperature (degC)	50
Average Confining Stress (kPa)	0
Average Deviator Stress (kPa)	599.3
Micro strain at flow point	31359

Table 28 - 15% RAP Replicate 2 Flow Number Data

PG 70-22 15% RAP Replicate 2	
Specimen Avg Diameter (mm)	100.353
Specimen Avg Height (mm)	149.055
Target Temperature (degC)	50
Target Confining Stress (kPa)	0
Target Contact Stress (kPa)	30
Target Deviator Stress (kPa)	600
Termination micro strain	50000
Termination cycles	10000
Sampling Interval (cycles)	1
Flow number (cycles)	555
Avg contact stress (kPa)	30
Max load Std Error (%)	7.8
Average Temperature (degC)	50
Average Confining Stress (kPa)	0
Average Deviator Stress (kPa)	599.4
Micro strain at flow point	31114

Table 29 - 25% RAP Replicate 1 Flow Number Data

PG 70-22 25% RAP Replicate 1	
Specimen Avg Diameter (mm)	100.36
Specimen Avg Height (mm)	149.565
Target Temperature (degC)	50
Target Confining Stress (kPa)	0
Target Contact Stress (kPa)	30
Target Deviator Stress (kPa)	600
Termination micro strain	50000
Termination cycles	10000
Sampling Interval (cycles)	1
Flow number (cycles)	591
Avg contact stress (kPa)	30
Max load Std Error (%)	8.2
Average Temperature (degC)	50
Average Confining Stress (kPa)	0
Average Deviator Stress (kPa)	599.4
Micro strain at flow point	31213

Table 30 - 25% RAP Replicate 2 Flow Number Data

PG 70-22 25% RAP Replicate 2	
Specimen Avg Diameter (mm)	100.38
Specimen Avg Height (mm)	148.815
Target Temperature (degC)	50
Target Confining Stress (kPa)	0
Target Contact Stress (kPa)	30
Target Deviator Stress (kPa)	600
Termination micro strain	50000
Termination cycles	10000
Sampling Interval (cycles)	1
Flow number (cycles)	611
Avg contact stress (kPa)	30
Max load Std Error (%)	7.4
Average Temperature (degC)	50
Average Confining Stress (kPa)	0
Average Deviator Stress (kPa)	599.4
Micro strain at flow point	26702

Dynamic Modulus Sample Properties (Summer 2015)

Table 31 - DM Specimen Volumetrics

Binder	% RAP	Replicate	Pb	Gmm	Gmb	Gsb	VTM	VMA	VFA
PG 70-22	0	1	4.9%	2.527	2.35	2.679	7.0%	16.6%	57.8%
		2	4.9%	2.527	2.336	2.679	7.5%	17.1%	56.1%
		3	4.9%	2.527	2.349	2.679	7.1%	16.6%	57.3%
	15	1	4.6%	2.535	2.346	2.676	7.5%	16.4%	54.2%
		2	4.6%	2.535	2.36	2.676	6.9%	15.9%	56.5%
		3	4.6%	2.535	2.368	2.676	6.6%	15.6%	57.6%
	25	1	4.9%	2.526	2.345	2.695	7.1%	17.3%	58.8%
		2	4.9%	2.526	2.363	2.695	6.5%	16.6%	60.9%
		3	4.9%	2.526	2.361	2.695	6.7%	16.7%	59.8%
PG 64-22	25	1	4.9%	2.522	2.34	2.695	7.2%	17.4%	58.7%
		2	4.9%	2.522	2.354	2.695	6.7%	16.9%	60.4%
		3	4.9%	2.522	2.351	2.695	6.8%	17.0%	60.1%

Table 32 - DM Specimen Height and Diameter

Binder	% RAP	Replicate	Average Height (mm)	Average Diameter (mm)
PG 70-22	0	1	150.74	100.48
		2	151.66	100.26
		3	151.67	100.35
	15	1	151.11	100.45
		2	151.53	100.42
		3	151.19	100.44
	25	1	150.92	100.44
		2	150.03	100.39
		3	152.02	100.37
PG 64-22	25	1	151.26	100.37
		2	151.82	100.41
		3	150.13	100.43

Dynamic Modulus Data (Summer 2014)

Table 33 - PG 70-22 0% RAP Replicate 1 – 4°C DM Test Data

PG 70-22 0% RAP Replicate 1 – 4°C	10 Hz	1 Hz	0.1 Hz
Dynamic modulus (MPa)	13146	9399	5993
Phase angle (Degrees)	11.99	16.34	21.88
Average temperature (°C)	3.9	3.9	3.9
Average confining pressure (kPa)	0.9	0.9	0.9
Average micro strain	99	98	101
Load drift (%)	0.2	0	0
Load standard error (%)	0.8	0.4	0.4
Average deformation drift (%)	-59.9	-103.1	-178.1
Average deformation standard error (%)	2.9	2.7	3
Deformation uniformity (%)	15.1	12.6	11.4
Phase uniformity (°)	0.5	0.7	0.9

Table 34 - PG 70-22 0% RAP Replicate 1 – 20°C DM Test Data

PG 70-22 0% RAP Replicate 1 – 20°C	10 Hz	1 Hz	0.1 Hz
Dynamic modulus (MPa)	6144	3343	1603
Phase angle (Degrees)	23.37	29.19	32.99
Average temperature (°C)	20.3	20.3	19.9
Average confining pressure (kPa)	0.6	0.6	0.4
Average micro strain	97	94	96
Load drift (%)	0.1	0	0
Load standard error (%)	1.3	0.4	0.5
Average deformation drift (%)	-240.1	-291.7	-299.4
Average deformation standard error (%)	5.5	4.1	3.9
Deformation uniformity (%)	12.3	12.2	12.9
Phase uniformity (Degrees)	1.1	1.1	1.3

Table 35 - PG 70-22 0% RAP Replicate 1 – 40°C DM Test Data

PG 70-22 0% RAP Replicate 1 – 40°C	10 Hz	1 Hz	0.1 Hz	0.01 Hz
Dynamic modulus (MPa)	1108	447.9	198.8	111.3
Phase angle (Degrees)	37.07	33.64	28.11	22.11
Average temperature (°C)	40.1	40.2	40.2	40.1
Average confining pressure (kPa)	0	0	0	0
Average micro strain	91	94	95	103
Load drift (%)	0.5	0.1	-0.1	-0.1
Load standard error (%)	4	1.4	2.8	1.5
Average deformation drift (%)	-402.7	-176.9	79.2	3260.6
Average deformation standard error (%)	9	4.4	5.2	100.5
Deformation uniformity (%)	12.7	13.6	14.5	15.7
Phase uniformity (Degrees)	1.5	1.6	0.6	1.1

