The Effect of High RAP and High Asphalt Binder Content on the Dynamic Modulus and Fatigue Resistance of Asphalt Concrete

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ABSTRACT

This thesis investigates the effects of using various percentages of RAP and asphalt binder contents on the dynamic modulus and fatigue resistance of asphalt concrete. Two RAP percentages (20% and 40%) and three binder percentages (plant-mixed, plant-mixed + 0.5%, and plant-mixed + 1.0%) were evaluated. A Superpave gyratory compactor and an asphalt vibratory compactor were used to prepare dynamic modulus samples and fatigue beam samples at 7% air voids. Three replicate samples for each percentage of RAP and asphalt binder content were prepared for testing purposes. An Interlaken Technology Corporation servohydraulic testing machine and a Material Testing System servohydraulic machine were used to determine the dynamic modulus and fatigue resistance of the asphalt samples. Analysis of variance (ANOVA) was used to determine if any of the factors (air voids, percent RAP, and percent asphalt binder) affected the performance criteria (dynamic modulus and fatigue life cycles). Results suggest that as the amount of RAP increases in asphalt concrete, both the dynamic modulus and fatigue life will increase. As per the literature, these results were expected for the dynamic modulus, but not for the fatigue life. It is suspected that the increase in fatigue life for the 40% RAP mixes may be due to the use of a softer binder (PG 64-22 instead of PG 70-22). It was also found that by increasing the amount of binder in the mixture, the stiffness of asphalt concrete will decrease, but the fatigue life will improve. The fatigue life results showed a strong trend of this improvement for the 20% RAP samples, however, the results for the 40% RAP samples were inconclusive. For dynamic modulus, it was found that the percent RAP, additional binder, frequency, and temperature were all statistically significant with 95% confidence. For the fatigue life, ANOVA showed that the percent RAP and additional binder were statistically significant with 95% confidence. These results suggest that by utilizing a higher percentage of RAP and asphalt binder, it is possible to meet or improve upon the dynamic modulus and fatigue life of the lower percentage of RAP samples.

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LIST OF ABBREVIATIONS

A.A.M.A.S.	Asphalt Aggregate Mixture Analysis System
A.A.S.H.T.O.	American Association of State Highway and Transportation Officials
A.C.	Asphalt Content
A.N.O.V.A.	Analysis of Variance
A.V.	Air Voids
A.V.C.	Asphalt Vibratory Compactor
D.O.T.	Department of Transportation
G.B.	Specific Gravity of Asphalt Binder
G.M.B.	Bulk Specific Gravity of Asphalt Mixture
G.M.M.	Theoretical Maximum Specific Gravity of Asphalt Mixture
G.S.E.	Effective Specific Gravity of Aggregate
H.M.A.	Hot Mix Asphalt
I.D.O.T.	Illinois Department of Transportation
I.T.C.	Interlaken Technology Corporation
M.E.P.D.G.	Mechanistic-Empirical Pavement Design Guide
M.T.S.	Material Testing System
N.C.A.T.	National Center for Asphalt Technology
N.C.H.R.P.	National Cooperative Highway Research Program
O.D.O.T.	Oklahoma Department of Transportation
P.G.	Performance Grade
P.B.	Percent Asphalt Binder by Weight of Total Mixture
P.S.	Percent Aggregate by Weight of Total Mixture
R.A.P.	Reclaimed Asphalt Pavement
S.A.S.	Statistical Analysis System
S.G.C.	Superpave Gyratory Compactor
V.D.O.T.	Virginia Department of Transportation
V.T.T.I.	Virginia Tech Transportation Institute

CHAPTER I - INTRODUCTION

BACKGROUND

Due to the rise in oil prices as well as an increased awareness towards greener, more sustainable practices, state departments of transportations (DOTs) have been considering alternate, greener methods in the production of asphalt concrete. One of these methods is the use of reclaimed asphalt pavement (RAP) in newer construction projects. The use of RAP in asphalt mixtures has steadily increased in recent years *(1)*. Currently, as much as 100 million tons of asphalt concrete are reclaimed each year, of which, approximately 80% can be reused as RAP *(2)*.

The term "higher percentages of RAP" is typically considered when the RAP levels are used in excess of 20 to 25% *(1, 3)*. One of the main reasons against using higher percentages of RAP in asphalt concrete projects is that there is a limited understanding of how the RAP interacts with the virgin materials, in particular, how the RAP binder interacts with the virgin binder. Currently, the composite performance grade (PG) of the RAP binder and virgin binder is the most studied property of RAP mixes. Most studies have reported that adding RAP (in excess of 20%) results in an increase of the virgin binder PG by one grade *(1, 4)*. This bump in PG is a result of the RAP's higher PG. RAP exhibits higher PG in relation to similar virgin PG because it has undergone short and long term aging, which increases both the stiffness and viscosity of the binder. This is due to the oxidation and volatilization that occurs and transforms the resins and oils of an asphalt binder into asphaltenes. Researchers have spent a considerable amount of time investigating the properties of the asphalt concrete mixtures that include RAP. Though not all results are universally applicable, it has generally been found that as the amount of RAP in a mixture is increased, there will be an increase in rutting resistance in addition to a decrease in cracking resistance *(5-7)*.

Variability of RAP

RAP is an inherently variable material due to how it is obtained. RAP is collected by milling the original pavement and placing it into a stockpile, which often results in the material containing patches, chip seal, and other maintenance treatments. The RAP may also contain material that is gathered from various courses of the pavement: the base course, the intermediate course, and the surface course. There are many cases as well where RAP from several different projects may be mixed into one single stockpile. This single stockpile may contain RAP that was collected from private works which is not built to the same original standard. This variability in material properties and sources is one of the main concerns a pavement engineer has when using RAP.

To ensure that all the properties of RAP samples taken from asphalt plants have low variability, standards must be set for stockpiling. In order to do this, different stockpiling methods have been evaluated to determine which methods minimize variability. The US DOT also has set stockpiling procedures in an effort to minimize variability within aggregate stockpiles *(8)*. It is important that RAP has minimal stockpile variability in order to quantify the effects that it will have on the virgin binder. Variation within a stockpile is determined through a variety of asphalt property tests such as moisture content, asphalt content (AC), theoretical maximum specific gravity (G_{mm}), and viscosity. The grain size distribution of RAP stockpiles is also used to quantify their variability *(9)*. Zhou et al. provides some suggestions to improve stockpiling management *(10)*:

- Eliminate contamination of RAP stockpiles.
- Keep RAP stockpiles as separate as possible.
- Blend thoroughly before processing or fractionating the multiple-source RAP stockpiles.
- Avoid over-processing (avoid generating too much fines passing # 200 sieve size).
- Use good practice when storing the processed RAP (such as using the paved, sloped storage area).
- Characterize and number the processed RAP stockpiles.

West conducted a survey for the National Center for Asphalt Technology (NCAT) to gather information on RAP management practices. Results of this survey are shown in Figure 1. West found that 53% of the responders do not employ any special stockpiling for RAP, whereas the other 47% of the responders maintained separate stockpiles for different sources of RAP. West suggested several reasons for keeping separate stockpiles, some of which include, but are not limited to: agency specifications allowed only DOT RAP in mixes for DOT projects, millings were to be kept separate from other multiple source RAP material, and to improve the consistency within the RAP stockpiles *(11)*.

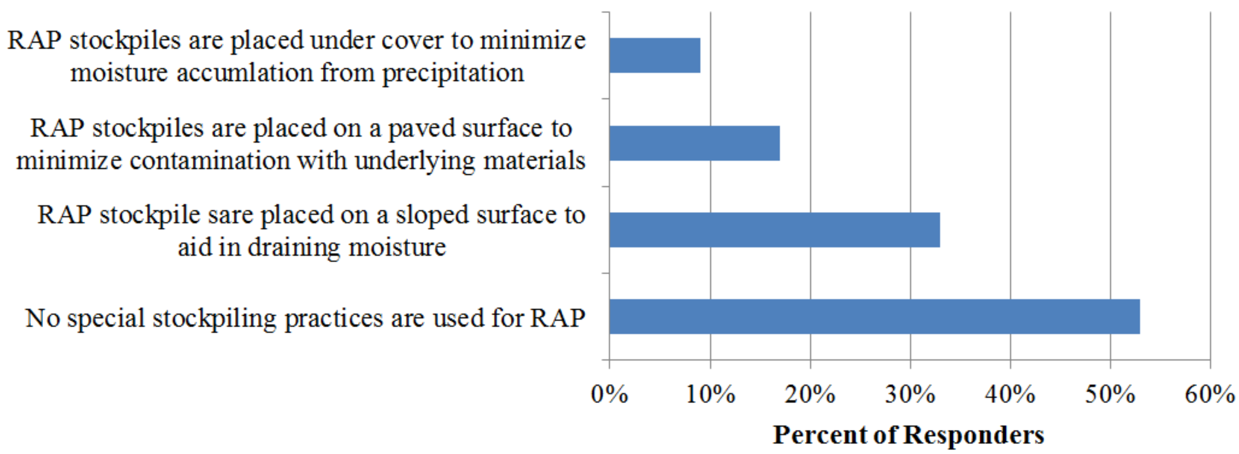

Figure 1. Summary of RAP Stockpiling Processes *(11)*

West also collected information on the crushing and processing of RAP materials, which is shown in Figure 2. It can be seen that a majority of the responders only crush their RAP to a single size, with only a small percentage fractionating the RAP into different sizes. There is also a small percentage of responders who do nothing to the RAP prior to reusing it in a new asphalt concrete mix *(11)*.

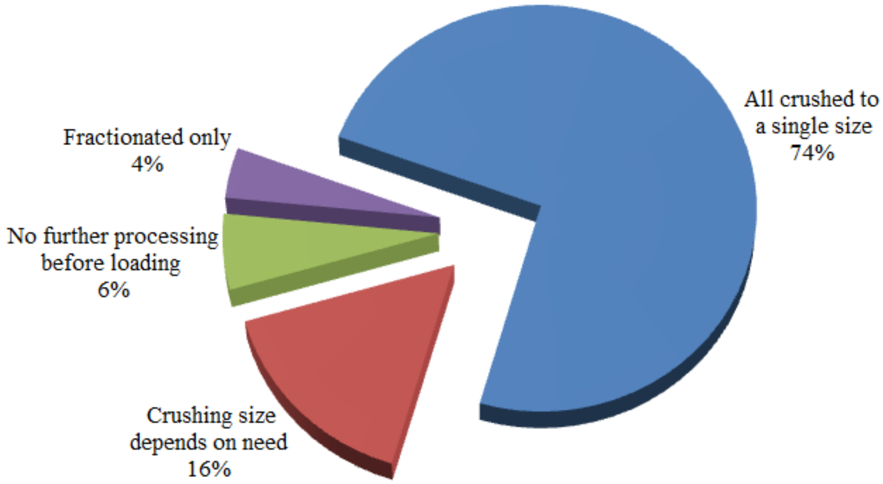

Figure 2. Summary of How RAP is Crushed *(11)*

RAP in Asphalt Concrete

In addition to collecting information about standard RAP practices and procedures, West also gathered data regarding how much RAP is typically used in surface and non-surface mixes. In the study, West found that the average RAP content that was used in surface mixes and non-surface mixes were 16% and 20% respectively *(11)*. The Virginia DOT (VDOT) specifies an allowable RAP percent of 20% RAP in surface mixes. When more than 20% RAP is used in a surface mix, a softer PG for both the high and low temperatures must be used *(12)*. If RAP exceeds 30% RAP in the surface mix, blending charts must be used to select the appropriate binder *(12)*. For base mixes, a similar method was done to determine the correct binder. In the base mixes, an allowable RAP percent of 25% RAP was set and 35% RAP could be used with softer binders and blending charts respectively *(12)*. Also in the West study, it was determined that 46% of the responders use the same percentage of RAP in both the surface and non-surface mixes *(11)*. In addition, responders were asked to identify what were the limiting factors that prevented higher RAP contents in the surface and non-surface mixes. Responders were asked to identify whether or not the following five factors were sometimes, often, always, or never a factor *(11)*:

- Plant limitations
- RAP is too variable for good production control of mixes
- Meeting volumetric properties
- Specific RAP limits in specifications
- Limited quantity of RAP available

The main limiting factor for higher RAP contents was the agency RAP specifications. Plant limitations, RAP being too variable, and a limited supply of RAP seemed to have little to no bearing on the usage of high RAP contents. Meeting volumetric properties had mixed responses, often being a factor for some responders and not at all for others *(11)*.

Much research has also been conducted on the effects of lower percentages of RAP and its effects on the performance of asphalt concrete. In general, it has been found that utilizing RAP in lower amounts has little to no effect on a new pavement. Performance issues in a pavement generally arise when high RAP contents are utilized. Copeland offered several suggestions and issues that need to be addressed when using high RAP contents in asphalt mixtures *(8)*:

- Additional processing and quality control
- Characterizing RAP
- Changing the virgin binder grade
- Preparing materials for mix design
- Blending/comingling the virgin and RAP binders
- Performance

Fractionation of RAP

As shown by West, the two main factors that limit the percentages of RAP in asphalt concrete mixes are the agency RAP specifications and meeting volumetric properties *(11)*. Both of these factors primarily tie into one underlying reason – the variability of RAP. One possible way of decreasing the variability associated with RAP is by fractionating the RAP aggregates. Currently, VDOT does not require the fractionation of RAP.

Fractionation is the process in which RAP is separated into at least two different sizes. As was shown earlier, most agencies only crush (fractionate) their RAP to one single sieve size (the most popular size was found to be ½ inch). There are certain machines capable of crushing aggregates into smaller sieve sizes such as the No. 4 and No. 8 sieve. In fractionation, aggregates are sieved through specific sizes and separated into two piles, one pile containing the aggregates above the specified size and one below. This process continues until you achieve stockpiles with the desired sizes. Currently, fractionation is used to raise the RAP percentage in six states. This increase in the allowance of RAP is possible because fractionation reduces the variability in aggregate size in large RAP stockpiles. It should be noted that this process does not eliminate all RAP stockpile variability and that good quality control procedures should be used along with fractionation. Copeland echoed this sentiment saying that effective quality control measures are the most crucial factors for using higher percentages of RAP *(8)*.

PROBLEM STATEMENT

When compared to virgin materials, RAP materials are highly variable. The asphalt binder content, gradation, stiffness, etc. of RAP are much more difficult for an engineer to incorporate into the design that must ensure a proper balance between the performance criteria (rutting, cracking, etc.) and the cost. One of the major drawbacks of using RAP in asphalt concrete is that it has the potential to increase the fatigue cracking susceptibility in a pavement. As the percentage of RAP increases in a mix, the stiffness of the asphalt concrete will increase, which will potentially increase the extent of fatigue cracking in the pavement. One potential solution to this is to increase the amount of virgin binder in the mix. Research conducted by Maupin and Diefenderfer suggested that increasing the AC improved, or had the potential to improve, the durability, permeability, and fatigue characteristics of a mix *(13)*. Ideally, the RAP would improve the rutting resistance of the mix and the additional asphalt binder would improve the cracking resistance in a mix. This would increase the overall pavement life which would, in turn, save money and increase roadway safety.

OBJECTIVES

The main objective of this study is to quantify the effects of higher percentages of RAP and asphalt binder on the dynamic modulus and fatigue life of asphalt concrete. In this study, two different percentages of RAP (20% and 40%) were investigated at three different ACs (plant-mix, plant-mix + 0.5%, and plant-mix + 1.0%) to determine their effects on the dynamic modulus and fatigue cracking of asphalt concrete. The hypothesis was that the decreased fatigue performance observed in higher levels of RAP will be offset by the additional AC. Specific steps to accomplish this are outlined below.

- Conduct a thorough literature review on previous and on-going studies related to the usage of higher percentages of RAP and asphalt binder in asphalt mixtures and the subsequent effects.
- Perform dynamic modulus and fatigue testing on all of the compacted asphalt samples.
- Analyze test results.

RESEARCH SCOPE

To accomplish the objectives of this study, asphalt mixes and asphalt binders used in the commonwealth of Virginia were collected. After obtaining the mixtures and asphalt binder, the laboratory at VTTI was used to mix and compact the samples. A standard mixing bucket was used to prepare the additional asphalt binder samples (plant-mix + 0.5% and plant-mix + 1.0%). The Superpave gyratory compactor (SGC) and asphalt vibratory compactor (AVC) were used to compact the dynamic modulus specimens and fatigue beam specimens respectively. Volumetric properties for the mixtures were measured and evaluated. An Interlaken Technology Corporation (ITC) servohydraulic machine was used to evaluate the dynamic modulus of each mixture and a Material Testing Systems (MTS) servohydraulic machine was used to characterize the fatigue resistance of each mixture. The results of these tests were used to determine if the added RAP or asphalt binder had any effect on the performance measures of the asphalt mixes. This information can be beneficial to pavement researchers because it may maximize the amount of RAP in a pavement, potentially leading to longer lasting, cheaper pavements.

Chapter II provides a literature review of dynamic modulus and fatigue resistance of asphalt mixes containing RAP. Case studies and cost analysis are also provided. Chapter III discusses the experimental design and data collection. Chapter IV presents the results of the volumetrics, dynamic modulus, fatigue resistance, and analysis of variance (ANOVA) of the asphalt mixes. Chapter V summarizes the results found in Chapter IV and provides conclusions on the overall project. Recommendations for future work are also presented.

CHAPTER II - LITERATURE REVIEW

BACKGROUND

Introduction

Two of the main distresses that afflict asphalt pavements are rutting and fatigue cracking. In this study, the dynamic modulus test was conducted to determine the stiffness of the asphalt mixtures and the third-point fatigue test was used to characterize the fatigue resistance of the asphalt mixtures. The following section includes a brief summary of dynamic modulus and fatigue cracking and how they relate to asphalt pavement. A summary of past and on-going research related to each of these distresses and how RAP relates to them will be presented in a later section.

Dynamic Modulus

For linear viscoelastic materials, the dynamic modulus is defined by the stress-strain relationship under continuous sinusoidal loading *(14)*. Temperatures, rate of loading, age, and mixture characteristics (i.e. binder stiffness, binder content, air voids, and aggregate gradation) are all factors that affect the dynamic modulus values of asphalt concrete *(15)*. By applying a uniaxial sinusoidal load to a specimen and measuring the strain, the dynamic modulus of asphalt concrete can be calculated from Equation 1.

$$E^* = \frac{\sigma}{\varepsilon} = \frac{\sigma_0 e^{i\omega t}}{\varepsilon_0 e^{i(\omega t - \Phi)}} = \frac{\sigma_0 \sin(\omega t)}{\varepsilon_0 \sin(\omega t - \Phi)} \tag{1}$$

Where,

σ_0 = Peak (maximum) stress
ε_0 = Peak (maximum) strain
Φ = Phase angle, degrees
ω = Angular velocity
t = Time, seconds
i = Imaginary component of the complex modulus

As shown in Equation 1, the dynamic modulus is the ratio of the amplitude of the sinusoidal stress at a given loading frequency to the amplitude of the sinusoidal strain at the same loading frequency *(14)*. The phase angle in Equation 1 is the angle where the strain lags the stress. For purely elastic materials, the phase angle (Φ) is 0^o because the stress and strain occur in phase. This essentially means that one occurs simultaneously with the other. For purely viscous materials, the phase angle between the stress and strain is 90^o, with the strain lagging behind the stress *(16)*.

The dynamic modulus test is conducted over a range of temperatures and frequencies. The Mechanistic-Empirical Pavement Design Guide (MEPDG) recommends performing the test at the following temperatures: -10°C, 4.4°C, 21.1°C, 37.8°C, and 54.4°C *(15)*. For each temperature, the following frequencies should be tested: 25Hz, 10Hz, 5Hz, 1Hz, 0.5Hz, and 0.1Hz *(15)*. The temperature chamber at VTTI was unable to hold a temperature of -10°C, therefore it was not used in the study. Some studies suggest that determining the dynamic modulus at -10°C is not required to construct a master curve *(17)*. The properties that are obtained from this test provide insight into the viscous properties of the material and can be correlated with in-service rutting measurements *(18)*.

Fatigue Cracking

One of the most problematic distresses found in Virginia is fatigue cracking *(19)*. Fatigue cracking in asphalt concrete is a series of interconnected cracks that is generally caused by repeating traffic loading. In a well-designed pavement, the strains in asphalt concrete should be low enough that fatigue is not a problem. Some pavements, however, provide inadequate structural support which can be caused by a variety of factors such as: decrease in pavement load supporting characteristics (loss of layer support, stripping, etc.), increase in loading, inadequate structural design, and poor construction are some of the more common ones. It has generally been observed that fatigue cracking occurs more often in stiffer mixtures because the asphalt cannot dissipate energy as efficiently when compared with a more flexible mixture. With the asphalt concrete not efficiently dissipating energy, microcracks will form quicker and more abundantly which eventually leads to macrocracks.

The flexural fatigue test is the most commonly used test to characterize the fatigue life of asphalt concrete at intermediate temperatures. This type of testing is conducted to simulate the strain that an asphalt concrete pavement will experience during repeated traffic loading. To simulate the fatigue that an asphalt concrete will experience, a sinusoidal load, located at one-third distances from the beam ends, is applied to a rectangular beam with a length of 381mm (15 inches), a height of 51mm (2 inches), and a width of 64mm (2.5 inches). This is done in order to simplify the analysis by producing uniform bending in the central third of the specimen. The third-point loading mode fatigue test apparatus is shown in Figure 3.

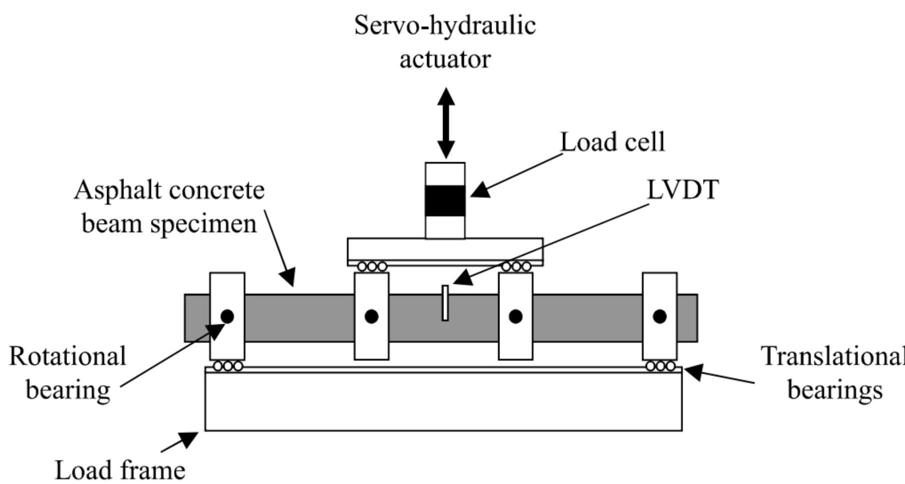

Figure 3. Third-Point Loading Mode Fatigue Test Apparatus *(20)*

Given in Huang, the general equations for the analysis of a simply supported beam can be used *(21)*.

$$\sigma_t = \frac{3aP}{bd^2} \quad (2)$$

$$\varepsilon_t = \frac{12d\delta}{3L^2 - 4a^2} \quad (3)$$

$$E = \frac{Pa(3L^2 - 4a^2)}{4bd^{3\delta}} \quad (4)$$

Where,

σ_t	=	Tensile stress
ε_t	=	Tensile strain
δ	=	Vertical deflection
P	=	Applied load
L	=	Beam span
a	=	Distance between the load and the nearest support (L/3)
b	=	Beam width
d	=	Beam depth
E	=	Stiffness modulus

FINDINGS FROM PAST AND ON-GOING STUDIES

Overview

A compilation of journal and conference papers are reviewed on the effects of RAP on dynamic modulus and fatigue cracking in asphalt concrete. A brief synopsis of the reason for the study, the objectives of the study, the methods and materials used, and the conclusions of the study are provided. The content for each of these summaries reflect the views of the authors of the paper. The major results and findings from these studies are summarized at the end of the section.

Dynamic Modulus

Li et al. (2004) – Recycled Asphalt Pavement (RAP) Effects on Binder and Mixture Quality (22)

It has been noted that the recycling of asphalt pavement is beneficial from the technical, environmental, and economical perspectives. For approximately 30 years, Minnesota has been using RAP in asphalt concrete. Depending on the traffic level, Minnesota currently allows 20% RAP to 30% RAP to be used in asphalt concrete. The primary objective for Li et al. was to investigate the effect of various types and percentages of RAP on asphalt binder and asphalt mixture properties.

In this study, the researchers prepared and tested ten typical Minnesota asphalt mixtures. The ten mixtures that were chosen included three percentages of RAP (0%, 20%, 40%), two virgin asphalt binders (PG 58-28 and PG 58-34), and two different RAP sources (RAP and millings). RAP material was blended with the virgin aggregate in order to produce a similar gradation for all mixtures.

A target air void (AV) level of 5.0 ± 1.0% was set for all compacted specimens. For dynamic modulus testing, five temperatures (-20^{o}C, -10^{o}C, 4.4^{o}C, 21.1^{o}C and 37.8^{o}C) and six frequencies (25Hz, 10Hz, 5Hz, 1Hz, 0.5Hz, and 0.1Hz) were used. The researchers found that as the amount of RAP increases in asphalt concrete, the dynamic modulus will also increase. It was also concluded that the RAP source had an effect on the dynamic modulus values, with the mixtures containing millings exhibiting a higher dynamic modulus than the mixtures with RAP.

Cross et al. (2007) – Determination of Dynamic Modulus Master curves for Oklahoma HMA Mixtures (17)

The primary objective for Cross et al. in this study was to gather sufficient data to develop a procedure where the Oklahoma DOT (ODOT) could achieve a high level of reliability for asphalt concrete master curves without performing detailed dynamic modulus testing for each mixture. In the study, the researchers collected asphalt mixtures from ODOT projects over a two-year time period. Mixtures included four aggregate types that are typically found in Oklahoma: limestone, sandstone, granite/rhyolite, and crushed gravel. Many of the mixtures also contained 25% RAP, which were sampled from a RAP stockpile.

A target AV level of 4.5% ± 1.0% was achieved for all compacted specimens. For dynamic modulus testing, four temperatures (4.4^{o}C, 21.1^{o}C, 37.8 ^{o}C, and 54.4^{o}C) and six frequencies (25Hz, 10Hz, 5Hz, 1Hz, 0.5Hz, and 0.1Hz) were used. Determining the effects of RAP on the dynamic modulus was outside of the scope of the project, but the researchers did find that the presence of RAP increased the average stiffness of the mixtures. The researchers also claimed that using 25% RAP in a mixture has the same effect on the dynamic modulus that raising the PG of the binder one grade does.

Al-Qadi et al. (2009) – Determination of Usable Residual Asphalt Binder in RAP (23)

The Illinois DOT (IDOT) works under the assumption that the binder found in RAP contributes 100% to a new asphalt concrete. Recent research has indicated that some of the asphalt binder in a RAP mixture acts as a “black rock” and does not participate in the blending process with virgin binder. The primary objective for Al-Qadi et al. in this study was to characterize the amount of binder contribution of RAP materials during the mixing process. With this, the researchers would then develop a procedure to determine the degree of blending in a recycled mix to implement in the mix design procedure. To accomplish these objectives, the researchers developed an experimental program to determine the amount of working RAP binder by comparing mixtures prepared with RAP to mixtures prepared with virgin asphalt binder and recovered RAP asphalt binder.

In the study, three different percentages of RAP were used: 0% RAP, 20% RAP, and 40% RAP. The mixtures were prepared according to IDOT specifications utilizing IDOT approved materials. The asphalt concrete mixtures with 20% RAP and 40% RAP included four sets of specimens: Set 1 = assuming 100% RAP binder mobilization, Set 2 = 0% RAP binder mobilization, Set 3 = 50% RAP binder mobilization, and Set 4 = 100% RAP binder mobilization. Sets 2-4 used recovered aggregates and asphalt binders when preparing mixes, where Set 1 used actual RAP materials.

A target AV level of 4.0% was set for all compacted specimens. For dynamic modulus testing, three temperatures (-10^{o}C, 4^{o}C, and 20^{o}C) and seven frequencies (25Hz, 10Hz, 5Hz, 1Hz, 0.5Hz, and 0.1Hz, 0.01Hz) were used. The researchers felt that the data clearly showed that the amount of RAP had an effect on the dynamic modulus of the mixture. It was noted, though, that the dynamic modulus values for mixtures with 20% RAP did not change significantly from the 0% RAP mixtures, which shows that the RAP binder has little effect on mixture properties at low percentages. For the mixtures containing 20% RAP, the researchers felt the results did not warrant binder bumping to achieve a similar dynamic modulus to the 0% RAP mixtures, however, they did feel that double bumping was necessary for the 40% RAP samples.

Apeagyei and Diefenderfer (2011) – Asphalt Concrete Rutting Resistance Assessment by Flow Number Test (24)

Recently, VDOT increased the threshold of allowable RAP from 20% to 30% for Superpave mixtures. Much of the literature points to RAP being a positive influence on asphalt concrete performance, but there is still a need to quantify the rutting-performance effects of high RAP mixtures. The primary focus of this study was to evaluate the effects of RAP on permanent deformation or rutting in asphalt concrete. The primary objective was to compare the rutting resistance of asphalt concrete mixtures designed for same traffic levels but containing varying amounts of RAP.

In this study, the researchers considered mixtures that were capable of withstanding highway traffic between 3 million and 10 million equivalent single axle loads over a 20 year design period. Five asphalt concrete mixtures with nominal maximum aggregate sizes of 12.5mm (0.5 inches) and 25.0mm (1 inch) were produced in accordance with VDOT specifications. RAP amounts in this mixture ranged from 0% RAP to 25% RAP by weight of mixture.

A target AV level of 7.0% ± 0.5% was attempted for all compacted specimens. The average AV content of the specimens actually ranged from 6.95% to 7.85%. For dynamic modulus testing, five temperatures (-10 ^{o}C, 4^{o}C, 20^{o}C, 38 ^{o}C, and 54^{o}C) and six frequencies (25Hz, 10Hz, 5Hz, 1Hz, 0.5Hz, and 0.1Hz) were used. The researchers found both expected and unexpected results in their dynamic modulus data. First, it was found that the mixture containing 0% RAP was the least stiff at low temperatures. The mixture containing 25% RAP was only slightly stiffer than the mixtures containing 0% RAP and 10% RAP at low temperatures. The mixtures containing 15% RAP and 20% RAP were relatively stiffer than the mixtures containing 0% RAP, 10% RAP, and 25% RAP at low temperatures. At higher temperatures, the mixture containing 20% RAP was again the stiffest, followed by the mixtures containing 0% RAP and 25% RAP. It was hypothesized that the mixture containing 25% RAP may have been made using a lower PG binder. It was also hypothesized that the gradation and the base binder used may account for the behavior of the mixture containing 20% RAP.

Solanki et al. (2012) – Volumetric and Mechanistic Characteristics of Asphalt Mixes Containing Recycled Asphalt Pavement (2)

In Oklahoma, the threshold amount of RAP that can be used in the base course of a pavement is set at 25%. No RAP is currently allowed in the surface course. Lack of field and laboratory data on high percentages of RAP and variations in RAP quality are the major reasons associated with the low percentage of RAP used in Oklahoma pavements. The primary objective of this study is to determine the change in volumetric and mechanistic characteristics with the addition of RAP.

In this study, the researchers collected RAP millings from I-35 in McClain County, Oklahoma in addition to virgin aggregates: #67 rocks, 5/8 inch chips, screenings, manufacture sand, and natural sand. A virgin binder of PG64-22 from Valero, Oklahoma was also collected for mix design and laboratory testing. When designing the mixtures, 25% RAP and 40% RAP by weight were used.

A target AV level of 7.0% ± 0.5% was achieved for all compacted specimens. For dynamic modulus testing, five temperatures (-10^{o}C, 4.4^{o}C, 21.1^{o}C, 37.8^{o}C, and 54.4^{o}C) and six frequencies (25Hz, 10Hz, 5Hz, 1Hz, 0.5Hz, and 0.1Hz) were used. The researchers found that the mixture containing 40% RAP had a higher dynamic modulus than the mixture containing 25% RAP. They found that the 40% RAP mix had dynamic modulus values approximately 81%, 53%, and 65% higher at a reduced frequency of 10^{-7}Hz, 1Hz, and 10^{7}Hz respectively.

Fatigue Cracking

Puttagunta et al. (1997) – A Comparison of the Predicted Performance of Virgin and Recycled Mixes (25)

Numerous factors affect the performance of a pavement, including but not limited to, the material properties, climatic conditions, and traffic loadings. At the time of this study, the Marshall and Hveem mix design methods were the most commonly used methods to design asphalt mixtures. It was found, however, that these mix designs do not generally meet the performance criteria of fatigue cracking, rutting, and moisture damage. Due to these limitations, new mix designs were being considered. The Strategic Highway Research Program developed the Superpave mix design and the American Association of State Highway and Transportation Officials (AASHTO) developed the Asphalt Aggregate Mixture Analysis System (AAMAS) mix design to try and overcome these shortcomings. The objective of this study was to evaluate and compare the performance predictions based on AAMAS criteria of the Marshall designed virgin and recycled mixes having the same physical properties.