Table 36 - PG 70-22 0% RAP Replicate 2 - 4°C DM Test Data

PG 70-22 0% RAP Replicate 2 - 4°C	10 Hz	1 Hz	0.1 Hz
Dynamic modulus (MPa)	12906	9385	6192
Phase angle (Degrees)	11.24	15.11	20.21
Average temperature (°C)	4.1	4.1	3.9
Average confining pressure (kPa)	0.7	0.7	0.7
Average micro strain	98	99	101
Load drift (%)	0	0	0
Load standard error (%)	0.9	0.4	0.4
Average deformation drift (%)	-50.2	-85.7	-148.7
Average deformation standard error (%)	1.6	1.5	2
Deformation uniformity (%)	7.7	7.7	8.1
Phase uniformity (Degrees)	0.2	0.5	1

Table 37 - PG 70-22 0% RAP Replicate 2 - 20°C DM Test Data

PG 70-22 0% RAP Replicate 2 - 20°C	10 Hz	1 Hz	0.1 Hz
Dynamic modulus (MPa)	5310	2875	1400
Phase angle (Degrees)	23.71	28.9	32.07
Average temperature (°C)	19.8	19.8	20.1
Average confining pressure (kPa)	0.1	0.1	0.2
Average micro strain	97	94	95
Load drift (%)	0	0.1	0
Load standard error (%)	1.3	0.4	0.5
Average deformation drift (%)	-217	-265.5	-281.5
Average deformation standard error (%)	4.5	3.8	4
Deformation uniformity (%)	11.3	11.3	13.5
Phase uniformity (Degrees)	0.7	1.1	1.3

Table 38 - PG 70-22 0% RAP Replicate 2 - 40°C DM Test Data

PG 70-22 0% RAP Replicate 2 - 40°C	10 Hz	1 Hz	0.1 Hz	0.01 Hz
Dynamic modulus (MPa)	1281	540.9	241.8	137.3
Phase angle (Degrees)	35.69	33.42	28.23	23.97
Average temperature (°C)	40.1	40.2	40.1	40.2
Average confining pressure (kPa)	0	0	0	0
Average micro strain	90	92	95	102
Load drift (%)	0.2	0	-0.1	0.4
Load standard error (%)	3.7	1	1.9	1.7
Average deformation drift (%)	-406	-244.2	-102	43.6
Average deformation standard error (%)	8.5	4.5	4.8	6.1
Deformation uniformity (%)	17.7	18	21.4	23.6
Phase uniformity (Degrees)	1.8	1.7	1.1	1.1

Table 39 - PG 70-22 0% RAP Replicate 3 - 4°C DM Test Data

PG 70-22 0% RAP Replicate 3 - 4°C	10 Hz	1 Hz	0.1 Hz
Dynamic modulus (MPa)	13255	9362	5983
Phase angle (Degrees)	12.39	16.96	22.5
Average temperature (°C)	4.1	4.1	3.9
Average confining pressure (kPa)	0.7	0.7	0.7
Average micro strain	99	98	99
Load drift (%)	0	0	0
Load standard error (%)	0.9	0.4	0.4
Average deformation drift (%)	-66	-113.2	-190.4
Average deformation standard error (%)	2	2	2.9
Deformation uniformity (%)	25.4	23.1	19.9
Phase uniformity (Degrees)	0.2	0.6	0.9

Table 40 - PG 70-22 0% RAP Replicate 3 - 20°C DM Test Data

PG 70-22 0% RAP Replicate 3 - 20°C	10 Hz	1 Hz	0.1 Hz
Dynamic modulus (MPa)	5620	2923	1371
Phase angle (Degrees)	25.62	31.02	33.79
Average temperature (°C)	19.9	19.8	20
Average confining pressure (kPa)	0.3	0.3	0.4
Average micro strain	98	94	95
Load drift (%)	0.2	0	0
Load standard error (%)	1.3	0.4	0.4
Average deformation drift (%)	-274.8	-321.5	-330.6
Average deformation standard error (%)	5.2	4.4	4.3
Deformation uniformity (%)	6.6	7.7	8.4
Phase uniformity (Degrees)	0.3	0.6	0.7

Table 41 - PG 70-22 0% RAP Replicate 3 - 40°C DM Test Data

PG 70-22 0% RAP Replicate 3 - 40°C	10 Hz	1 Hz	0.1 Hz	0.01 Hz
Dynamic modulus (MPa)	1137	466.5	204.4	113
Phase angle (Degrees)	36.43	33.19	27.74	22.37
Average temperature (°C)	40.3	40.3	40.3	40.1
Average confining pressure (kPa)	0	0	0	0
Average micro strain	89	93	96	104
Load drift (%)	0.5	0	0.1	0.1
Load standard error (%)	4.3	0.8	1.2	1
Average deformation drift (%)	-421.7	-249.8	-102.4	18.2
Average deformation standard error (%)	8.8	4.7	5.2	7.1
Deformation uniformity (%)	4.5	3.9	3.5	4.3
Phase uniformity (Degrees)	0.9	1	0.4	0.2

Table 42 PG 70-22 15% RAP Replicate 1 - 4°C DM Test Data

PG 70-22 15% RAP Replicate 1 - 4°C	10 Hz	1 Hz	0.1 Hz
Dynamic modulus (MPa)	14857	10845	7336
Phase angle (Degrees)	11.21	15.02	19.92
Average temperature (°C)	4.4	4.3	4.1
Average confining pressure (kPa)	0.7	0.7	0.7
Average micro strain	100	99	100
Load drift (%)	0.1	0.1	0
Load standard error (%)	0.9	0.4	0.4
Average deformation drift (%)	-53.9	-91.5	-154.1
Average deformation standard error (%)	1.8	1.8	2.4
Deformation uniformity (%)	9.4	11.6	13.8
Phase uniformity (Degrees)	0.3	0.4	0.4

Table 43 - PG 70-22 15% RAP Replicate 1 – 20°C DM Test Data

PG 70-22 15% RAP Replicate 1 – 20°C	10 Hz	1 Hz	0.1 Hz
Dynamic modulus (MPa)	8470	5079	2723
Phase angle (Degrees)	19.39	24.91	29.84
Average temperature (°C)	20	20	20
Average confining pressure (kPa)	0.5	0.4	0.4
Average micro strain	100	97	96
Load drift (%)	0.2	0.1	0
Load standard error (%)	1	0.4	0.5
Average deformation drift (%)	-163	-229.3	-291.1
Average deformation standard error (%)	3.4	3.4	3.9
Deformation uniformity (%)	17.7	15.5	14.2
Phase uniformity (Degrees)	0.2	0.3	0.4