In this study, core samples were obtained from a section of Highway 11 between Regina, Canada, and Saskatoon, Canada one month after it had been recycled using 50% RAP. These samples were used to determine the mixtures physical properties so that mixtures could be replicated with 0% RAP, 25% RAP, and 50% RAP in the laboratory. The indirect tensile resilient modulus test was used to determine the fatigue cracking susceptibility of the asphalt mixtures. A repeated haversine load at a frequency of 1Hz with a loading period of 0.1 seconds and a rest period of 0.9 seconds was done for this test.

The asphalt specimens were compacted to an AV content between 4.8% and 4.9% for all three RAP percentages. Testing was conducted at 5^{o}C, 22^{o}C, and 40^{o}C. The researchers found that at 5^{o}C, the mixture containing 50% RAP had a lower fatigue resistance than the other two mixes. At 22^{o}C and 40^{o}C, all three RAP mixtures performed similarly and there was no significant impact from the RAP.

McDaniel et al. (2000) – Recommended Use of Reclaimed Asphalt Pavement in the Superpave Mix Design Method (26)

The National Cooperative Highway Research Program (NCHRP) undertook a massive project in 2000 that was investigating the effects of RAP on an asphalt pavement and how it interacts with the virgin materials. In their report, *Incorporation of Reclaimed Asphalt Pavement in the Superpave System* (NCHRP 9-12), three separate studies were conducted: the “black rock” study, the “binder effects” study, and the “mixture effects” study. The main objective of the “mixture effects” study was to assess the effects of RAP on the total mixture properties.

In this study, three sources of RAP, two virgin binders, and one virgin aggregate source was used. The three RAP sources came from Florida, Connecticut, and Arizona, and these were chosen to represent a RAP with low stiffness, medium stiffness, and high stiffness respectively. A PG 52-34 and PG 64-22 asphalt binder and a 12.5mm (0.5 inches) nominal max Kentucky limestone and natural sand aggregate blend were also used for this study. Four different percentages of RAP (0% RAP, 10% RAP, 20% RAP, and 40% RAP) were incorporated into the mixtures for the “mixture effects” study. To evaluate the fatigue cracking susceptibility of the mixture, the four-point beam fatigue test was conducted.

Two strain levels (400με and 800με) were chosen to simulate a thick pavement with good structural support and a thin pavement with a weak structure respectively. Testing was conducted at 20^{o}C at a frequency of 10Hz at these two strain levels. Failure was consider at 50% decrease in initial stiffness or 500,000 cycles, whichever occurred first. A target AV content of 7.0% ± 1.0% was achieved for fatigue testing. McDaniel et al. concluded that the addition of higher amounts of RAP will decrease the life of the asphalt pavement if no adjustment is made to the virgin binder grade. The researchers also found that when using a percentage of RAP below 20%, the fatigue life is statistically the same as the virgin mixture.

Maupin and Diefenderfer (2006) – Design of a High-Binder–High-Modulus Asphalt Mixture (13)

Recent studies have suggested that it may be beneficial to design and construct very dense underlying layers to improve the fatigue and durability characteristics. The main concept is to create long-life underlying layers of asphalt pavement that will not need major reconstruction for extended periods of time (approximately 50 years). Surface layers can be periodically replaced as needed. Fatigue cracking has always been considered to originate from the base layers and propagate upwards, so improving the base layers has the potential to improve the fatigue performance of an asphalt pavement. The main objective of this study was to investigate the design of an asphalt mixture having more than the normal amount of binder and high stiffness.

In this study, a 19.0mm (0.75 inches) Superpave intermediate mixture with a PG 64-22 binder was chosen as the original mix. This asphalt mixture was then modified with an increase AC (up to an additional 1.2% AC), stiffer binders (PG 70-22 and PG 76-22), and RAP (25% RAP) to increase durability and maintain stability. In order to quantify the fatigue cracking susceptibility of the asphalt mixture, the third-point beam fatigue test was utilized.

Three replicate samples were created for each mixture. A target AV content of 7.0% ± 0.5% was chosen for the asphalt mixtures. The number of passes/gyrations that was needed to obtain this AV content was held constant for the asphalt concrete mixtures with additional AC. Fatigue testing was conducted at 25^{o}C with a frequency of 10Hz and a strain level of 400με. Failure was considered the point at which the stiffness reduced to 50% of the original stiffness. The researchers found that there was a slight increase in the flexural stiffness when the AC was increased by approximately 0.5%. The flexural stiffness then showed a considerable decrease as the AC was increased passed this point. The fatigue life of the specimens generally increased as the AC increased for all mixtures, with the most noticeable difference occurring when more than 0.8% AC was used. The original mix (PG 64-22) had the highest fatigue life of all the mixtures at the optimal AC. For the modified mixtures, the mixture that had the best fatigue life was the PG 76-22 mixture followed by the RAP mixture and then the PG 70-22 mixture. The researchers concluded that an increase in AC of at least 1.0% was necessary to see an appreciable improvement in the fatigue properties.

Tabaković et al. (2010) – Influence of Recycled Asphalt Pavement on Fatigue Performance of Asphalt Concrete Base Courses (27)

Similar to the United States, Europe has seen a constant increase in asphalt production of the last decade. As the asphalt production increases, the consumption of virgin materials also increases. The maximum amount of RAP that is permitted by the National Roads Authority (in Europe) is 20% for a coated asphalt base, however, Irish construction industries have failed to embrace the addition of RAP in new construction projects. The primary objective of this paper was to examine the physical properties of RAP and the influence of RAP on the mechanical properties of a 20mm (0.8 inches) binder course mix.

In this study, three different percentages of RAP (10% RAP, 20% RAP, and 30% RAP) and control samples containing no RAP were incorporated into the mix design. The RAP was collected from a local stockpile, with the specific origins of the RAP unknown. Through preliminary testing, it was determined that the RAP had an AC of 1.83% and a relative density of 2626 kg/m^3 (164 lb/ft^3). In order to quantify the fatigue cracking susceptibility of the asphalt mixture, the indirect tensile fatigue test was utilized.

Nine specimens for each mixture with a diameter of 100mm and a height of 70mm were produced at a target AV content of 6%. Testing was conducted at 20^{o}C to a repeated constant load with 124ms loading and a pulse repetition time of 1.5 seconds. The data showed that the mixture containing 10% RAP had the lowest fatigue cracking resistance, while the mixture containing 30% RAP had the highest fatigue cracking resistance. The mixtures containing 0% RAP and 20% RAP performed similarly. The researchers concluded that RAP could be used as an alternative aggregate material for a 20mm binder course mixture.

Al-Qadi et al. (2012) – Impact of High RAP Content on Structural and Performance Properties of Asphalt Mixtures (28)

Hot-in place recycling and cold-in-place recycling of RAP allow engineers utilize as much as 100% of the RAP when designing the pavement. Conventional RAP mixture designs, however, rarely increase above 25% RAP. The maximum amount of RAP that IDOT allows in high-volume roads, on average, is 15% RAP. The primary objective of this study was to examine the impact of high RAP in asphalt concrete on the mix performance.

In this study, Al-Qadi et al. conducted fatigue testing to characterize the fatigue cracking susceptibility in asphalt concrete mixtures. A rolling wheel compactor was used to create asphalt concrete beams and the researchers defined the failure criterion as a 50% reduction in initial stiffness. A target AV level of 7.0% ± 0.5% was set for all compacted specimens. A strain-controlled four-point beam fatigue test was performed on the samples described above. The test was conducted at 20^{o}C at six strain levels (1000µε, 800µε, 700µε, 500µε, 400µε, and 300µε). Based on the slope of the fatigue curve criterion (K_2), the researchers claimed that the fatigue life of asphalt concrete slightly improved with the addition of RAP. It was also found that single-bumping and double-bumping the asphalt binder showed an improvement in the fatigue results.

POTENTIAL SAVINGS FROM USING RAP

Belgium Study

Two studies were found that examine the potential savings from using RAP in an asphalt concrete mix. The first one was a 2007 Belgium study. In their methodology, the researchers first calculated the materials cost for a 1000 kg (2205 lb) batch of asphalt concrete as well as the production costs for a solely virgin asphalt concrete plant compared to a RAP plant. Found in Table 1, Table 2, and Table 3 are the costs for materials, productions, and combined savings *(29)*.

Table 1. Calculation of the Materials Cost in a 1000 kg Batch of Asphalt Concrete *(29)*

Material	Percent in Asphalt Concrete	Unit Price ($/ton)	Asphalt Concrete w/o Recycling	Asphalt Concrete w/ 40% RAP
Stones	58	10	5.8	3.5
Sand	30	8	2.4	1.5
Filler	7	20	1.4	0.84
Asphalt	5	100	5.0	3.0
RAP	0-40	5	0	2.0
Subtotal			$14.6/ton	$10.8/ton

Table 2. Calculation of the Production Costs in a 1000 kg Batch of Asphalt Concrete *(29)*

Cost Element ($/ton Asphalt Concrete)	Plant w/ No Recycling	Plant w/ Recycling
Investment in Equipment + Financing Costs	1.48	2.04
Maintenance of Equipment	0.45	0.78
Quality Control	0.22	0.44
Energy Use	1.55	1.94
Subtotal	$3.80/ton	$5.20/ton

Table 3. Summary of Costs for a 1000 kg Batch of Asphalt Concrete *(29)*

Cost in 1,000 kg Batch of Asphalt Concrete	Asphalt Concrete w/o RAP	Asphalt Concrete w/ 40% RAP
Materials Cost	$14.60/ton	$10.80/ton
Production Cost	$3.80/ton	$5.20/ton
Total Cost	$18.40/ton	$16.00/ton

As can be seen in Table 3, there is a potential to save $2.40/ton by using 40% RAP in an asphalt concrete mix.

NAPA Study

A study by the National Asphalt Pavement Association (NAPA) was also done which first determined the actual value for RAP and then showed the potential savings in an asphalt concrete mix when the RAP was obtained by millings or purchased. To determine the value of RAP, NAPA assumed that the AC in RAP was 4%, the cost of virgin asphalt was $350/ton, and the cost of virgin aggregates was $10/ton. The calculations for both the value of RAP as well as the savings from RAP are shown in Table 4 and Table 5 below *(29)*.

Table 4. Value of RAP from NAPA Study *(29)*

Material	Equation	Cost
Asphalt Cement in RAP	$350/ton * 0.04	$14.00/ton
Aggregate in RAP	$10/ton * 0.96	$9.60/ton
Total Value of RAP	$14.00/ton + $9.60/ton	$23.60/ton

Table 5. Cost Associated with Obtaining and Processing RAP from NAPA Study *(29)*

Material	RAP Obtained from Millings	RAP Purchased
Value of RAP	$23.60/ton	$23.60/ton
RAP Cost	N/A	-$2.00/ton
Plant Cost for Extra Equipment	-$0.75/ton	-$0.75/ton
Trucking Cost	-$3.00/ton	N/A
Processing and Handling Cost	-$5.00/ton	-$5.00
Extra Quality Control Cost	-$0.25/ton	-$0.25/ton
Total Savings	$14.60/ton	$15.60/ton
Savings/10% RAP in Mix	$1.46/ton (6%)	$1.56/ton (7%)
Savings/20% RAP in Mix	$2.92/ton (12%)	$3.12/ton (13%)
Savings/30% RAP in Mix	$4.38/ton (19%)	$4.68/ton (20%)
Savings/40% RAP in Mix	$5.84/ton (25%)	$6.24/ton (26%)

As can be seen in Table 5, there is a potential to save $6.24/ton when the RAP is purchased. Based on a recent study, $16.2 billion was spent on new roads and bridges in 2006. Given a 26% savings when purchasing and using 40% RAP, there is a potential to save approximately $4.2 billion annually in new roads and bridges *(29)*.

LITERATURE REVIEW SUMMARY

Use of RAP in asphalt pavements has been at the forefront of the asphalt industry because it is economically and environmentally beneficial. Numerous research has been conducted to assess the effects of higher percentages of RAP in asphalt concrete. Though much of the research is promising and shows that increased amounts of RAP can maintain or improve the performance of asphalt concrete, many states are still reluctant to use high percentages of RAP. Many states currently use approximately 15% to 20% RAP in their asphalt mixes. As stated in the objectives section, the purpose of this research is to determine the performance effects of adding higher percentages of RAP and asphalt binder in an asphalt pavement. This study is also intended to see if the increased stiffness of the mixture due to the increased percentage of RAP can be counteracted by using additional asphalt binder in the mix. The results of the studies above along with the technology available at VTTI led to the direction of this thesis. The key concepts from this literature review are the following.

- Most of the research on all of the topics concluded that Superpave asphalt mixtures can successfully incorporate upwards of 50% RAP in the mix design.
- A general trend was noticed that as the amount of RAP increases in the asphalt mixture, the dynamic modulus of the mixture will also increase.
- For RAP percentages at or below 20% to 25%, most researchers saw little statistical difference in the dynamic modulus when compared to the virgin mixture. Due to the mixtures being statistically similar, it was suggested that binder-bumping was not required.
- A general trend was noticed that as the amount of RAP increases in the asphalt mixture, the rutting of the mixture will decrease.
- No significant trend was noticed on the fatigue life for mixtures containing increased percentages of RAP. Some studies suggested that the fatigue life improved as the amount of RAP increased, while others suggested that it decreased.

- Increasing the AC in a mixture improves fatigue life. In order to see an appreciable increase in the fatigue life, some studies suggested that an increase of 1.0% AC should be used.
- For RAP percentages at or below approximately 20%, most researchers saw little statistical difference in the fatigue cracking resistance when compared to the virgin mixture.

These findings allowed for the development of the experimental plan that can be found in the next chapter.

CHAPTER III - EXPERIMENTAL DESIGN AND DATA COLLECTION

OVERVIEW

Based on the findings from the literature review in Chapter II, an experiment was designed to evaluate the effects of additional RAP and higher ACs on the performance of asphalt pavement. All work was conducted in the VTTI Materials Characterization Laboratory in Blacksburg, VA.

SAMPLE COLLECTION

After preliminary discussions with VDOT and other representatives of asphalt producers, it was decided that 20% RAP and 40% RAP samples would be collected from producers located in the northern Virginia district. Enough material was collected such that it would last the duration of the project.

Both the 20% RAP and 40% RAP mixtures are categorized as SM-9.5, which is a typical surface mixture used in Virginia. Specifics for each of these two mixes are shown in Table 6.

Table 6. Mix Specifics for 20% and 40% RAP Asphalt Samples

	20% RAP	40% RAP
Asphalt Mix	SM 9.5	SM 9.5
Asphalt Binder	PG 70-22	PG 64-22
Mixing Temperature	149°C (300°F)	149°C (300°F)
Compaction Temperature	143°C (290°F)	143°C (290°F)
Asphalt Percentage	5.18%	5.42%
Effective Asphalt	4.93%	5.17%
F/A Ratio	1.2	1.2

A sieve analysis was also provided along with the specifics shown in Table 6. Table 7 and Figure 4 show the sieve analysis for both the 20% RAP and the 40% RAP.

Table 7. Sieve Analysis Provided by Asphalt Producer for Two RAP Mixes

	20% RAP		40% RAP		
Screen	**% Retained**	**% Passing**	**% Retained**	**% Passing**	**Job Mix**
50mm (2")	0.0	100.0	0.0	100.0	
37.5mm (1 ½")	0.0	100.0	0.0	100.0	
25mm (1")	0.0	100.0	0.0	100.0	
19mm (¾")	0.0	100.0	0.0	100.0	
12.5mm (½")	0.7	99.3	1.3	98.7	**99**
9.5mm (⅜")	10.1	89.2	8.4	90.3	**93**
5.6mm (#3 ½)	0.0	89.2	0.0	90.3	
4.75mm (#4)	31.6	57.6	31.8	58.5	**60**
2.36mm (#8)	15.8	41.8	16.5	42.0	**43**
1.18mm (#16)	10.0	31.8	9.9	32.1	
0.600mm (#30)	8.9	22.9	9.0	23.1	
0.300mm (#50)	8.5	14.4	8.6	14.5	
0.150mm (#100)	5.0	9.4	5.1	9.4	
0.075mm (#200)	3.3	6.1	3.1	6.3	**5.5**

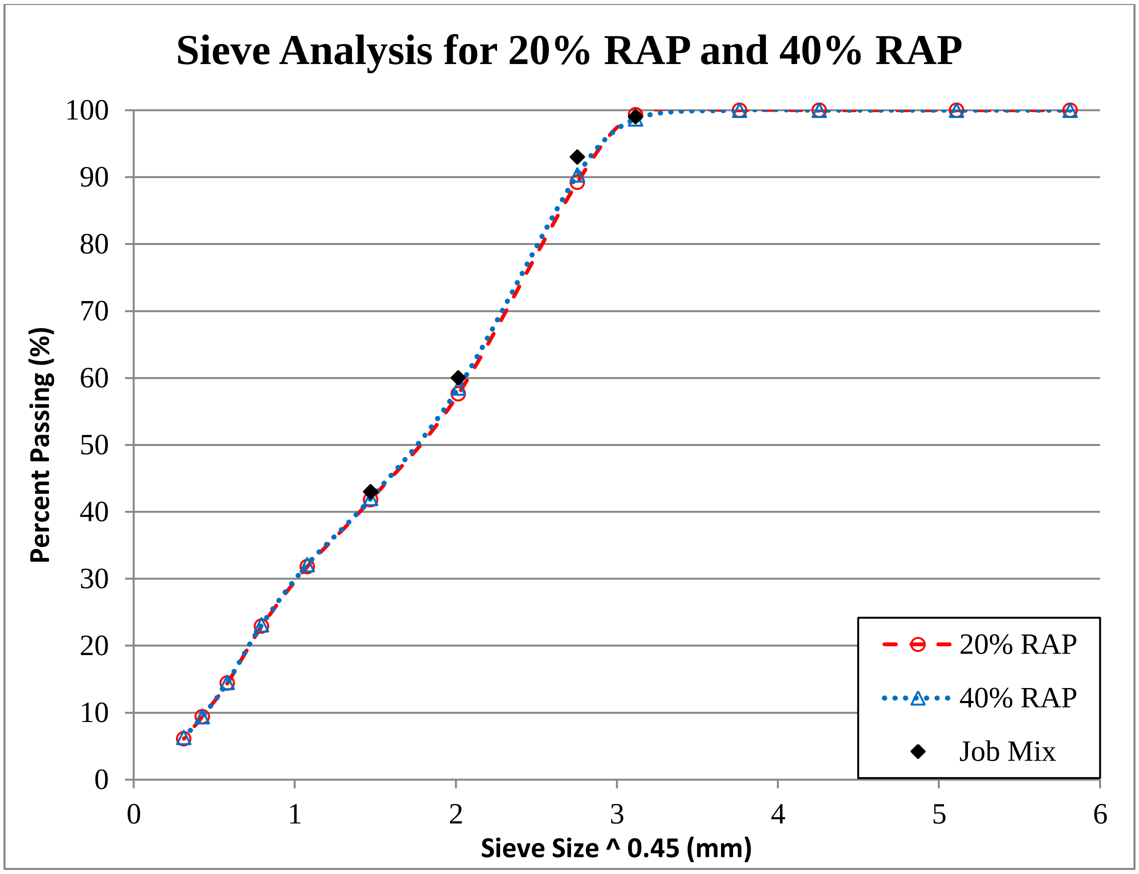

Figure 4. Sieve Analysis Provided by Asphalt Producer for Two RAP Mixes

DETERMINATION OF THEORETICAL MAXIMUM SPECIFIC GRAVITY (G_{MM})

After obtaining the material, the first step in any project involving making asphalt samples is to determine the G_{mm}. The G_{mm} is a fundamental asphalt concrete characteristic that is necessary in order to calculate the AV of a compacted asphalt concrete mixture. The G_{mm} of an asphalt concrete mixture is the specific gravity of that sample excluding AV, so in theory, if all the AV were eliminated from an asphalt concrete sample, the combined specific gravity of the remaining aggregate and asphalt binder would be the G_{mm}. Figure 5 shows the G_{mm} apparatus located in the VTTI laboratory.

Figure 5. Gmm Apparatus at VTTI Laboratory

For this project, loose asphalt concrete samples were heated at 121°C (250°F) in an oven for approximately two hours or until the sample is easily separated. Three replicate samples of the asphalt concrete in excess of 1000g (2.2 lbs) were taken in correspondence of the AASHTO standard. The loose asphalt concrete sample was separated such that there were no clumps of fine particles that would be able to pass through the 6.35mm (0.25 inches) sieve size. This process is shown in Figure 6.

Figure 6. Separation of Fine Aggregate Clumps for Gmm Testing

After separating the sample, the aggregates were weighed in air and water to determine the G_{mm}. Prior to weighing in water, the sample was partially submerged in distilled water and agitated for 17 minutes with a constant vacuum pressure of 4 kPa (30 mm Hg). The sample was then fully submerged in distilled water at a temperature of approximately 25°C (77°F) in accordance with the AASHTO standard. The G_{mm} was then calculated using Equation 5.

$$G_{mm} = \frac{A}{A-C} \tag{5}$$

Where,

G_{mm} = Theoretical maximum specific gravity of asphalt sample
A = Mass of oven dry sample in air, g
C = Mass of water displaced by sample at 25^{o}C, g

DETERMINATION OF ASPHALT CONTENT

Along with the G_{mm}, another fundamental property that must be determined is the AC of the sample. The ignition oven is widely used in industry due to its accuracy and simplistic approach. A photo of the VTTI ignition oven is shown in Figure 7.

Figure 7. Ignition Oven at VTTI Laboratory

In the ignition oven method, the change in mass of asphalt concrete is obtained after burning the RAP sample in an oven at 538^{o}C (1000^{o}F) until the asphalt binder is burned off. Due to the ventilation and high temperatures, some aggregate mass may also be burned off and lost which can cause an error in the prediction of the AC. Brown and Mager at NCAT carried out a study that would determine the accuracy and precision of the ignition oven method. They found that using the ignition oven to determine the AC of asphalt concrete can be just as accurate as the extraction recovery method without significantly altering the gradation *(30)*. A slightly altered version of this process was done for the purpose of this project. When material was heated and separated to conduct the G_{mm} testing, two samples exceeding 1500g (3.3 lbs) were taken for use in the ignition oven. The heating from the G_{mm} process allowed for the asphalt samples to be completely dried. The dried asphalt samples were then used in the ignition oven to determine the AC. An ignition oven correction factor was unable to be developed due to a lack of material.

MIXING OF HIGH RAP/HIGH BINDER ASPHALT SAMPLES

One of the main objectives of this project is to determine if additional binder in a sample can improve the performance of the asphalt pavement. In order to accomplish this, RAP mixes were modified by increasing the AC of the mixtures (Figure 8). It is important to note that the percent binder that was added (0.5% and 1.0%) was in reference to the total asphalt mixture and not the AC.

Figure 8. Mixing Bucket at VTTI Laboratory

The procedure for mixing the additional asphalt binder samples was as follows. First, the ovens were turned on to approximately 152°C (305°F) and allowed to warm up. Once the ovens reached temperature, the 20% and 40% RAP samples and asphalt binder that were obtained from the asphalt producer were placed in the oven. The asphalt bucket and mixing arm were also placed in the oven to heat up. Once the material was heated up to 140°C (300°F), the material was taken out, placed in the mixing bucket, and weighed. The amount of binder that was added was dependent on the amount of material placed in the bucket (i.e. for the addition of 1.0% binder with a sample weighing 10000g (22 lbs), an additional 100g (3.5oz) of binder would be added). Once the binder was added to the mixture in the mixing bucket, it was mixed for approximately five minutes or until the aggregates were sufficiently coated with the additional binder. To try and maintain the mixing temperature, a propane gas torch was used outside of the mixing bucket while mixing, as shown in Figure 9.

Figure 9. Using Propane Torch to Maintain Temperature

COMPACTING ASPHALT SAMPLES

Both of the RAP asphalt mixes were compacted at 143^{o}C (290^{o}F) as specified by the asphalt producer. To try and maintain the compaction temperature, the compaction molds were heated as well. Very minimal time was spent transferring the material into the molds (approximately one minute) and into the compaction device. After specimens were compacted, they were stored at 25^{o}C (77^{o}C) in a way that provided full support to prevent warping. All specimens were compacted to a target AV content of 7.0 ± 0.5%. Since this project calls for dynamic modulus and fatigue beam samples, two different compactors were used and are outlined below.

Superpave Gyratory Compactor (SGC)

Dynamic modulus testing requires samples that are 152mm (6 inches) in length and 102mm (4 inches) in diameter. In order to compact this type of sample, the SGC, shown in Figure 10, was used.

Figure 10. Superpave Gyratory Compactor at VTTI

The SGC compacts samples at a pressure of 600kPa (87psi) to a length of 178mm (7 inches) and a diameter of 152mm (6 inches). When using the SGC, the operator is capable of compacting to a specific height or number of gyrations. For this project, the samples were compacted to seven inches and the gyrations were allowed to vary. After the samples were compacted and cooled, they were cut and cored to a length of 152mm (6 inches) and diameter of 102mm (4 inches), as needed for the dynamic modulus testing. The corer and saw that were used to accomplish this is shown in Figure 11.

Figure 11. Asphalt Corer (Left) and Asphalt Saw (Right) at VTTI

Asphalt Vibratory Compactor (AVC)

Fatigue testing requires samples with the following dimensions: 51mm (2 inches) high, 64mm (2.5 inches) wide, and 381mm (15 inches) long. In order to compact this type of sample, the AVC, shown in Figure 12, was utilized.

Figure 12. Asphalt Vibratory Compactor at VTTI

The main variable that can be controlled when using the AVC is the amount of time that the asphalt sample is compacted. It was determined that the maximum amount of time a sample would need to be fully compacted was 35 seconds. To make sure that compaction time would not be an additional variable that could affect the performance of the mixture, a compaction time of 35 seconds was used for every asphalt sample. This was done keeping in mind that the samples with additional asphalt binder required less time to fully compact.

DETERMINATION OF BULK SPECIFIC GRAVITY

After compacting asphalt samples, it is necessary to determine the AV content of each of the samples. In order to calculate the AV content of a sample, two properties must be determined: the G_{mm} and the bulk specific gravity of the asphalt sample (G_{mb}). Both of these properties are vital in the design of an asphalt pavement, and incorrect values will lead to incorrect AV which leads to an incorrect mix design. Figure 13 shows the equipment used to determine the G_{mb} at the VTTI laboratory.

Figure 13. Gmb Equipment at VTTI

In order to determine the G_{mb} of an asphalt sample, three weights are required: weight in air, weight in water, and weight saturated surface dried (SSD). First, the asphalt samples were dried to a constant mass and weighed at room temperature 25°C (77°F). The sample was then fully submerged in distilled water at a temperature of approximately 25°C (77°F) in accordance with the AASHTO standard. After approximately ten minutes in the distilled water, the specimen was taken out and quickly wiped down with a damp towel for no longer than five seconds. The weight of the SSD specimen was then recorded. The G_{mb} of the sample could then be determined by Equation 6.

$$G_{mb} = \frac{A}{B-C} \qquad (6)$$

Where,

G_{mb}	=	Bulk specific gravity of the asphalt sample
A	=	Mass of asphalt specimen in air, g
B	=	Mass of SSD specimen, g
C	=	Mass of asphalt specimen in water at 25°C, g

SAMPLE PREPARATION METHODOLOGY

As was stated in Maupin and Diefenderfer, an additional 1.0% asphalt binder would need to be added to the asphalt mixture in order to see an appreciable difference in the performance. Knowing this, a testing matrix was created for all of the mixes that would be tested. This same testing matrix, shown in Table 8, was used for the dynamic modulus samples and fatigue beam samples.

Table 8. Testing Matrix Showing Number of Specimens for Each Asphalt Mixture

Mix	Asphalt Content	Specimens
20% RAP	Plant-Mix	3
	Plant-Mix + 0.5%	3
	Plant-Mix + 1.0%	3
40% RAP	Plant-Mix	3
	Plant-Mix + 0.5%	3
	Plant-Mix + 1.0%	3

For this project, a total of 36 samples were compacted with an AV content between 6.5% and 7.5%. A total of 18 asphalt cylinders and 18 rectangular beams were created for dynamic modulus testing and fatigue testing respectively.

DYNAMIC MODULUS TESTING

The first step in dynamic modulus testing was to ensure that the asphalt samples reached an equilibrium temperature prior to testing. Shown in Table 9, Dougan et al. provided recommended equilibrium times for asphalt samples to achieve a target temperature from room temperature.

Table 9. Recommended Equilibrium Times for Dynamic Modulus Samples *(14)*

Specimen Temperature, °C (°F)	Time, hrs, from room temperature at 25°C (77°F)
4.4 (40)	Overnight
21.1 (70)	1
37.8 (100)	2
54.4 (130)	2

**Note that the temperature equilibrium times may vary depending on the type of environmental chamber in use. Some testing laboratories reported as much as 6 hours to reach the equilibrium temperature.*

Three sets of linear variable differential transducers with a gauge length of 102mm (4 inches) were mounted on aluminum studs to measure displacements in the asphalt specimens. A steel jig was used to make sure the aluminum studs were equally spaced on the asphalt sample when epoxying. Four temperatures and six frequencies were chosen for the dynamic modulus testing. The dynamic modulus values that were used for this project are shown in Table 10.

Table 10. Dynamic Modulus Testing Specifics

Temperature, °C (°F)	Frequency, Hz	Pressure, kPa (psi)	Cycles
4.4 (40)	25	621 (90)	200
	10	621 (90)	200
	5	552 (80)	100
	1	552 (80)	20
	0.5	483 (70)	15
	0.1	483 (70)	15
21.1 (70)	25	483 (70)	200
	10	483 (70)	200
	5	379 (55)	100
	1	379 (55)	20
	0.5	276 (40)	15
	0.1	276 (40)	15
37.8 (100)	25	276 (40)	200
	10	276 (40)	200
	5	172 (25)	100
	1	172 (25)	20
	0.5	103 (15)	15
	0.1	103 (15)	15
54.4 (130)	25	103 (15)	200
	10	103 (15)	200
	5	69 (10)	100
	1	69 (10)	20
	0.5	34 (5)	15
	0.1	34 (5)	15

FATIGUE BEAM TESTING

For this project, fatigue testing was performed under a controlled-strain condition with the failure criteria defined as a 50% reduction in the specimen's initial stiffness. The initial stiffness of the beam was considered at the 50^{th} cycle to allow for preconditioning of the beam. The testing was conducted at a strain level of 400με for each specimen at a frequency level of 10Hz and an ambient air temperature of 20^oC (68^oF). The target AV content of 7.0 ± 0.5 AV was achieved for all samples tested.

CHAPTER IV - RESULTS AND ANALYSIS

OVERVIEW

This section presents the results of each of the tests that were performed in the lab at VTTI. The following results are presented in this chapter: G_{mm}, AC, G_{mb}, dynamic modulus, and fatigue life. Summary, conclusions, and recommendations are provided in Chapter V.

THEORETICAL MAXIMUM SPECIFIC GRAVITY RESULTS

Three replicate samples with a mass exceeding 1000g were prepared to determine the G_{mm} for the 20% RAP and the 40% RAP. The G_{mm} results for these mixtures with no additional binder are presented in Table 11 and Table 12.

Table 11. Gmm Results for 20% RAP Mix

Sample	Mass of Oven Dried Sample in Air, g	Mass of Sample and Bowl in Water at 25°C, g	Mass of Bowl in Water at 25°C, g	Mass of Sample in Water, g	G_{mm}
1	1067.6	2115.6	1455.0	660.6	2.623
2	1123.9	2147.0	1455.0	692.0	2.602
3	1097.4	2132.8	1455.0	677.8	2.615
				Average	**2.614**

Table 12. Gmm Results for 40% RAP Mix

Sample	Mass of Oven Dried Sample in Air, g	Mass of Sample and Bowl in Water at 25°C, g	Mass of Bowl in Water at 25°C, g	Mass of Sample in Water, g	G_{mm}
1	1106.0	2133.7	1454.5	679.2	2.591
2	1104.3	2135.7	1454.5	681.2	2.610
3	1153.5	2165.6	1454.5	711.1	2.607
				Average	**2.603**

The results found in Table 11 and Table 12 are similar to those provided by the asphalt producer. The G_{mm} results for the 20% RAP and 40% RAP from the asphalt producer were 2.624 and 2.602 respectively. The next step for this project was to determine the G_{mm} of the mixtures with additional binder content. In an effort to preserve asphalt material, the G_{mm} was estimated for these mixtures. This method is presented later in the paper.

ASPHALT CONTENT RESULTS

When material was heated up and separated for the determination of the G_{mm} of the mixture, additional material was saved to determine the AC of the mixtures. Two replicate samples with a mass exceeding 1500g were prepared to determine the AC of the 20% RAP and 40% RAP. The AC results for these mixtures are presented in Table 13 and Table 14.