Table 44 - PG 70-22 15% RAP Replicate 1 – 40°C DM Test Data

PG 70-22 15% RAP Replicate 1 – 40°C	10 Hz	1 Hz	0.1 Hz	0.01 Hz
Dynamic modulus (MPa)	2019	865.9	368.2	182
Phase angle (Degrees)	35.09	34.74	30.97	25.75
Average temperature (°C)	40.3	40.3	40.4	40.3
Average confining pressure (kPa)	0	0	0	0
Average micro strain	91	91	96	107
Load drift (%)	0.3	-0.1	0.1	-0.2
Load standard error (%)	2.6	0.5	0.4	1.2
Average deformation drift (%)	-492.3	-325.4	-164.9	-35.1
Average deformation standard error (%)	10.2	5.2	5	6.5
Deformation uniformity (%)	8.9	10	10.7	8.2
Phase uniformity (Degrees)	0.4	0.2	1.1	1.7

Table 45 - PG 70-22 15% RAP Replicate 2 – 4°C DM Test Data

PG 70-22 15% RAP Replicate 2 – 4°C	10 Hz	1 Hz	0.1 Hz
Dynamic modulus (MPa)	15626	12241	8878
Phase angle (Degrees)	8.91	11.86	16.04
Average temperature (°C)	4.1	4.1	4
Average confining pressure (kPa)	0.7	0.7	0.7
Average micro strain	97	98	101
Load drift (%)	-0.1	0	0
Load standard error (%)	0.9	0.4	0.4
Average deformation drift (%)	-33.3	-54.7	-96.3
Average deformation standard error (%)	1.7	1.4	1.8
Deformation uniformity (%)	14.8	12.5	11
Phase uniformity (Degrees)	0.5	0.3	0.4

Table 46 - PG 70-22 15% RAP Replicate 2 – 20°C DM Test Data

PG 70-22 15% RAP Replicate 2 – 20°C	10 Hz	1 Hz	0.1 Hz
Dynamic modulus (MPa)	7944	4830	2610
Phase angle (Degrees)	19.11	24.74	29.56
Average temperature (°C)	19.8	19.7	20
Average confining pressure (kPa)	0.4	0.4	0.4
Average micro strain	97	96	96
Load drift (%)	0.1	0	0
Load standard error (%)	1	0.4	0.5
Average deformation drift (%)	-155.6	-213.9	-262
Average deformation standard error (%)	3.5	3.3	4.1
Deformation uniformity (%)	17.7	15.6	14.3
Phase uniformity (Degrees)	0.3	0.4	0.6

Table 47 - PG 70-22 15% RAP Replicate 2 – 40°C DM Test Data

PG 70-22 15% RAP Replicate 2 – 40°C	10 Hz	1 Hz	0.1 Hz	0.01 Hz
Dynamic modulus (MPa)	2099	933.9	409	206.7
Phase angle (Degrees)	33.24	33.58	30.82	26.45
Average temperature (°C)	40.4	40.4	40.4	40.2
Average confining pressure (kPa)	0	0	0	0
Average micro strain	90	91	95	104
Load drift (%)	0.3	0	-0.1	0.1
Load standard error (%)	2.9	0.4	0.4	1.4
Average deformation drift (%)	-404.3	-275.5	-157	-41.3
Average deformation standard error (%)	9.3	4.7	4.4	5.7
Deformation uniformity (%)	10.2	9.7	9.9	8.5
Phase uniformity (Degrees)	0.7	0.7	1.5	1.4

Table 48 - PG 70-22 15% RAP Replicate 3 – 4°C DM Test Data

PG 70-22 15% RAP Replicate 3 – 4°C	10 Hz	1 Hz	0.1 Hz
Dynamic modulus (MPa)	18992	14610	10403
Phase angle (Degrees)	9.15	12.44	16.85
Average temperature (°C)	3.9	3.9	3.8
Average confining pressure (kPa)	0.8	0.8	0.8
Average micro strain	98	101	104
Load drift (%)	8.3	0	0
Load standard error (%)	7.7	0.4	0.4
Average deformation drift (%)	-54.7	-60.9	-103.4
Average deformation standard error (%)	7	1.5	1.9
Deformation uniformity (%)	3.8	3.3	2.5
Phase uniformity (Degrees)	0.1	0.1	0.3

Table 49 - PG 70-22 15% RAP Replicate 3 – 20°C DM Test Data

PG 70-22 15% RAP Replicate 3– 20°C	10 Hz	1 Hz	0.1 Hz
Dynamic modulus (MPa)	10068	6113	3344
Phase angle (Degrees)	18.62	24.19	29.22
Average temperature (°C)	20	20	20
Average confining pressure (kPa)	0.5	0.5	0.5
Average micro strain	104	99	99
Load drift (%)	0.2	0.1	0
Load standard error (%)	1	0.4	0.5
Average deformation drift (%)	-155.4	-212.9	-257.6
Average deformation standard error (%)	3.4	3.3	3.7
Deformation uniformity (%)	5.2	3.6	2.1
Phase uniformity (Degrees)	0.1	0.2	0.4

Table 50 - PG 70-22 15% RAP Replicate 3 – 40°C DM Test Data

PG 70-22 15% RAP Replicate 3– 40°C	10 Hz	1 Hz	0.1 Hz	0.01 Hz
Dynamic modulus (MPa)	2622	1162	509.5	253.2
Phase angle (Degrees)	32.95	33.19	30.11	25.41
Average temperature (°C)	40.1	40.1	40.2	40.2
Average confining pressure (kPa)	0	0	0	0
Average micro strain	96	92	96	107
Load drift (%)	0.3	0	0.2	-0.2
Load standard error (%)	2.5	0.5	1.3	1.1
Average deformation drift (%)	-418.5	-267.5	-144.7	-33.8
Average deformation standard error (%)	9.8	4.9	4.8	6.5
Deformation uniformity (%)	13.1	12.9	12.3	12.5
Phase uniformity (Degrees)	0.5	1.1	1.4	1.9

Table 51 - PG 70-22 25% RAP Replicate 1– 4°C DM Test Data

PG 70-22 25% RAP Replicate 1– 4°C	10 Hz	1 Hz	0.1 Hz
Dynamic modulus (MPa)	16180	12846	9592
Phase angle (Degrees)	8.41	10.71	14.07
Average temperature (°C)	4	3.9	3.8
Average confining pressure (kPa)	0.9	0.9	0.8
Average micro strain	102	101	104
Load drift (%)	0.1	0.1	0
Load standard error (%)	0.9	0.4	0.4
Average deformation drift (%)	-30.8	-42	-72.7
Average deformation standard error (%)	2.2	1.8	1.7
Deformation uniformity (%)	14.9	13.2	11
Phase uniformity (Degrees)	0.3	0.2	0.2