Table 13. AC Results from Ignition Oven for 20% RAP

Sample	Original Sample Weight, g	Sample Weight After Burn, g	Weight Loss, %
1	1573.9	1486.3	5.566
2	1570.8	1484.2	5.513
		Average	**5.539**

Table 14. AC Results from Ignition Oven for 40% RAP

Sample	Original Sample Weight, g	Sample Weight After Burn, g	Weight Loss, %
1	1571.2	1476.9	6.002
2	1568.8	1474.9	5.985
		Average	**5.994**

The results in Table 13 and Table 14 are slightly higher than those provided by the asphalt producer. The AC results for the 20% RAP and 40% RAP from the asphalt producer were 5.18% and 5.42% respectively. This slight difference in AC content may be due to the producer's using an ignition oven correction factor with their samples. With the AC for the 20% RAP and 40% RAP known, the G_{mm} of the asphalt mixtures with additional binder could be estimated.

THEORETICAL MAXIMUM SPECIFIC GRAVITY ESTIMATION

The first step in this process was to first look at the data that was supplied by the asphalt producer. The following table is a summary of the asphalt mixture specifics that was supplied by the asphalt producer for both the 20% and 40% RAP mixes.

Table 15. Asphalt Mixture Specifics Supplied from Asphalt Producer

Producer's Data – 20% RAP		Producer's Data – 40% RAP	
Ps	94.82	**Ps**	94.71
Gse	2.860	**Gse**	2.842
Pb	5.18	**Pb**	5.42
Gb	1.046	**Gb**	1.037
Gmm	2.624	**Gmm**	2.602

Where,

P_s = Aggregate percentage by mass
G_{se} = Effective specific gravity of aggregate
P_b = Asphalt content, percent by mass of aggregate
G_b = Specific gravity of asphalt binder
G_{mm} = Theoretical maximum specific gravity of mixture

The next steps in order to estimate the G_{mm} for additional binder contents was to perform the G_{mm} testing and ignition oven on the mixes to see how closely their results matched the asphalt producer's values. As was shown in a previous section, the G_{mm} for the 20% RAP and 40% RAP was 2.614 and 2.603

respectively. These values are very similar to the laboratory values calculated at the plant. The AC for both of these materials was also calculated using the ignition oven, which was shown earlier. The AC was 5.539% and 5.994% for the 20% RAP and 40% RAP respectively. Using the specific gravity of the binder supplied from the asphalt producer and the values just stated, the G_{mm} for the mixtures with additional binder could be determined.

The G_{se} of the aggregate could be estimated using Equation 7.

$$G_{se} = \frac{P_s}{\left(\frac{100}{G_{mm}}\right)-\left(\frac{P_b}{G_b}\right)} \quad (7)$$

The values used in Equation 7 are shown below in Table 16. When calculating the G_{se}, the G_{mm} and AC that were determined in the lab were used. It was found that the G_{se} for the 20% RAP and 40% RAP were 2.866 and 2.880 respectively.

Table 16. Estimation of Gse for 20% RAP and 40% RAP Mixtures

Our Data - 20% RAP		**Our Data - 40% RAP**	
Ps	94.46	**Ps**	94.01
Pb (lab)	5.54	**Pb (lab)**	5.99
Gb	1.046	**Gb**	1.037
Gmm (lab)	2.614	**Gmm (lab)**	2.603
Gse (est)	2.866	**Gse (est)**	2.880

With the G_{se} estimated, the G_{mm} for the mixtures containing additional binder content could be calculated. In order to accomplish this, an initial mixture weight was assumed. Using the percentages found in Table 16, the weight of binder and aggregate could be determined. In order to determine how much extra binder must be added, the total mixture weight is multiplied by the percent binder increase (either 0.5% or 1.0%). With additional asphalt binder added, new percentages of binder and aggregate are calculated. With all of these new values, the G_{mm} can be estimated. Table 17 shows the 20% RAP scenario with additional binder contents.

Table 17. Gmm Estimation for 20% RAP with Additional Binder Contents

20% RAP + 0.5% Binder		**20% RAP + 1.0% Binder**	
Mixture (g)	10000	**Mixture (g)**	10000
Pb Old (Lab)	5.54	**Pb Old (Lab)**	5.54
Mass Binder (g)	553.9	**Mass Binder (g)**	553.9
Mass Agg (g)	9446.1	**Mass Agg (g)**	9446.1
Added Binder (g)	50	**Added Binder (g)**	100
Total Binder (g)	603.9	**Total Binder (g)**	653.9
Total Mixture (g)	10050	**Total Mixture (g)**	10100
Pb New	6.01	**Pb New**	6.47
Ps New	93.99	**Ps New**	93.53
Gb	1.046	**Gb**	1.046
Gse	2.866	**Gse**	2.866
Gmm	2.595	**Gmm**	2.576

The same process was carried out for the 40% RAP mixture and is shown in Table 18.

Table 18. Gmm Estimation for 40% RAP with Additional Binder Contents

40% RAP + 0.5% Binder		40% RAP + 1.0% Binder	
Mixture (g)	10000	**Mixture (g)**	10000
Pb Old (Lab)	5.99	**Pb Old (Lab)**	5.99
Mass Binder (g)	599.4	**Mass Binder (g)**	599.4
Mass Agg (g)	9400.6	**Mass Agg (g)**	9400.6
Added Binder (g)	50	**Added Binder (g)**	100
Total Binder (g)	649.4	**Total Binder (g)**	699.4
Total Mixture (g)	10050	**Total Mixture (g)**	10100
Pb New	6.46	**Pb New**	6.92
Ps New	93.54	**Ps New**	93.08
Gb	1.037	**Gb**	1.037
Gse	2.880	**Gse**	2.880
Gmm	2.584	**Gmm**	2.565

Table 19 is a summary of all the G_{mm} values used for this project.

Table 19. Summary of Gmm Values for 20% RAP and 40% RAP with Additional Asphalt Binder

	+ 0.0%	+ 0.5%	+ 1.0%
20% RAP	2.614	2.595	2.576
40% RAP	2.603	2.584	2.565

BULK SPECIFIC GRAVITY/AIR VOIDS RESULTS

Dynamic Modulus Samples

As was previously mentioned, dynamic modulus samples were compacted using the SGC. These samples were then cut and cored to a length of 152mm (6 inches) and a diameter of 102mm (4 inches). A target AV level of 7.0% ± 0.5% was achieved for all of the samples tested. The first set of samples tested were the ones with no additional binder added. The results for the G_{mb} and AV are shown below in Table 20.

Table 20. G_{mb} and AV Results for Dynamic Modulus Samples with 0.0% Asphalt Binder

	Sample	Gmm	Gmb	AV (%)
20% RAP	A2-A	2.614	2.428	7.097
	A3-A	2.614	2.431	6.988
	A4-A	2.614	2.434	6.888
40% RAP	B1-A	2.603	2.421	6.984
	B2-A	2.603	2.428	6.712
	B3-A	2.603	2.423	6.910

The gyrations versus height data that was obtained from the SGC for all of these samples is shown in Figure 14 and Figure 15. For both the 20% RAP and 40% RAP with no additional AC, the gyration versus height data shows little to no variation between the three replicate samples. Individual gyration versus height curves for all of the samples can be found in Appendix A.

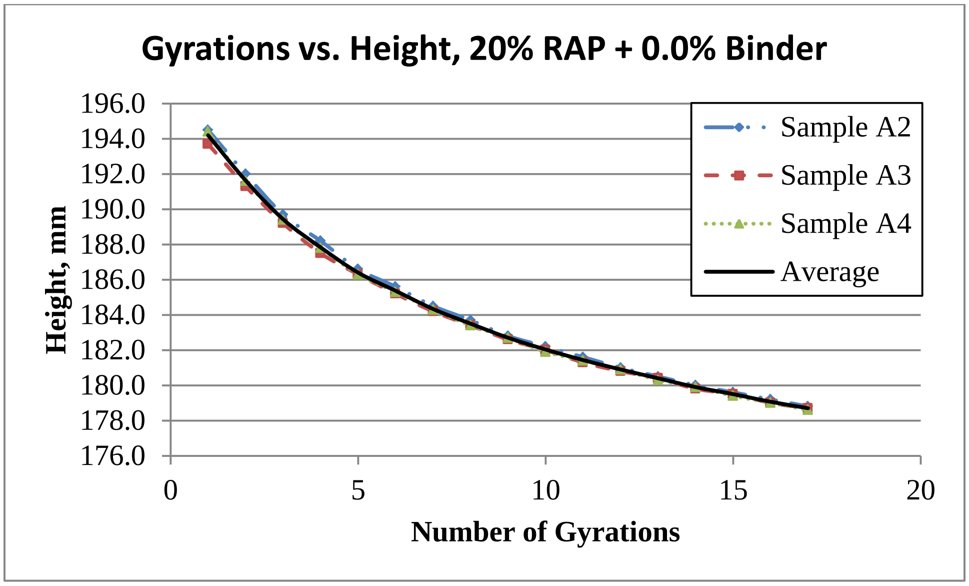

Figure 14. Gyration vs. Height Data for 20% RAP + 0.0% Binder

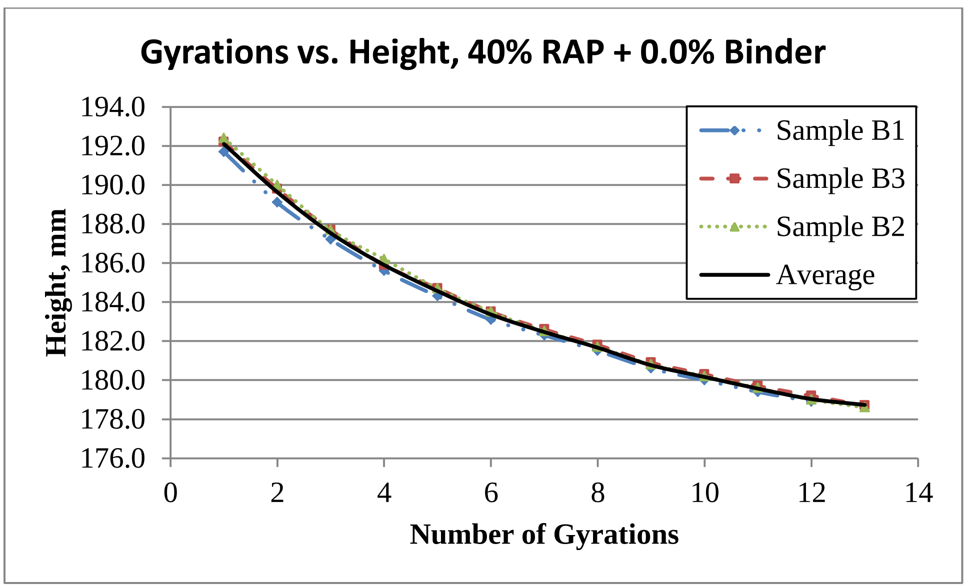

Figure 15. Gyration vs. Height Data for 40% RAP + 0.0% Binder

The next set of samples tested were the ones with an additional 0.5% additional binder added. The results for the G_{mb} and AV are shown below in Table 21.

Table 21. G_{mb} and AV Results for Dynamic Modulus Samples with 0.5% Asphalt Binder

	Sample	Gmm	Gmb	AV (%)
20% RAP	C1-A	2.595	2.411	7.108
	C2-A	2.595	2.411	7.085
	C3-A	2.595	2.407	7.240
40% RAP	D1-A	2.584	2.405	6.940
	D3-A	2.584	2.398	7.212
	D4-A	2.584	2.396	7.281

The gyrations versus height data for these samples are shown in Figure 16 and Figure 17. It can be seen from these figures that there is slightly more variation between the gyrations versus height curves when compared to the samples with no additional AC. It should be noted that the AV results are slightly more varied as well when compared to the samples with no additional binder.

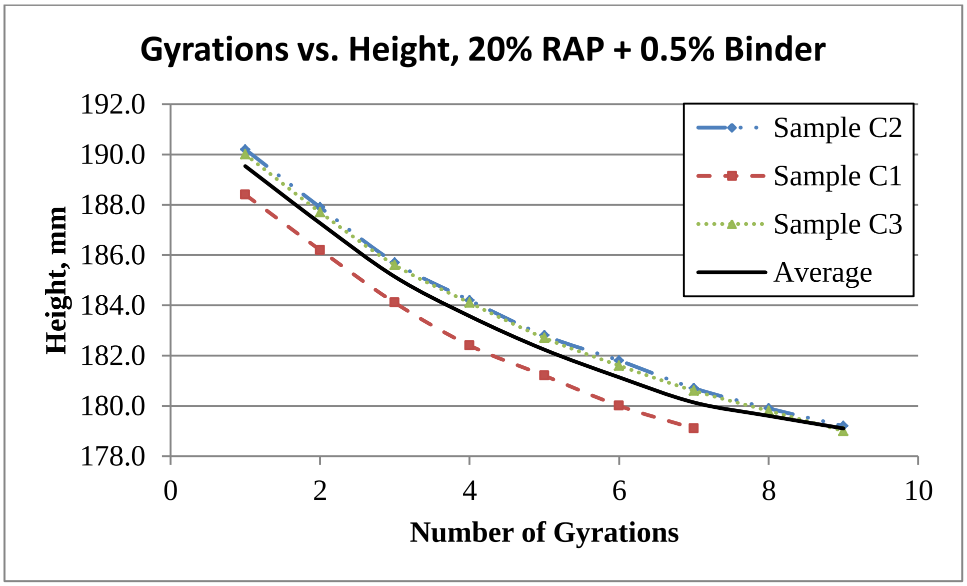

Figure 16. Gyration vs. Height Data for 20% RAP + 0.5% Binder

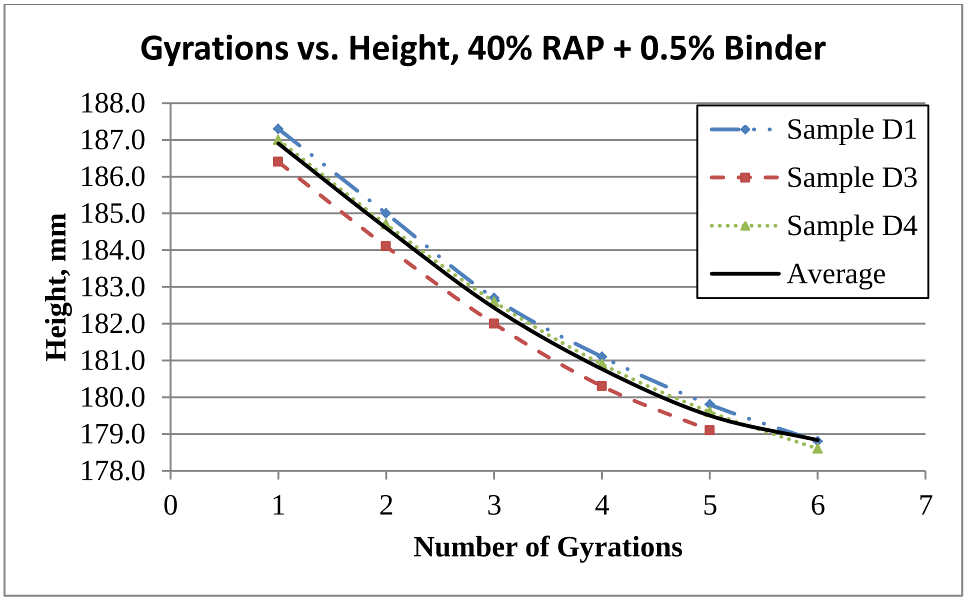

Figure 17. Gyration vs. Height Data for 40% RAP + 0.5% Binder

The final set of samples tested were the ones with an additional 1.0% additional binder added. The results for the G_{mb} and AV are shown below in Table 22.

Table 22. G_{mb} and AV Results for Dynamic Modulus Samples with 1.0% Asphalt Binder

	Sample	Gmm	Gmb	AV (%)
20% RAP	E1-A	2.576	2.428	7.122
	E2-A	2.576	2.431	7.312
	E3-A	2.576	2.434	6.834
40% RAP	F5-A	2.565	2.421	7.181
	F10-A	2.565	2.428	7.059
	F11-A	2.565	2.423	7.116

The gyrations versus height data for these samples are shown in Figure 18 and Figure 19. It can be seen again from these figures that there is slightly more variation between the gyrations versus height curves when compared to the samples with no additional AC. It should be noted that the AV results are slightly more varied as well when compared to the samples with no additional binder. The results are similar to the 0.5% additional AC samples, except for a decrease in the number of gyrations.