Table 52 - PG 70-22 25% RAP Replicate 1– 20°C DM Test Data

PG 70-22 25% RAP Replicate 1– 20°C	10 Hz	1 Hz	0.1 Hz
Dynamic modulus (MPa)	8839	5773	3422
Phase angle (Degrees)	16.85	21.24	26.04
Average temperature (°C)	20	20	20
Average confining pressure (kPa)	0.4	0.4	0.4
Average micro strain	101	99	99
Load drift (%)	0	0.1	0
Load standard error (%)	1	0.4	0.5
Average deformation drift (%)	-115.3	-149.4	-204
Average deformation standard error (%)	3.8	2.7	3.1
Deformation uniformity (%)	5.6	7.5	10
Phase uniformity (Degrees)	0.6	0.2	0.2

Table 53 - PG 70-22 25% RAP Replicate 1– 40°C DM Test Data

PG 70-22 25% RAP Replicate 1– 40°C	10 Hz	1 Hz	0.1 Hz	0.01 Hz
Dynamic modulus (MPa)	2551	1252	608.6	326.5
Phase angle (Degrees)	30.03	30.91	28.97	24.88
Average temperature (°C)	40.2	40.2	40.2	40.1
Average confining pressure (kPa)	0	0	0	0
Average micro strain	93	91	93	103
Load drift (%)	0.4	0	0	-0.2
Load standard error (%)	2.2	0.6	1.5	1
Average deformation drift (%)	-335.5	-247.9	-168.7	-77.6
Average deformation standard error (%)	8	4.4	4.4	5.7
Deformation uniformity (%)	7.1	7.8	8.6	9.7
Phase uniformity (Degrees)	0.1	0.5	0.1	0.3

Table 54 - PG 70-22 25% RAP Replicate 2– 4°C DM Test Data

PG 70-22 25% RAP Replicate 2– 4°C	10 Hz	1 Hz	0.1 Hz
Dynamic modulus (MPa)	17033	13621	10046
Phase angle (Degrees)	8.28	10.83	14.56
Average temperature (°C)	4	4	3.9
Average confining pressure (kPa)	0.7	0.7	0.7
Average micro strain	96	97	102
Load drift (%)	0.1	0	0
Load standard error (%)	1	0.4	0.4
Average deformation drift (%)	-28.4	-45	-78.5
Average deformation standard error (%)	4.1	3.4	2.8
Deformation uniformity (%)	27.8	20.5	14.1
Phase uniformity (Degrees)	0.2	0.3	0.2

Table 55 - PG 70-22 25% RAP Replicate 2– 20°C DM Test Data

PG 70-22 25% RAP Replicate 2– 20°C	10 Hz	1 Hz	0.1 Hz
Dynamic modulus (MPa)	8965	5605	3148
Phase angle (Degrees)	17.34	22.61	27.6
Average temperature (°C)	19.9	19.9	20
Average confining pressure (kPa)	0.5	0.5	0.4
Average micro strain	97	98	99
Load drift (%)	0.1	0.1	0
Load standard error (%)	1.1	0.4	0.5
Average deformation drift (%)	-133.1	-185.4	-243.3
Average deformation standard error (%)	4.6	3.6	3.8
Deformation uniformity (%)	24.4	18.7	15.7
Phase uniformity (Degrees)	0.4	0.4	0.4

Table 56 - PG 70-22 25% RAP Replicate 2– 40°C DM Test Data

PG 70-22 25% RAP Replicate 2 – 40°C	10 Hz	1 Hz	0.1 Hz	0.01 Hz
Dynamic modulus (MPa)	2448	1145	529	272
Phase angle (Degrees)	31.49	32.22	29.71	25.21
Average temperature (°C)	40.4	40.4	40.4	40.2
Average confining pressure (kPa)	0	0	0	0
Average micro strain	93	92	94	105
Load drift (%)	0.4	0	0	-0.2
Load standard error (%)	2.4	0.5	0.6	1.4
Average deformation drift (%)	-391.7	-287.4	-180.7	-76.9
Average deformation standard error (%)	8.7	5	4.8	6.1
Deformation uniformity (%)	2.4	1.2	1.3	3.8
Phase uniformity (Degrees)	0.2	0.4	0.6	0.8

Table 57 - PG 70-22 25% RAP Replicate 3 – 4°C DM Test Data

PG 70-22 25% RAP Replicate 3 – 4°C	10 Hz	1 Hz	0.1 Hz
Dynamic modulus (MPa)	15941	12770	9434
Phase angle (Degrees)	8.13	11.01	14.67
Average temperature (°C)	4.1	4.1	4
Average confining pressure (kPa)	0.7	0.7	0.7
Average micro strain	104	98	101
Load drift (%)	0	0.1	0
Load standard error (%)	0.9	0.4	0.4
Average deformation drift (%)	21.8	-44.1	-76.5
Average deformation standard error (%)	3.6	2.1	2.1
Deformation uniformity (%)	19.2	19.9	19.7
Phase uniformity (Degrees)	0.5	0.5	0.4

Table 58 - PG 70-22 25% RAP Replicate 3 – 20°C DM Test Data

PG 70-22 25% RAP Replicate 3 – 20°C	10 Hz	1 Hz	0.1 Hz
Dynamic modulus (MPa)	8170	5078	2864
Phase angle (Degrees)	17.8	22.68	27.42
Average temperature (°C)	19.9	20	20.1
Average confining pressure (kPa)	0.4	0.5	0.3
Average micro strain	99	98	97
Load drift (%)	0.1	0.1	0
Load standard error (%)	1.1	0.4	0.6
Average deformation drift (%)	-126.5	-176.2	-231.8
Average deformation standard error (%)	3.3	3	3.5
Deformation uniformity (%)	6.1	6.1	6.6
Phase uniformity (Degrees)	0.3	0.3	0.3

Table 59 - PG 70-22 25% RAP Replicate 3 – 40°C DM Test Data

PG 70-22 25% RAP Replicate 3 – 40°C	10 Hz	1 Hz	0.1 Hz	0.01 Hz
Dynamic modulus (MPa)	2615	1257	589.7	297.6
Phase angle (Degrees)	30.29	31.79	30.2	26.02
Average temperature (°C)	40.2	40.2	40.3	40.2
Average confining pressure (kPa)	0	0	0	0
Average micro strain	96	92	94	105
Load drift (%)	0.4	0.1	0	0.2
Load standard error (%)	2.1	0.4	0.5	1.1
Average deformation drift (%)	-350.8	-280.3	-210.2	-112.4
Average deformation standard error (%)	7.7	4.3	4.3	5.3
Deformation uniformity (%)	13.6	13.1	12.4	11.5
Phase uniformity (Degrees)	0.8	1	1.2	1.3