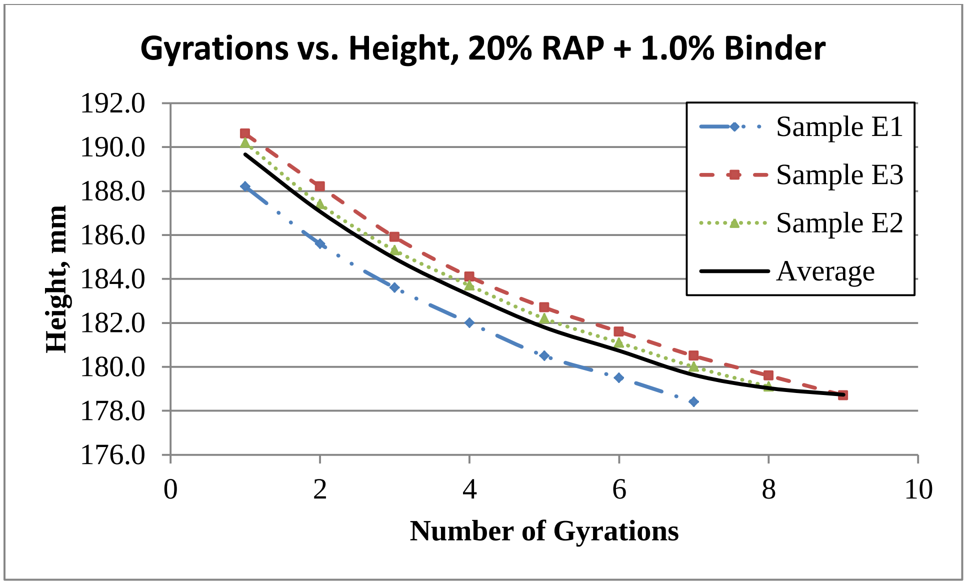

Figure 18. Gyration vs. Height Data for 20% RAP + 1.0% Binder

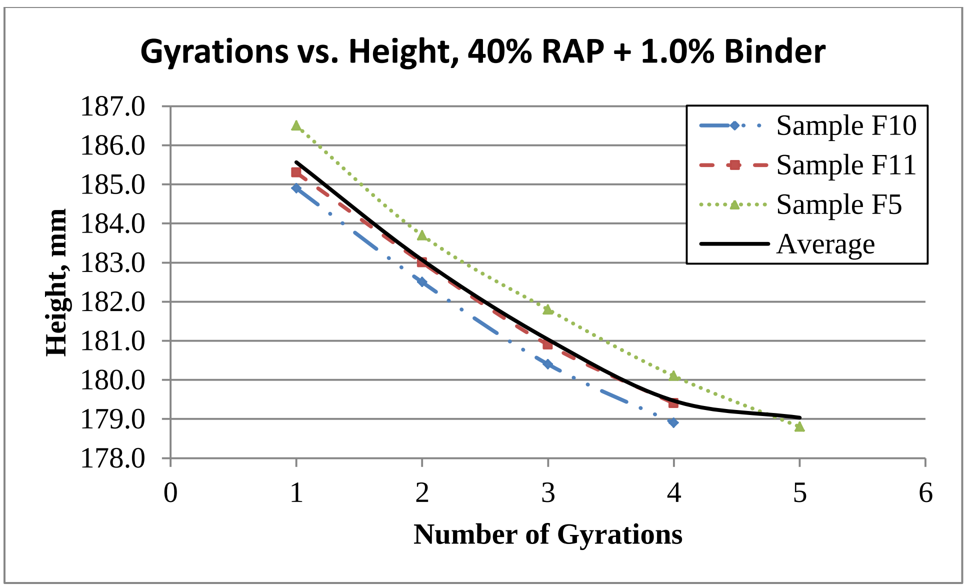

Figure 19. Gyration vs. Height Data for 40% RAP + 1.0% Binder

The average gyrations versus height were also plotted and are shown below in Figure 20. It can be seen in this figure that the 40% RAP had a lower initial height and required less gyrations to obtain the 178mm height (7 inches) than the 20% RAP counterpart (i.e. the 40% RAP + 0.0% binder had a lower initial height and required less gyrations than the 20% RAP + 0.0% binder). This may be a result of the 40% RAP using a softer binder (PG 64-22) than the 20% RAP (PG70-22). It is also interesting to note how similar the 20% RAP + 0.5% binder (green) and the 20% RAP + 1.0% binder (orange) averages are to each other.

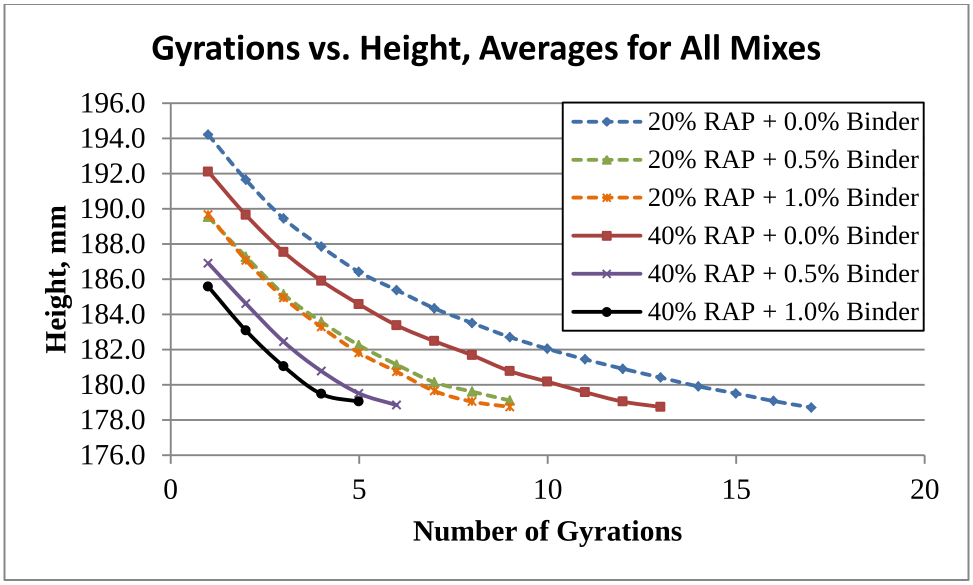

Figure 20. Average Gyration vs. Height Data for All Mixes

An interesting trend was noticed between the original dynamic modulus samples and the cut and cored samples. Table 23 shows the decrease in AV percentage between the original dynamic modulus samples and the cut and cored samples for each binder content.

Table 23. Decrease in AV for Original Samples and Cut and Cored Samples

0.0% AC	0.5% AC	1.0% AC
1.4%	1.0%	0.8%

From Table 23, it can be seen that there is a smaller decrease in AV between the original samples and the cut and cored samples as the amount of binder increases. This is likely a result of the additional binder permeating the entire sample more uniformly and creating a more homogenous sample.

Fatigue Beam Samples

As was previously mentioned, fatigue beam samples were compacted using the AVC. Volumetrics for all of the samples compacted for this project can be seen in Appendix B. A target AV level of 7.0% ± 0.5% was achieved for all of the samples tested. The first set of samples tested were the ones with no additional binder added. The results for the G_{mb} and AV are shown below in Table 24.

Table 24. G_{mb} and AV Results for Fatigue Beam Samples with 0.0% Asphalt Binder

	Sample	Gmm	Gmb	AV (%)
20% RAP	A5	2.614	2.430	7.013
	A11	2.614	2.434	6.852
	A14	2.614	2.429	7.080
40% RAP	B4	2.603	2.424	6.870
	B10	2.603	2.423	6.923
	B12	2.603	2.432	6.568

It should be noted that achieving the target AV content for fatigue beam samples was much more difficult than achieving the AV content for the dynamic modulus samples. When the same weight was used for the dynamic modulus samples, there was only a slight discrepancy in the AV percent (typically under 0.5% difference). When the same weight was used for the fatigue beams, however, there was a much higher discrepancy in the AV percent (greater than 1.5% difference). The next set of samples tested were the ones with an additional 0.5% additional binder added. The results for the G_{mb} and AV are shown below in Table 25.

Table 25. G_{mb} and AV Results for Fatigue Beam Samples with 0.5% Asphalt Binder

	Sample	Gmm	Gmb	AV (%)
20% RAP	C3	2.595	2.404	7.377
	C5	2.595	2.415	6.934
	C7	2.595	2.425	6.555
40% RAP	D7	2.584	2.416	6.517
	D11	2.584	2.404	6.965
	D13	2.584	2.403	7.002

The higher variability that was mentioned above can be seen more clearly here. In the 20% RAP samples, the AV percent ranges from 6.5% to 7.4%, despite the fact that all three samples had roughly the same weight. The final set of samples tested were the ones with an additional 1.0% additional binder added. The results for the G_{mb} and AV are shown below in Table 26.

Table 26. G_{mb} and AV Results for Fatigue Beam Samples with 1.0% Asphalt Binder

	Sample	Gmm	Gmb	AV (%)
20% RAP	E2	2.576	2.408	6.509
	E11	2.576	2.407	6.542
	E13	2.576	2.408	6.521
40% RAP	F6	2.565	2.398	6.500
	F8	2.565	2.386	6.981
	F9	2.565	2.398	6.520

All of the samples displayed in Table 24, Table 25, and Table 26 were within the target AV level and thus, used for determining the fatigue resistance. Results on the performance of these fatigue beams can be seen in a later section.

DYNAMIC MODULUS RESULTS

Dynamic modulus testing was conducted on 18 samples at four temperatures (4.4^{o}C, 21.1^{o}C, 37.8^{o}C, and 54.4^{o}C) and six frequencies (25Hz, 10Hz, 5Hz, 1Hz, 0.5Hz, and 0.1Hz). Individual dynamic modulus master curves for each group of samples, raw data to construct the master curves, and dynamic modulus coefficient of variation for each group of samples are presented in Appendix C. The dynamic modulus master curves for the 20% RAP samples are presented in Figure 21. An Excel Solver was used to minimize the difference between the dynamic modulus values for the construction of the curves. An average sigmoidal master curve of the three samples for each binder content was calculated and plotted in this figure.

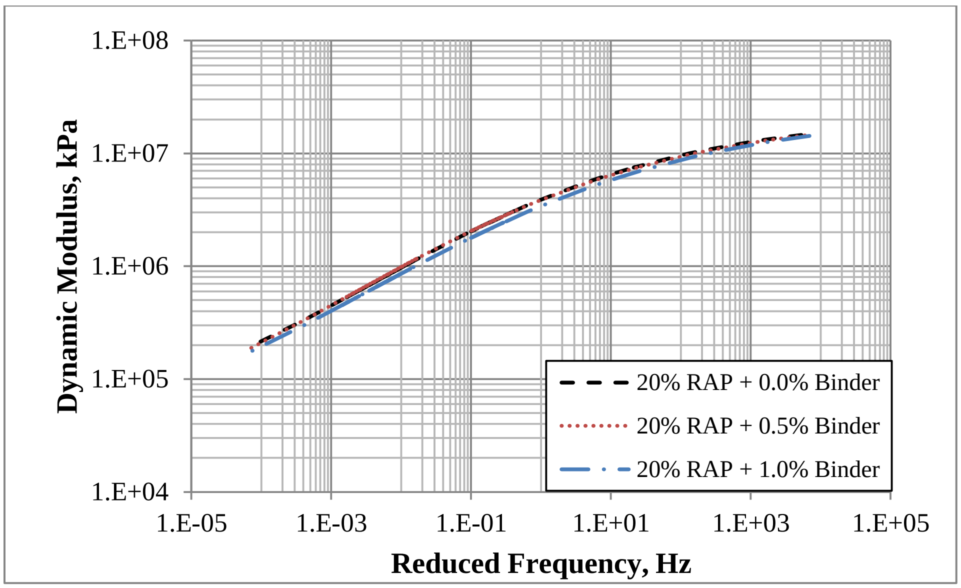

Figure 21. Dynamic Modulus Master Curves for 20% RAP Samples

As can be seen in Figure 21, there is very little change between the three different binder contents for 20% RAP. The 20% RAP + 0.0% binder and 20% RAP + 0.5% binder samples are extremely similar (on average, less than 1% difference), with the 20% RAP + 1.0% binder samples only being slightly lower dynamic modulus values than the other two (on average, 7% and 6% lower). The coefficient of variation at each temperature and frequency between the binder contents was calculated and is presented in Table 27.

Table 27. Dynamic Modulus Coefficient of Variation Between Binder Contents for 20% RAP

	4.4°C	**21.1°C**	**37.8°C**	**54.4°C**
25 Hz	0.16%	6.37%	9.24%	8.66%
10 Hz	1.80%	6.34%	9.40%	8.86%
5 Hz	2.10%	6.52%	9.84%	8.51%
1 Hz	2.65%	6.96%	9.86%	6.82%
0.5 Hz	2.86%	7.19%	9.97%	6.13%
0.1 Hz	3.34%	7.75%	9.70%	5.57%

The next master curves that were generated were for the 40% RAP samples. Similar to Figure 21, an average sigmoidal master curve for the three samples at each binder content were calculated.

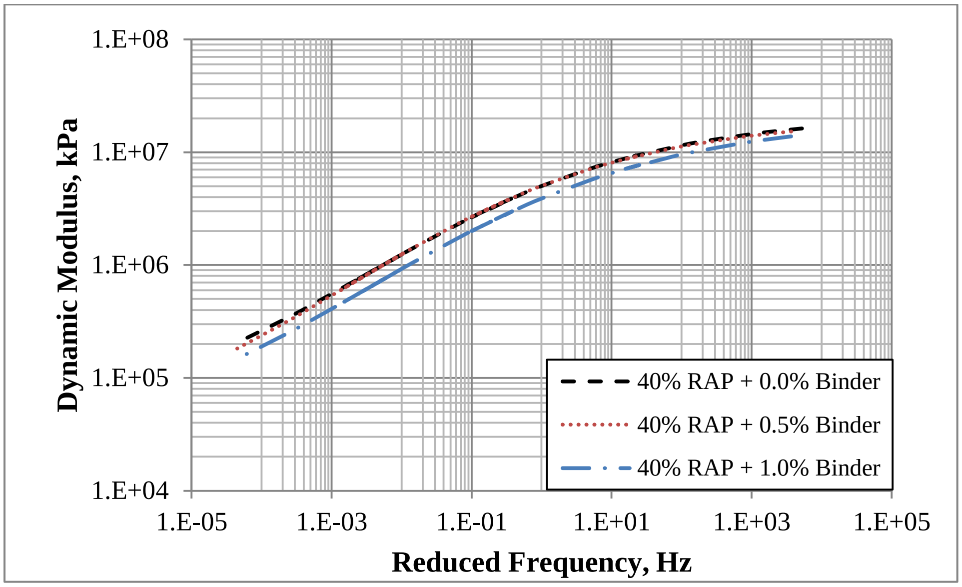

Figure 22. Dynamic Modulus Master Curves for 40% RAP Samples

Figure 22 shows more variation in the master curves than Figure 21. Similar to the 20% RAP samples, there appears to be little variation in the samples containing an additional 0.0% asphalt binder and 0.5% asphalt binder (on average, the 0.5% AC sample has 4% lower dynamic modulus values). When an additional 1.0% asphalt binder was used, however, there is a moderate drop in the stiffness when compared to the 0.0% and 0.5% AC samples (on average, 20% and 16% lower). The coefficient of variation at each temperature and frequency between the binder contents was calculated and is presented in Table 28.

Table 28. Dynamic Modulus Coefficient of Variation Between Binder Contents for 40% RAP

	4.4°C	21.1°C	37.8°C	54.4°C
25 Hz	9.27%	9.68%	14.78%	16.56%
10 Hz	9.64%	11.21%	16.29%	16.81%
5 Hz	10.17%	11.91%	17.59%	16.88%
1 Hz	11.25%	14.05%	16.81%	19.56%
0.5 Hz	11.92%	14.87%	12.91%	21.53%
0.1 Hz	13.22%	17.45%	12.76%	18.70%

To examine if an increase in the percent of RAP affected the dynamic modulus of the mixture, all of the master curves are presented below in Figure 23.