Table 60 - PG 64-22 25% RAP Replicate 1 – 4°C DM Test Data

PG 64-22 25% RAP Replicate 1 – 4°C	10 Hz	1 Hz	0.1 Hz
Dynamic modulus (MPa)	16145	12422	8845
Phase angle (Degrees)	9.19	12.21	16.55
Average temperature (°C)	4.3	4.2	4
Average confining pressure (kPa)	0.7	0.7	0.7
Average micro strain	101	100	103
Load drift (%)	0	0.1	0
Load standard error (%)	1	0.4	0.4
Average deformation drift (%)	-35.5	-58.4	-104.4
Average deformation standard error (%)	1.5	1.3	1.7
Deformation uniformity (%)	13.3	13.3	12.9
Phase uniformity (Degrees)	0.1	0.1	0.2

Table 61 - PG 64-22 25% RAP Replicate 1– 20°C DM Test Data

PG 64-22 25% RAP Replicate 1– 20°C	10 Hz	1 Hz	0.1 Hz
Dynamic modulus (MPa)	8334	5105	2793
Phase angle (Degrees)	18.39	23.82	28.79
Average temperature (°C)	20	20	20
Average confining pressure (kPa)	0.4	0.4	0.4
Average micro strain	101	98	97
Load drift (%)	0.2	0	0
Load standard error (%)	1.1	0.4	0.5
Average deformation drift (%)	-148.2	-212.1	-270.5
Average deformation standard error (%)	3.1	3.2	3.8
Deformation uniformity (%)	7.6	8.7	8.7
Phase uniformity (Degrees)	0.2	0.1	0.1

Table 62 - PG 64-22 25% RAP Replicate 1– 40°C DM Test Data

PG 64-22 25% RAP Replicate 1– 40°C	10 Hz	1 Hz	0.1 Hz	0.01 Hz
Dynamic modulus (MPa)	2070	909.5	395	194.7
Phase angle (Degrees)	33.8	33.52	30.05	25.46
Average temperature (°C)	40.3	40.3	40.3	40.1
Average confining pressure (kPa)	0	0	0	0
Average micro strain	91	91	95	108
Load drift (%)	0.3	0	0	0
Load standard error (%)	2.6	0.4	0.7	1.1
Average deformation drift (%)	-437.5	-275.8	-117.9	-3.8
Average deformation standard error (%)	9.8	5.1	5	6.7
Deformation uniformity (%)	2.8	2.8	0.7	4.5
Phase uniformity (Degrees)	0.5	0.9	1.9	1.8

Table 63 - PG 64-22 25% RAP Replicate 2 – 4°C DM Test Data

PG 64-22 25% RAP Replicate 2 – 4°C	10 Hz	1 Hz	0.1 Hz
Dynamic modulus (MPa)	16745	13282	9804
Phase angle (Degrees)	8.36	10.72	14.28
Average temperature (°C)	4.1	4.1	3.9
Average confining pressure (kPa)	0.7	0.7	0.7
Average micro strain	102	100	104
Load drift (%)	0.2	0.1	0
Load standard error (%)	1	0.4	0.4
Average deformation drift (%)	-27.6	-41.5	-68.7
Average deformation standard error (%)	1.3	1.2	1.2
Deformation uniformity (%)	17.8	17.4	17
Phase uniformity (Degrees)	0.3	0.4	0.5

Table 64 - PG 64-22 25% RAP Replicate 2 – 20°C DM Test Data

PG 64-22 25% RAP Replicate 2 – 20°C	10 Hz	1 Hz	0.1 Hz
Dynamic modulus (MPa)	7979	4974	2803
Phase angle (Degrees)	18.24	23.3	28
Average temperature (°C)	20	20	20
Average confining pressure (kPa)	0.6	0.6	0.6
Average micro strain	100	97	97
Load drift (%)	0.2	0	0
Load standard error (%)	1.1	0.4	0.6
Average deformation drift (%)	-136.7	-186.4	-231.8
Average deformation standard error (%)	3.1	3.1	3.5
Deformation uniformity (%)	1.5	3.3	5.4
Phase uniformity (Degrees)	0.4	0.9	1

Table 65 - PG 64-22 25% RAP Replicate 2 – 40°C DM Test Data

PG 64-22 25% RAP Replicate 2 – 40°C	10 Hz	1 Hz	0.1 Hz	0.01 Hz
Dynamic modulus (MPa)	2253	1059	491.2	252
Phase angle (Degrees)	31.7	32.25	29.75	25.33
Average temperature (°C)	40.4	40.4	40.4	40.4
Average confining pressure (kPa)	0	0	0	0
Average micro strain	95	91	95	105
Load drift (%)	0.5	0.1	0.4	-0.2
Load standard error (%)	3.3	0.5	1.5	1.2
Average deformation drift (%)	-363.8	-248.5	-149.2	-51.4
Average deformation standard error (%)	8.8	4.7	4.4	5.5
Deformation uniformity (%)	11.3	10.5	11.9	13.7
Phase uniformity (Degrees)	0.7	0.9	0.9	0.1

Table 66 - PG 64-22 25% RAP Replicate 3 – 4°C DM Test Data

PG 64-22 25% RAP Replicate 3 – 4°C	10 Hz	1 Hz	0.1 Hz
Dynamic modulus (MPa)	17517	13893	10138
Phase angle (Degrees)	8.54	11.19	14.83
Average temperature (°C)	4.2	4.2	4.1
Average confining pressure (kPa)	0.8	0.8	0.8
Average micro strain	99	99	104
Load drift (%)	0	0.1	0
Load standard error (%)	0.9	0.4	0.4
Average deformation drift (%)	-31.8	-48.4	-81.7
Average deformation standard error (%)	1.7	1.4	2.2
Deformation uniformity (%)	3.6	2	8.6
Phase uniformity (Degrees)	0.8	1	1.4

Table 67 - PG 64-22 25% RAP Replicate 3 – 20°C DM Test Data

PG 64-22 25% RAP Replicate 3 – 20°C	10 Hz	1 Hz	0.1 Hz
Dynamic modulus (MPa)	9674	6162	3549
Phase angle (Degrees)	16.18	20.81	25.68
Average temperature (°C)	20	20	20
Average confining pressure (kPa)	0.4	0.4	0.3
Average micro strain	103	101	102
Load drift (%)	0	0	0
Load standard error (%)	1	0.4	0.4
Average deformation drift (%)	-107.2	-152.9	-189.6
Average deformation standard error (%)	3.2	2.8	3.1
Deformation uniformity (%)	18.1	22.5	24.3
Phase uniformity (Degrees)	1.4	1.1	1

Table 68 - PG 64-22 25% RAP Replicate 3 – 40°C DM Test Data

PG 64-22 25% RAP Replicate 3 – 40°C	10 Hz	1 Hz	0.1 Hz	0.01 Hz
Dynamic modulus (MPa)	2615	1230	568.6	289.9
Phase angle (Degrees)	30.76	31.84	29.77	25.91
Average temperature (°C)	40.4	40.4	40.4	40.2
Average confining pressure (kPa)	0	0	0	0
Average micro strain	100	92	95	105
Load drift (%)	0.2	0	0.1	0.2
Load standard error (%)	2.6	0.4	0.3	1.3
Average deformation drift (%)	-353.2	-221.9	-126.1	-36.1
Average deformation standard error (%)	8.7	4.5	4.3	5.6
Deformation uniformity (%)	20.7	18.9	17.9	17.4
Phase uniformity (Degrees)	1.6	1	1.1	0.9

Appendix C

Fatigue Sample Properties (Summer 2014)

Table 69 - FT Specimen Volumetrics

Binder	% RAP	Replicate	Pb	Gmm	Gmb	Gsb	VTM	VMA	VFA
PG 70-22	0	1a	4.9%	2.527	2.357	2.679	6.7%	16.3%	58.8%
		1b	4.9%	2.527	2.358	2.679	6.7%	16.3%	59.0%
		1c	4.9%	2.527	2.349	2.679	7.0%	16.6%	57.6%
		2a	4.9%	2.527	2.348	2.679	7.1%	16.6%	57.5%
		2b	4.9%	2.527	2.35	2.679	7.0%	16.6%	57.8%
		2c	4.9%	2.527	2.357	2.679	6.7%	16.3%	58.8%
		3a	4.9%	2.527	2.342	2.679	7.3%	16.9%	56.6%
		3b	4.9%	2.527	2.342	2.679	7.3%	16.9%	56.6%
		3c	4.9%	2.527	2.342	2.679	7.3%	16.9%	56.6%
	15	1a	4.6%	2.535	2.37	2.676	6.5%	15.5%	58.0%
		1b	4.6%	2.535	2.371	2.676	6.5%	15.5%	58.2%
		1c	4.6%	2.535	2.365	2.676	6.7%	15.7%	57.3%
		2a	4.6%	2.535	2.362	2.676	6.8%	15.8%	56.8%
		2b	4.6%	2.535	2.358	2.676	7.0%	15.9%	56.2%
		2c	4.6%	2.535	2.361	2.676	6.9%	15.8%	56.6%
		3a	4.6%	2.535	2.36	2.676	6.9%	15.9%	56.5%
		3b	4.6%	2.535	2.362	2.676	6.8%	15.8%	56.8%
		3c	4.6%	2.535	2.36	2.676	6.9%	15.9%	56.5%
	25	1a	4.9%	2.526	2.358	2.695	6.7%	16.8%	60.4%
		1b	4.9%	2.526	2.351	2.695	6.9%	17.0%	59.3%
		1c	4.9%	2.526	2.363	2.695	6.5%	16.6%	61.2%
		2a	4.9%	2.526	2.361	2.695	6.5%	16.7%	60.9%
		2b	4.9%	2.526	2.362	2.695	6.5%	16.7%	61.0%
		2c	4.9%	2.526	2.357	2.695	6.7%	16.8%	60.2%
		3a	4.9%	2.526	2.362	2.695	6.5%	16.7%	61.0%
		3b	4.9%	2.526	2.362	2.695	6.5%	16.7%	61.0%
		3c	4.9%	2.526	2.359	2.695	6.6%	16.8%	60.5%
PG 64-22	25	1a	4.9%	2.522	2.345	2.695	7.0%	17.3%	59.3%
		1b	4.9%	2.522	2.35	2.695	6.8%	17.1%	60.1%
		1c	4.9%	2.522	2.332	2.695	7.5%	17.7%	57.5%
		2a	4.9%	2.522	2.356	2.695	6.6%	16.9%	61.0%
		2b	4.9%	2.522	2.353	2.695	6.7%	17.0%	60.5%
		2c	4.9%	2.522	2.355	2.695	6.6%	16.9%	60.8%
		3a	4.9%	2.522	2.356	2.695	6.6%	16.9%	61.0%
		3b	4.9%	2.522	2.353	2.695	6.7%	17.0%	60.5%
		3c	4.9%	2.522	2.349	2.695	6.9%	17.1%	59.9%

Table 70 - FT Specimen Height and Diameter

Binder	% RAP	Replicate	Average Height (mm)	Average Diameter (mm)
PG 70-22	0	1a	130.95	100.39
		1b	129.97	100.45
		1c	131.47	100.42
		2a	130.56	100.46
		2b	130.88	100.42
		2c	131.05	100.44
		3a	132.14	100.40
		3b	130.81	100.45
		3c	130.11	100.42
	15	1a	130.10	70.40
		1b	130.81	100.43
		1c	130.18	100.44
		2a	130.50	100.42
		2b	130.40	100.48
		2c	130.12	100.43
		3a	130.61	100.41
		3b	130.53	100.41
		3c	130.72	100.40
	25	1a	129.43	100.43
		1b	130.65	100.45
		1c	131.32	100.38
		2a	130.20	100.41
		2b	130.49	100.39
		2c	130.15	100.41
		3a	130.08	100.44
		3b	130.53	100.39
		3c	130.48	100.42
PG 64-22	25	1a	130.29	100.50
		1b	130.01	100.40
		1c	130.17	100.46
		2a	130.79	100.43
		2b	129.67	100.44
		2c	130.46	100.44
		3a	130.00	100.41
		3b	130.88	100.41
		3c	130.81	100.47

ALPHA-Fatigue Analysis Reports (Summer 2015)

North Carolina
State University

ALPHA-Fatigue
VECD Model Report

Project Name: SAMPLES 1 3 5 6 7 8
Analysis Performed by: LARA SMITH
Analysis Date: 8/14/2015
Testing Performed by: LARA SMITH
Default Directory: D:\AMPT\INPUTS
Output Directory: D:\AMPT\OUTPUTS\SAMPLES 1 3 5 6 7 8
Comments:

Number of Fatigue Tests: 6
Damage Model Function: Exponential

Damage Model Coefficients	
a	-2.70E-05
b	9.32E-01
y	N/A
z	N/A
alpha	3.716
Parameter r in Failure Crit.	1.31E+04
Parameter s in Failure Crit.	-1.80E-01

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

$$C = 1 - \mu S^z$$

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

Test Name	Temperature (deg. C)	Frequency (Hz)	$ E^* _{LVE}$ (MPa)	$ E^* _{finger}$ (MPa)	Nf	G^R
FT 1	14.1	10	8108.1	8270	9115	4.34E+00
FT 3	14.1	10	8094.6	10042	4895	1.82E+02
FT 5	14.2	10	8066.6	8310	8795	1.52E+01
FT 6	14.2	10	8053.3	8541	9015	1.63E+01
FT 7	14.2	10	8062.1	9082	8955	6.53E+00
FT 8	14.2	10	8075.4	8535	5335	1.31E+02

Figure 61 - PG 70-22 With 0% RAP Fatigue Report Page 1

Project Name: SAMPLES 1 3 5 6 7 8
Analysis Performed by: LARA SMITH
Analysis Date: 8/14/2015
Testing Performed by: LARA SMITH
Default Directory: D:\AMPT\INPUTS