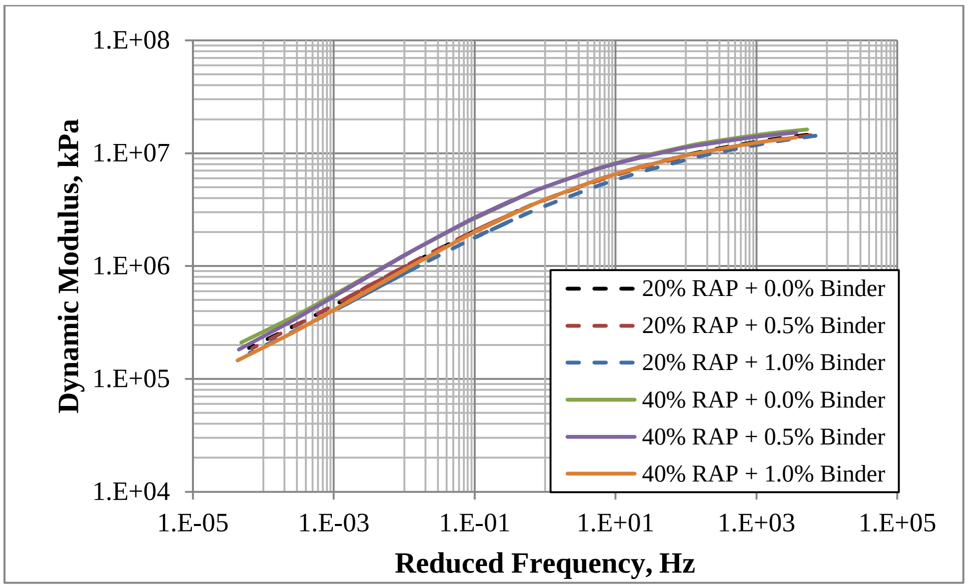

Figure 23. Dynamic Modulus Master Curves for 20% RAP and 40% RAP Samples

As is shown in Figure 23, the 40% RAP samples with 0.0% and 0.5% additional binder are stiffer than all of the 20% RAP samples. When an additional 1.0% binder was added to the 40% RAP mixtures, the dynamic modulus decreased such that it was approximately the same stiffness as the 20% RAP samples. In order to see if the percent of RAP or the additional binder added to the samples are statistically significant, ANOVA was conducted on the dynamic modulus values and is presented in a later section.

FATIGUE CRACKING RESULTS

Fatigue testing was conducted on 18 samples at ambient air temperature (20°C) at a frequency of 10 Hz and a controlled-strain of 400με. The initial stiffness of the beam was considered at the 50th cycle to allow for preconditioning of the beam and failure was considered 50% of the initial stiffness. The number of cycles for failure was interpolated between the point before failure and the point after failure. Individual fatigue resistance curves for each group of samples are presented in Appendix D. It should be noted that both the 20% RAP and 40% RAP samples with 0.0% additional binder needed to be sawed (~4 mm) to fit into the fatigue apparatus. The amount of weight that was used to reach 7% AV was too much to compact the full 51mm (2 inches) down, so the material rebounded after compaction. The fatigue resistance curves for the 20% RAP samples are presented in Figure 24. The average curve of the three samples at each binder content was calculated and plotted in this figure.

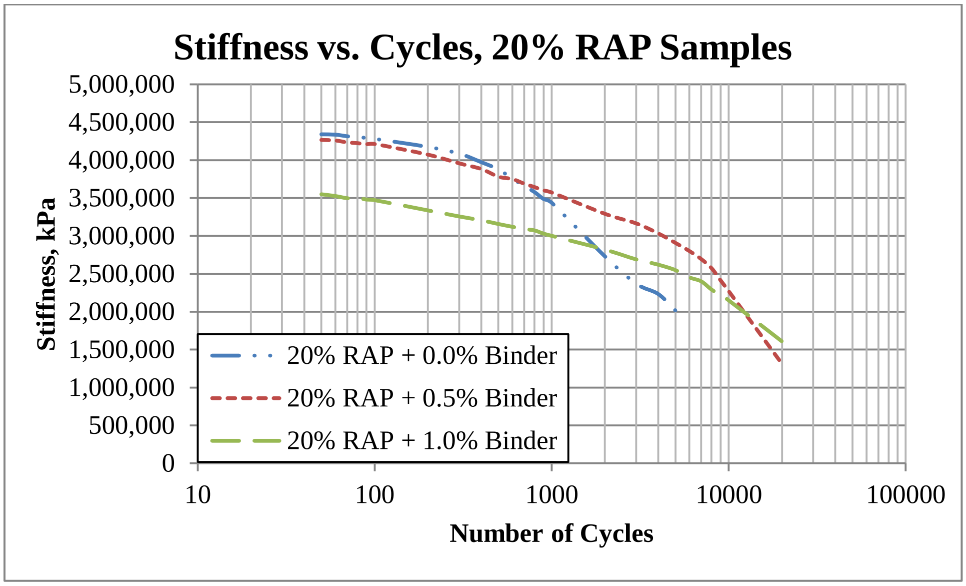

Figure 24. Fatigue Resistance Curves for 20% RAP Samples

From Figure 24, it appears that the additional binder did result in an increased fatigue life for the 20% RAP samples. The 0.0% binder and 0.5% binder samples had approximately the same initial stiffness, however, the 0.0% binder samples failed much quicker. The 1.0% binder samples had a considerable decrease in the initial stiffness, however, these samples outperformed all of the samples in terms of fatigue life. The stiffness values found in the fatigue beams were similar to the dynamic modulus samples, with the 0.5% AC samples having similar values to the 0.0% AC samples, and a significant drop in the 1.0% AC samples. The next fatigue resistance curves that were generated were for the 40% RAP samples. Similar to Figure 24, average fatigue resistance curves for the three samples at each binder content were calculated.

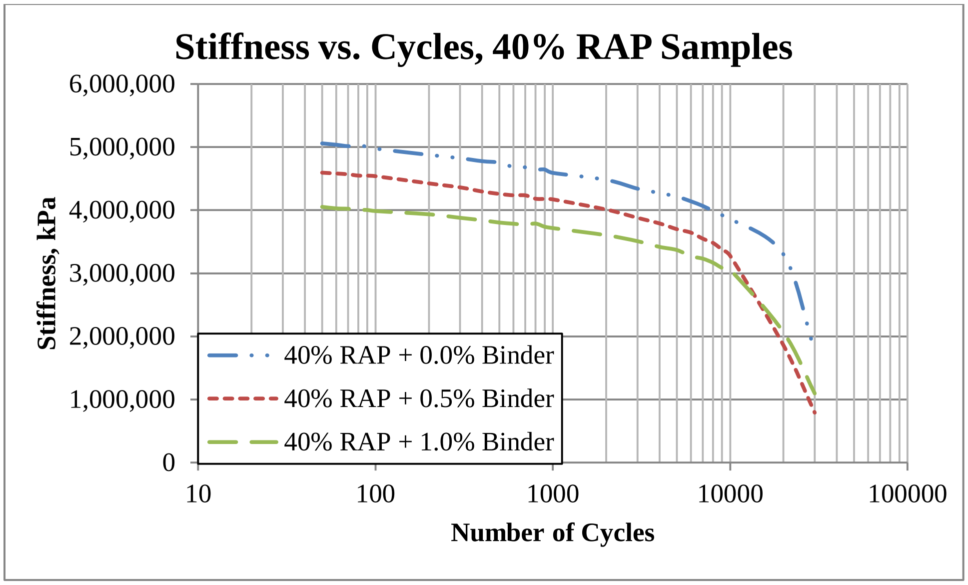

Figure 25. Fatigue Resistance Curves for 40% RAP Samples

As seen in Figure 25, it appears that the additional binder did not have an effect on the 40% RAP samples. The 0.0% and 1.0% binder samples have approximately the same fatigue life, with the 0.5% binder exhibiting a lower fatigue life. It appears that there is a steady drop in the initial stiffness values as the amount of binder increases in the sample. The stiffness trends observed in the 40% RAP samples for fatigue life are slightly different than those observed in the 40% RAP dynamic modulus samples. In the dynamic modulus samples, both the 0.0% and 0.5% binder samples had similar stiffness values with the 1.0% binder sample exhibiting a drop. To examine if an increase in the percent of RAP affected the fatigue life of the mixture, all of the fatigue curves are presented below in Figure 26. A summary of the fatigue life values can also be seen in Table 29.

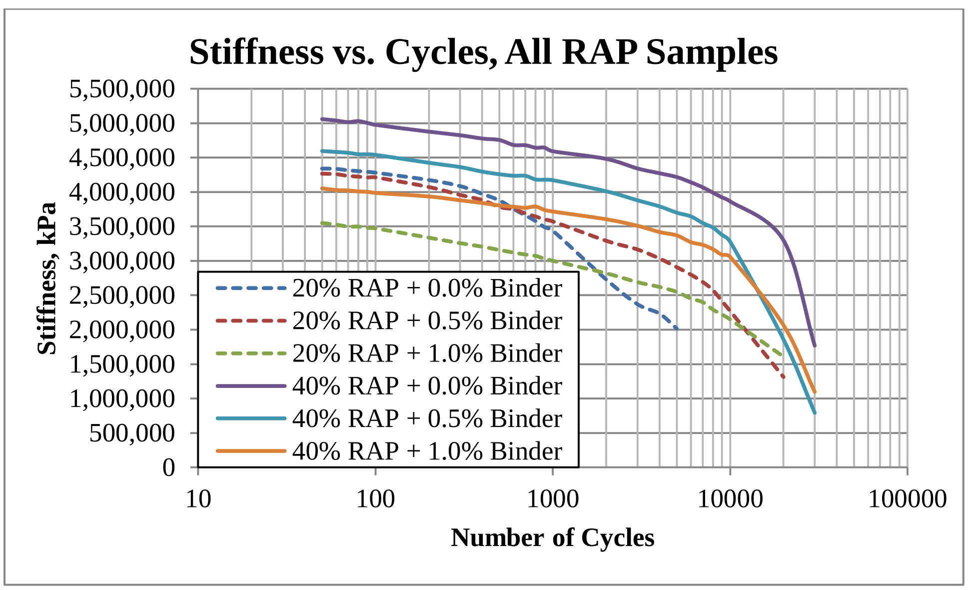

Figure 26. Fatigue Resistance Curves for 20% RAP and 40% RAP Samples

Table 29. Summary of Stiffness and Cycles to Failure for 20% RAP and 40% RAP Samples

Sample	% RAP	% Binder	Stiffness	Average	Cycles to Failure	Average	Coefficient of Variation
	%	%	*kPa*	*kPa*	#	#	%
A5	20	0.0	4694554		5532		
A11	20	0.0	4377783	4340333	6127	4395	
A14	20	0.0	3948662		1526		
C3	20	0.5	4330386		16271		
C5	20	0.5	4295519	4333279	14696	13102	56.6
C7	20	0.5	4373932		8338		
E2	20	1.0	3612231		18451		
E11	20	1.0	3342464	3598348	14104	17232	
E13	20	1.0	3840349		19141		
B4	40	0.0	5409662		25245		
B10	40	0.0	4707912	4888022	19434	22340	
B12	40	0.0	4546491		936*		
D7	40	0.5	4745985		48978*		
D11	40	0.5	4653756	4646637	23457	18399	10.8
D13	40	0.5	4540170		13342		
F6	40	1.0	4179191		31470		
F8	40	1.0	4070142	4102126	17279	22320	
F9	40	1.0	4057044		18211		

**These points were found to be outliers (shown in ANOVA section later). These points were not used to calculate the average number of cycles to failure seen in Table 29.*

From Figure 26 and Table 29, it can be seen that the 40% RAP samples had a higher initial stiffness and a longer fatigue life than the 20% RAP samples. The longer fatigue life in the 40% RAP samples may potentially be a result of the softer binder used during mixing and compaction when compared to the 20% RAP samples. It appears that the 20% RAP samples, in general, have a smoother transition to failure, whereas the 40% RAP samples have a sharp, rapid decrease in stiffness at the end of its fatigue life. Several VDOT studies showed a large variation in the number of cycles to failure during fatigue testing. Comparing similar materials (aggregate size and binders) with similar percentages of RAP (15% RAP to 25% RAP) at 400$\mu\varepsilon$, the number of cycles to failure were approximately 20000 cycles *(20)*, 100000 cycles *(13)*, 500000 cycles *(31)*, and 800000 cycles *(31)*. The effect of binder content on fatigue life was also investigated and is presented in Figure 27.

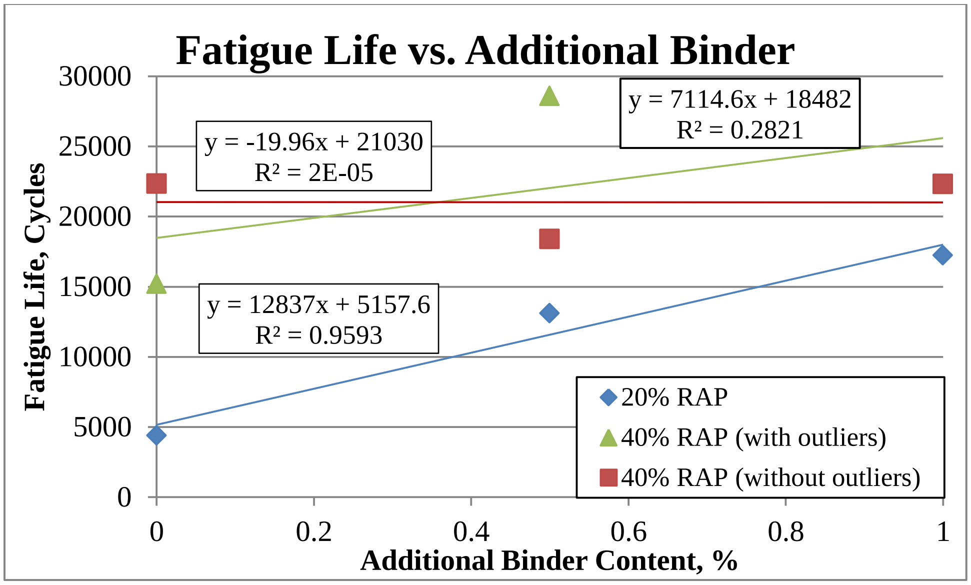

Figure 27. Fatigue Life Versus Additional Binder Content for RAP Samples

From Figure 27, it can be seen that the additional binder had a pronounced effect on the 20% RAP samples, but little to no effect on the 40% RAP samples. The fatigue life for the 20% RAP samples continued to increase as the amount of binder was added whereas the 40% RAP samples fluctuated around 20000 cycles. It appears that the 20% RAP samples may be plateauing since the rate of fatigue life improvement from 0.5% binder to 1.0% binder (4130 cycles) is much less than the improvement from 0.0% binder to 0.5% binder (8707 cycles). An additional AC greater than 1.0% would need to be added to the 20% RAP sample to see if the fatigue life is plateauing or not. In order to see if the percent of RAP or the additional binder added to the samples are statistically significant, ANOVA was conducted on the fatigue resistance data and is presented in the next section.

ANALYSIS OF VARIANCE (ANOVA) RESULTS

ANOVA was conducted on volumetric, dynamic modulus, and fatigue resistance data to determine if the percent RAP or the additional binder content was statistically significant towards the performance criteria. Two models (dynamic modulus and fatigue resistance) were generated in Statistical Analysis System (SAS) to determine which regressors, if any, had an effect on the performance of asphalt concrete. The independent variables that were used in these models were dynamic modulus and cycles to failure. The regressors that were tested against these variables were the percent RAP, percent binder, AV content, temperature, and frequency. Since temperature and frequency were constant for fatigue testing, they were not included in the fatigue model. The code that was inputted into SAS for all of the models generated can be found in Appendix E.

Dynamic Modulus ANOVA

The first model that was created used the following regressors: percent RAP, percent binder, AV content, temperature, and frequency. The ANOVA for this model is shown below in Table 30.

Table 30. ANOVA for Dynamic Modulus Model 1

Number of Observations Read	432
Number of Observations Used	432

Analysis of Variance					
Source	**DF**	**Sum of Squares**	**Mean Square**	**F Value**	**Pr > F**
Model	5	8.090082E15	1.618016E15	469.23	<.0001
Error	426	1.468957E15	3.448255E12		
Corrected Total	431	9.559038E15			

Root MSE	1856948	**R-Square**	0.8463
Dependent Mean	4805341	**Adj R-Sq**	0.8445
Coeff Var	38.64341		

Parameter Estimates							
Variable	**DF**	**Parameter Estimate**	**Standard Error**	**t Value**	**Pr > |t|**	**95% Confidence Limits**	
Intercept	**1**	11506901	4522438	2.54	0.0113	2617831	20395971
RAP	**1**	28543	8989.57503	3.18	0.0016	10873	46212
Binder	**1**	-684034	245793	-2.78	0.0056	-1167152	-200916
AV	**1**	-238164	642491	-0.37	0.7111	-1501012	1024683
Temp	**1**	-221343	4793.65465	-46.17	<.0001	-230765	-211921
Freq	**1**	141128	10172	13.87	<.0001	121134	161122

Table 30 shows that the dynamic modulus model utilizing all of the regressors produced a model with an adjusted R^2 value of 0.8445 and R^2 value of 0.8463. R^2 and adjusted R^2 are statistical values that are used to show how well data fits to the model. The R^2 shows the total variation in the dependent variable explained by the independent variables. Adjusted R^2 is a modification of R^2 in that it shows the percentage of variation in a model explained by only using the independent variables that truly affect the dependent variables. In the parameter estimates, all of the variables except for AV content appear to be significant with 95% confidence (additional binder at 94% confidence). Since the AV content did not appear to contribute to the model, an adjusted R^2 selection method was used in SAS to determine which variables should be used in the model to generate the highest R^2 and adjusted R^2. This selection process showed that removing AV content and only using percent RAP, percent binder, temperature, and frequency would create the best model. The results of this model in ANOVA are shown in Table 31.