Output Directory: D:\AMPT\OUTPUTS\SAMPLES 1 3 5 6 7 8

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>T_r</i>	21.1	deg. C
<i>E_a</i>	199.84	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>	1.48E+00
<i>β</i>	2.86E+00
<i>δ</i>	-3.82E-01
<i>γ</i>	-5.16E-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	1.54E+03	13102.33	11.87	1.36	4.92
4	1	1.54E+02	9382	16.14	0.2	5.84
4	0.1	1.54E+01	6056	21.53	1.95	5.5
20	10	1.36E+01	5691.33	24.23	7.41	5
20	1	1.36E+00	3047	29.7	8.45	3.87
20	0.1	1.36E-01	1458	32.95	8.67	2.61
40	10	7.23E-02	1175.33	36.4	7.88	1.9
40	1	7.23E-03	485.1	33.42	10.14	0.67
40	0.1	7.23E-04	215	28.03	10.87	0.91
40	0.01	7.23E-05	120.53	22.82	12.07	4.41

Figure 62 - PG 70-22 With 0% RAP Fatigue Report Page 2

Project Name: SAMPLES 1 3 5 6 7 8
Analysis Performed by: LARA SMITH
Analysis Date: 8/14/2015
Testing Performed by: LARA SMITH
Default Directory: D:\AMPT\INPUTS

Output Directory: D:\AMPT\OUTPUTS\SAMPLES 1 3 5 6 7 8

Comments:

Traditional Strain Fatigue Relationship (kPa units)	
K1	5.10E+04
K2	0.769
K3	-0.548

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

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	1.77E+04
K2	0.769
K3	-0.548

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

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	8
10	8
15	9
20	9
25	12

Figure 63 - PG 70-22 With 0% RAP Fatigue Report Page 3

Project Name: SAMPLES 10 11 12 13 16 18
Analysis Performed by: LARA SMITH
Analysis Date: 8/15/2015
Testing Performed by: LARA SMITH
Default Directory: D:\AMPT\INPUTS
Output Directory: D:\AMPT\OUTPUTS\SAMPLES 10 11 12 13 16 18
Comments:

Number of Fatigue Tests: 6
Damage Model Function: Exponential

Damage Model Coefficients	
a	-3.04E-05
b	8.84E-01
y	N/A
z	N/A
alpha	3.789
Parameter r in Failure Crit.	3.33E+04
Parameter s in Failure Crit.	-4.79E-01

$$C = e^{\alpha S^b}$$

$$C = 1 - yS^z$$

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

Test Name	Temperature (deg. C)	Frequency (Hz)	$ E _{LVE}$ (MPa)	$ E _{HNGR}$ (MPa)	Nf	G^R
FT 10	14.2	10	11250.9	10990	9015	9.06E+00
FT 11	14.2	10	11259.5	12363	475	2.64E+03
FT 12	14.2	10	11246.5	11569	6055	1.20E+02
FT 13	14.2	10	11249.8	10460	8655	9.51E+00
FT 16	14.2	10	11241.1	11648	8955	1.04E+01
FT 18	14.2	10	11238.4	10421	7855	7.00E+01

Figure 64 - PG 70-22 With 15% RAP Fatigue Report Page 1

Project Name: SAMPLES 10 11 12 13 16 18
 Analysis Performed by: LARA SMITH
 Analysis Date: 8/15/2015
 Testing Performed by: LARA SMITH
 Default Directory: D:\AMPT\INPUTS
 Output Directory: D:\AMPT\OUTPUTS\SAMPLES 10 11 12 13 16 18
 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	202.02	kJ/mol
a1	N/A	
a2	N/A	
A	N/A	
VTS	N/A	
C	N/A	

Mastercurve Function	
κ	1.59E+00
β	2.75E+00
δ	-7.58E-01
γ	-5.26E-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	1.63E+03	16491.67	9.76	13.34	12.96
4	1	1.63E+02	12565.33	13.11	15.15	12.83
4	0.1	1.63E+01	8872.33	17.6	17.28	11.63
20	10	1.36E+01	8627.33	19.04	12.53	2.05
20	1	1.36E+00	5340.67	24.61	12.74	1.53
20	0.1	1.36E-01	2892.33	29.54	13.66	1.05
40	10	6.85E-02	2246.67	33.76	14.58	3.44
40	1	6.85E-03	987.27	33.84	15.71	2.38
40	0.1	6.85E-04	428.9	30.63	16.96	1.5
40	0.01	6.85E-05	213.97	25.87	16.9	2.05

Figure 65 - PG 70-22 With 15% RAP Fatigue Report Page 2

Project Name: SAMPLES 10 11 12 13 16 18
Analysis Performed by: LARA SMITH
Analysis Date: 8/15/2015
Testing Performed by: LARA SMITH
Default Directory: D:\AMPT\INPUTS
Output Directory: D:\AMPT\OUTPUTS\SAMPLES 10 11 12 13 16 18
Comments:

Traditional Strain Fatigue Relationship (kPa units)	
K1	8.71E+03
K2	2.963
K3	-1.654

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

Traditional Stress Fatigue Relationship 1 (kPa units)	
K1	1.21E-04
K2	-3.456
K3	2.663

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

Traditional Stress Fatigue Relationship 2 (kPa units)	
K1	1.21E-04
K2	3.456
K3	-0.793

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

Traditional Strain Fatigue Relationship (psi units)	
K1	3.57E+02
K2	2.963
K3	-1.654

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

Traditional Stress Fatigue Relationship 1 (psi units)	
K1	2.62E-05
K2	-3.456
K3	2.663

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

Traditional Stress Fatigue Relationship 2 (psi units)	
K1	2.62E-05
K2	3.456
K3	-0.793

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

Endurance Limit (microstrain)	
Temperature (deg. C)	Endurance Limit
5	11
10	11
15	12
20	13
25	16

Figure 66 - PG 70-22 With 15% RAP Fatigue Report Page 3

Project Name: SAMPLES 19 22 23 25 26
Analysis Performed by: LARA SMITH
Analysis Date: 9/23/2015
Testing Performed by: LARA SMITH
Default Directory: D:\AMPT\INPUTS

Output Directory: D:\AMPT\OUTPUTS\SAMPLES 19 22 23 25 26

Comments:

Number of Fatigue Tests: 5
Damage Model Function: Exponential

Damage Model Coefficients	
a	-1.15E-05
b	9.87E-01
y	N/A
z	N/A
alpha	4.084
Parameter r in Failure Crit.	2.99E+04
Parameter s in Failure Crit.	-4.74E-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)	Nf	G^R
FT 19	14.2	10	11426.3	11402	8875	1.29E+01
FT 22	14.2	10	11428.2	11194	8995	1.25E+01
FT 23	14.2	10	11447.3	11164	975	2.49E+03
FT 25	14.2	10	11423.6	11468	7375	1.93E+01
FT 26	14.2	10	11414	11082	515	3.01E+03

Figure 67 - PG 70-22 With 25% RAP Fatigue Report Page 1

Project Name:	SAMPLES 19 22 23 25 26
Analysis Performed by:	LARA SMITH
Analysis Date:	8/23/2015
Testing Performed by:	LARA SMITH
Default Directory:	D:\AMPT\INPUTS
Output Directory:	D:\AMPT\OUTPUTS\SAMPLES 19 22 23 25 26
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	205.68	kJ/mol
a1	N/A	
a2	N/A	
A	N/A	
VTs	N/A	
C	N/A	

Mastercurve Function	
κ	1.79E+00
β	2.55E+00
δ	-7.35E-01
γ	-5.10E-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	1.79E+03	16384.67	8.27	3.5	1.69
4	1	1.79E+02	13079	10.85	3.6	1.39
4	0.1	1.79E+01	9690.67	14.43	3.28	2.21
20	10	1.37E+01	8658	17.33	4.94	2.74
20	1	1.37E+00	5485.33	22.18	6.61	3.66
40	10	1.37E-01	3144.67	27.02	8.87	3.16
40	1	8.26E-02	2538	30.6	3.32	2.54
40	0.1	8.26E-03	1218	31.64	5.19	2.11
40	0.01	8.26E-04	575.77	29.63	7.22	2.09
		8.26E-05	298.7	25.37	9.13	2.31

Figure 68 - PG 70-22 With 25% RAP Fatigue Report Page 2

Project Name: SAMPLES 19 22 23 25 26
Analysis Performed by: LARA SMITH
Analysis Date: 9/23/2015
Testing Performed by: LARA SMITH
Default Directory: D:\AMPT\INPUTS

Output Directory: D:\AMPT\OUTPUTS\SAMPLES 19 22 23 25 26

Comments:

Traditional Strain Fatigue Relationship (kPa units)	
K1	1.05E+04
K2	2.781
K3	-1.596

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

Traditional Stress Fatigue Relationship 1 (kPa units)	
K1	1.12E-08
K2	-4.096
K3	3.492

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

Traditional Stress Fatigue Relationship 2 (kPa units)	
K1	1.12E-08
K2	4.096
K3	-0.604

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

Traditional Strain Fatigue Relationship (psi units)	
K1	4.81E+02
K2	2.781
K3	-1.596

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

Traditional Stress Fatigue Relationship 1 (psi units)	
K1	3.49E-09
K2	-4.096
K3	3.492

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

Traditional Stress Fatigue Relationship 2 (psi units)	
K1	3.49E-09
K2	4.096
K3	-0.604

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

Endurance Limit (microstrain)	
Temperature (deg. C)	Endurance Limit
5	15
10	15
15	15
20	16
25	19

Figure 69 - PG 70-22 With 25% RAP Fatigue Report Page 3

Project Name: SAMPLES 28 29 30 31 34 36
 Analysis Performed by: LARA SMITH
 Analysis Date: 8/29/2015
 Testing Performed by: LARA SMITH
 Default Directory: D:\AMPT\INPUTS
 Output Directory: D:\AMPT\OUTPUTS\SAMPLES 28 29 30 31 34 36
 Comments:

Number of Fatigue Tests: 6
 Damage Model Function: Exponential

Damage Model Coefficients	
a	-4.86E-05
b	8.30E-01
y	N/A
z	N/A
alpha	3.93
Parameter r in Failure Crit.	2.61E+04
Parameter s in Failure Crit.	-3.55E-01

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

$$C = 1 - \gamma S^z$$

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

Test Name	Temperature (deg. C)	Frequency (Hz)	$ E _{LVE}$ (MPa)	$ E _{ngve}$ (MPa)	Nf	G^R
FT 28	14.2	10	11474.8	11019	8995	1.76E+01
FT 29	14.2	10	11465.7	10124	5615	3.02E+02
FT 30	14.2	10	11471.2	9894	4815	2.34E+02
FT 31	14.2	10	11477.6	11117	8875	1.83E+01
FT 34	14.2	10	11481.6	11156	9055	1.80E+01
FT 36	14.2	10	11489.7	11406	1495	6.43E+02

Figure 70 - PG 64-22 With 25% RAP Fatigue Report Page 1

Project Name: SAMPLES 28 29 30 31 34 36
Analysis Performed by: LARA SMITH
Analysis Date: 8/29/2015
Testing Performed by: LARA SMITH
Default Directory: D:\AMPT\INPUTS

Output Directory: D:\AMPT\OUTPUTS\SAMPLES 28 29 30 31 34 36

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

Mastercurve Function	
κ	1.70E+00
β	2.65E+00
δ	-7.58E-01
γ	-5.19E-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	1.98E+03	16802.33	8.7	4.09	5.02
4	1	1.98E+02	13199	11.37	5.6	6.7
4	0.1	1.98E+01	9595.67	15.22	6.99	7.78
20	10	1.38E+01	8662.33	17.6	10.32	7.02
20	1	1.38E+00	5413.67	22.64	12.03	7.11
20	0.1	1.38E-01	3046.33	27.49	14.22	5.88
40	10	5.68E-02	2312.67	32.09	11.99	4.85
40	1	5.68E-03	1066.17	32.54	15.04	2.69
40	0.1	5.68E-04	484.93	29.86	17.93	0.56
40	0.01	5.68E-05	245.53	25.57	19.52	1.19

Figure 71 - PG 64-22 With 25% RAP Fatigue Report Page 2

Project Name: SAMPLES 28 29 30 31 34 36
 Analysis Performed by: LARA SMITH
 Analysis Date: 8/29/2015
 Testing Performed by: LARA SMITH
 Default Directory: D:\AMPT\INPUTS
 Output Directory: D:\AMPT\OUTPUTS\SAMPLES 28 29 30 31 34 36
 Comments:

Traditional Strain Fatigue Relationship (kPa units)	
K1	3.06E+04
K2	1.766
K3	-1.056

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

Traditional Stress Fatigue Relationship 1 (kPa units)	
K1	9.18E-02
K2	-2.428
K3	1.799

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

Traditional Stress Fatigue Relationship 2 (kPa units)	
K1	9.18E-02
K2	2.428
K3	-0.629

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

Traditional Strain Fatigue Relationship (psi units)	
K1	3.99E+03
K2	1.766
K3	-1.056

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

Traditional Stress Fatigue Relationship 1 (psi units)	
K1	2.72E-02
K2	-2.428
K3	1.799

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

Traditional Stress Fatigue Relationship 2 (psi units)	
K1	2.72E-02
K2	2.428
K3	-0.629

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

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

Figure 72 - PG 64-22 With 25% RAP Fatigue Report Page 3