Table 31. ANOVA for Dynamic Modulus Model 2 (AV Excluded)

Number of Observations Read	432
Number of Observations Used	432

Analysis of Variance					
Source	**DF**	**Sum of Squares**	**Mean Square**	**F Value**	**Pr > F**
Model	4	8.089608E15	2.022402E15	587.69	<.0001
Error	427	1.46943E15	3.441289E12		
Corrected Total	431	9.559038E15			

Root MSE	1855071	**R-Square**	0.8463
Dependent Mean	4805341	**Adj R-Sq**	0.8448
Coeff Var	38.60436		

Parameter Estimates							
Variable	**DF**	**Parameter Estimate**	**Standard Error**	**t Value**	**Pr > |t|**	**95% Confidence Limits**	
Intercept	**1**	9835271	341216	28.82	<.0001	9164599	10505944
RAP	**1**	28912	8925.21552	3.24	0.0013	11369	46455
Binder	**1**	-725514	218622	-3.32	0.0010	-1155224	-295805
Temp	**1**	-221343	4788.81034	-46.22	<.0001	-230756	-211931
Freq	**1**	141128	10162	13.89	<.0001	121154	161102

After removing the AV content from the model, the adjusted R^2 and R^2 values changed to 0.8448 and 0.8463 respectively. In addition, all of the variables that are included in the model seem to have a significant effect on the dynamic modulus of the samples at the 95% confidence interval. From the model, as the percent of RAP and frequency increases, the dynamic modulus will also increase. Conversely, as the percent of binder and temperature increases, the dynamic modulus will decrease. This matches the findings in the literature review that was presented in Chapter II.

Fatigue Cracking ANOVA

The first model that was created used the following regressors: percent RAP, percent binder, and AV content. The ANOVA for this model is shown below in Table 32.

Table 32. ANOVA for Fatigue Resistance Model 1

Number of Observations Read	18
Number of Observations Used	18

Analysis of Variance					
Source	**DF**	**Sum of Squares**	**Mean Square**	**F Value**	**Pr > F**
Model	3	804853724	268284575	2.68	0.0869
Error	14	1400156482	100011177		
Corrected Total	17	2205010206			

Root MSE	10001	**R-Square**	0.3650
Dependent Mean	16808	**Adj R-Sq**	0.2289
Coeff Var	59.49998		

Parameter Estimates							
Variable	**DF**	**Parameter Estimate**	**Standard Error**	**t Value**	**Pr > |t|**	**95% Confidence Limits**	
Intercept	**1**	23175	73607	0.31	0.7575	-134696	181047
RAP	**1**	511.65602	237.75519	2.15	0.0493	1.72186	1021.59018
Binder	**1**	8863.74067	6510.71616	1.36	0.1949	-5100.35669	22828
AV	**1**	-3850.86901	10417	-0.37	0.7172	-26193	18491

Table 32 shows that the fatigue resistance model using all of the regressors resulted in an adjusted R^2 value of 0.2289 and R^2 value of 0.3650. In the parameter estimates, only percent RAP appears to be significant with 95% confidence. Similar to the dynamic modulus model, an adjusted R^2 selection method was used in SAS to determine which variables should be used in the model to generate the highest R^2 and adjusted R^2. This selection process showed that removing AV content and only using percent RAP and percent binder would create the best model. In addition, it also appeared that there may be some outliers in the fatigue data. In order to determine potential outliers, an influence analysis was performed in SAS on the fatigue data and is shown in Table 33.

Table 33. Influence Analysis on Fatigue Resistance Data to Determine Outliers

Output Statistics		
Obs	**Residual**	**RStudent**
1	-870.4178	-0.0936
2	-895.4077	-0.0970
3	-4618	-0.5052
4	8059	0.8920
5	2452	0.2640
6	-17413	-2.4587
7	6838	0.9144
8	3557	0.3684
9	-4260	-0.4591
10	26001	4.2863
11	2205	0.2318
12	-7768	-0.8461
13	1244	0.1362
14	-2976	-0.3247
15	1980	0.2165
16	3995	0.4360
17	-8344	-1.0281
18	-9187	-1.0324

In general, if the absolute value of the R-student residual is greater than 2, it is considered as a potential outlier. In Table 33, two observation points (6 and 10) have an R-student residual greater than 2. Since everything was kept constant during testing (temperature, frequency, orientation of loading), the influence analysis would suggest that these two points are outliers. These observation points were removed from the model and the second model using percent RAP and percent added binder was calculated. The results of this model in ANOVA are shown in Table 34.

Table 34. ANOVA for Fatigue Resistance Model 2 (AV and Outliers Excluded)

Number of Observations Read	16
Number of Observations Used	16

Analysis of Variance					
Source	**DF**	**Sum of Squares**	**Mean Square**	**F Value**	**Pr > F**
Model	2	509429207	254714603	8.44	0.0045
Error	13	392137941	30164457		
Corrected Total	15	901567148			

Root MSE	5492.21786	**R-Square**	0.5650
Dependent Mean	15789	**Adj R-Sq**	0.4981
Coeff Var	34.78509		

Parameter Estimates							
Variable	**DF**	**Parameter Estimate**	**Standard Error**	**t Value**	**Pr > |t|**	**95% Confidence Limits**	
Intercept	**1**	-1178.23977	4444.86640	-0.27	0.7951	-10781	8424.31029
RAP	**1**	455.41652	138.90208	3.28	0.0060	155.33683	755.49621
Binder	**1**	7292.26316	3333.64980	2.19	0.0476	90.35061	14494

After removing the AV content and outliers from the model, the adjusted R^2 and R^2 values changed to 0.4981 and 0.5650 respectively (118% and 55% improvement). In addition, both the percent RAP and percent additional binder seem to have a significant effect on the fatigue life of the samples at the 95% confidence interval. The model suggests that the fatigue life of samples will increase as the percentage of RAP or the percentage of binder increases. The findings on the effects of additional binder on the fatigue life from the literature review matched the results found in this study. The results for the percent RAP in the literature review were inconclusive, so no comparison can be drawn.

CHAPTER V - SUMMARY, CONCLUSIONS, AND RECOMENDATIONS

SUMMARY

In the wake of many sustainable initiatives, transportation agencies have explored various methods to make roads "greener." There may be no better way to achieve this than to treat the problem at its source, the pavement itself. One of the biggest advances in sustainable pavements is the recycling of materials. This is typically accomplished using RAP.

Hundreds of millions of tons of asphalt concrete are reclaimed each year, and this material is just stockpiled in landfills waiting to be used. It is estimated that approximately 80% of the asphalt concrete that is reclaimed can be reused as RAP *(2)*. Many states, however, only choose to use approximately 15-20% RAP in new construction projects, mainly because the effects of RAP and asphalt binder have not been fully quantified. One of the logical steps to increasing the amount of RAP in newer pavements is to determine the effects on performance that it has on pavements.

Commonly used asphalt materials in Virginia were collected from a producer in northern Virginia for this project. Two performance characteristics, dynamic modulus and fatigue resistance, were studied. The main objectives of this thesis were to determine the effects of adding higher percentages of RAP and asphalt binder in asphalt pavements, as well as see if the increased stiffness of the mixture due to the increased percentage of RAP can be counteracted by using additional asphalt binder in the mix.

In order to accomplish these goals, two different percentages of RAP (20% and 40%) were investigated at three different ACs (plant-mixed, plant-mixed + 0.5%, and plant-mixed + 1.0%) to determine their effects on the dynamic modulus and fatigue cracking of asphalt concrete. Dynamic modulus samples and fatigue beams were compacted in the lab to a target AV level of 7.0% ± 0.5%. Three replicate samples were created for each percent of RAP and each binder content. In all, 36 samples were suitable for testing purposes (18 dynamic modulus and 18 fatigue).

An ITC dynamic modulus machine and a MTS servohydraulic machine were used to perform the dynamic modulus and fatigue resistance testing. The dynamic modulus testing was conducted at four temperatures (4.4^{o}C, 21.1^{o}C, 37.8^{o}C, 54.4^{o}C) and six frequencies (25Hz, 10Hz, 5Hz, 1Hz, 0.5Hz, 0.1Hz). The fatigue testing was conducted at a controlled-strain of 400με, a frequency of 10Hz, and an ambient air temperature of 20^{o}C. After collecting data from these tests, ANOVA was performed to see what variables influenced the performance in the mixes.

FINDINGS

Below is a summary the main findings from this thesis.

- On average, the number of gyrations required to obtain 7.0% AV in the 40% RAP samples was fewer than the 20% RAP samples. This is most likely attributed to the reduced amount of mass required to hit the 7.0% AV in the 40% RAP samples when compared to the 20% RAP samples. Two possible underlying reasons for the reduced mass may be the increased initial AC in the 40% RAP samples or the softer binder that was used when mixing.

- G_{mb} and AV data was collected on the dynamic modulus samples before and after they were cut and cored. An interesting trend was observed in the difference in AV percentage between the original dynamic modulus samples and the cut and cored samples for each binder content. It was shown that there is a smaller decrease in AV between the original samples and the cut and cored samples as the amount of binder increases. For the 0.0%, 0.5%, and 1.0% additional binder samples, the difference in AV content was 1.4%, 1.0%, and 0.8% respectively. This is likely a result of the additional binder permeating the entire sample more uniformly and creating a more homogenous sample.

- The dynamic modulus of the mixture decreased as the AC increased. The effect was more pronounced at higher temperatures and lower frequencies. This trend was also observed in the initial stiffness of the fatigue beams with the 0.0% and 0.5% binder samples having a higher initial stiffness than the 1.0% binder samples.

- The dynamic modulus of the mixture increased as the percent of RAP increased from 20% RAP to 40% RAP. This trend was also observed in the initial stiffness of the fatigue beams, with the 40% RAP fatigue beams having a higher initial stiffness than their 20% RAP fatigue beam counterparts.

- In the 20% RAP samples, the fatigue life improved as the amount of binder increased (4395 cycles, 13102 cycles, and 17232 cycles). The rate of improvement decreased, however, from 0.5% to 1.0% additional binder when compared to 0.0% to 0.5% additional binder. There was no discernible trend in the 40% RAP samples. In the 40% RAP samples, the fatigue life decreased as the AC increased from 0.0% to 0.5% (22340 cycles and 18399 cycles), but increased when the AC increased from 0.5% to 1.0% additional binder (18399 cycles and 22320 cycles).

- The fatigue life of the mixture improved as the percent of RAP increased. For the 0.0%, 0.5%, and 1.0% samples, the 40% RAP samples had a long fatigue life than the 20% RAP samples by on average 17945 cycles, 5298 cycles, and 5088 cycles respectively. This result is contrary of what was expected. The longer fatigue life may be a result of the softer binder and/or higher binder content utilized in the 40% RAP samples.

- ANOVA of the dynamic modulus data showed that the percent RAP, percent additional binder, temperature, and frequency all were statistically significant at the 95% confidence interval. The signs on the ANOVA show that the dynamic modulus increases as the percent RAP or frequency increases, but decreases as the percent binder or temperature increases.

- ANOVA of the fatigue resistance data showed that the percent RAP and percent additional binder were statistically significant at the 95% confidence interval.. The signs on the ANOVA show that the fatigue life increases as the percent RAP or percent binder increases.

CONCLUSIONS

It was found that both the percentage of RAP and AC had a significant effect on the dynamic modulus and fatigue life of asphalt concrete. The 40% RAP mixtures had a dynamic modulus comparable or higher than a 20% RAP mixtures with no additional binder. The original hypothesis that increasing the AC of a mixture will improve the fatigue characteristics of asphalt concrete was confirmed. It was found that the fatigue life improves as both the percentage of RAP and the percentage of binder increases. It was not anticipated that increasing the percentage of RAP would improve the fatigue life, but this may be a result of the softer PG that was mixed with the 40% RAP samples or their higher initial binder content.

RECOMMENDATIONS

This thesis attempted to quantify the effects of RAP and additional asphalt binder on the dynamic modulus and fatigue life of asphalt concrete. Below are several recommendations to further elaborate on these effects and improve upon the methodology. These include, but are not limited to the following:

1) Reheating and recompacting the fatigue samples was potentially considered for this project due to the lack of material. A study should be conducted to see if there is any statistical significance in the performance of an asphalt sample that has been reheated and recompacted.

2) With a limited amount of material, it was only possible to conduct fatigue testing at one strain. In order to better quantify the fatigue resistance of asphalt concrete, fatigue testing should be conducted at multiple strain levels (i.e. 200$\mu\varepsilon$, 300$\mu\varepsilon$).

3) For the 20% RAP fatigue samples, the rate of improvement in the fatigue life was decreasing as the percentage of binder increased. Fatigue testing on additional binder samples in excess of 1.0% should be researched to determine the optimal AC for the 20% RAP samples.

4) Additional performance measures should be evaluated to determine the effects of RAP and percent binder on them. Some additional tests that could be conducted are flow number and permeability.

5) The results that were obtained during fatigue testing were much lower than anticipated. Testing between labs is highly encouraged to ensure that an accurate portrayal of the fatigue life is captured.

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APPENDIX A – GYRATIONS VS. HEIGHT RAW DATA

DYNAMIC MODULUS SAMPLES

20% RAP + 0.0% Asphalt Binder

Table A1. Gyrations vs. Height Raw Data for 20% RAP + 0.0% Binder Samples

Sample A2		Sample A3		Sample A4	
Gyrations	**Height (mm)**	**Gyrations**	**Height (mm)**	**Gyrations**	**Height (mm)**
1	194.5	1	193.7	1	194.4
2	192.0	2	191.3	2	191.6
3	189.7	3	189.2	3	189.4
4	188.2	4	187.5	4	187.8
5	186.6	5	186.3	5	186.3
6	185.6	6	185.2	6	185.3
7	184.5	7	184.2	7	184.3
8	183.7	8	183.4	8	183.4
9	182.8	9	182.6	9	182.7
10	182.2	10	182.0	10	181.9
11	181.6	11	181.3	11	181.4
12	181.0	12	180.8	12	180.9
13	180.5	13	180.4	13	180.3
14	180.0	14	179.8	14	179.9
15	179.6	15	179.5	15	179.4
16	179.2	16	179.0	16	179.0
17	178.8	17	178.7	17	178.6

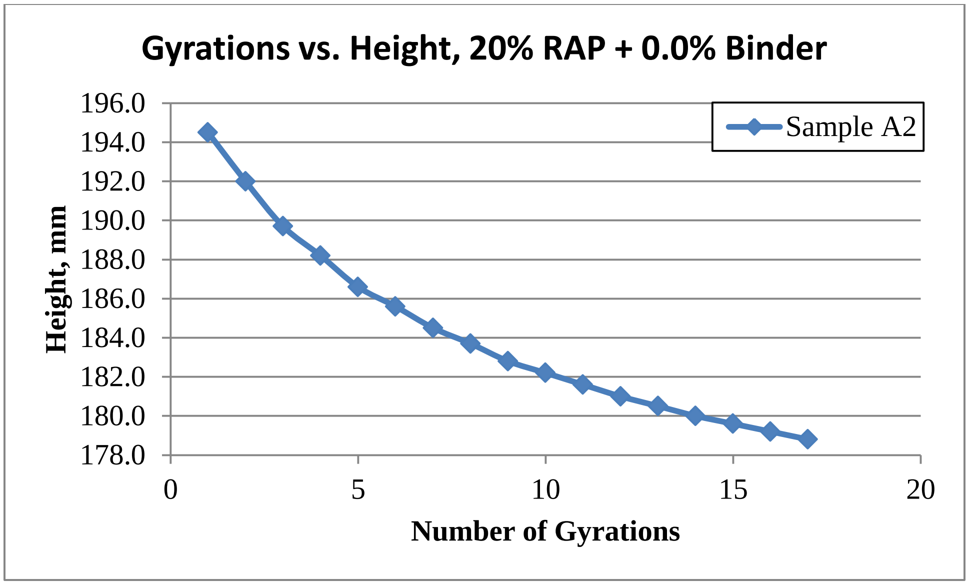

Figure A1. Gyrations vs. Height Plot for Sample A2

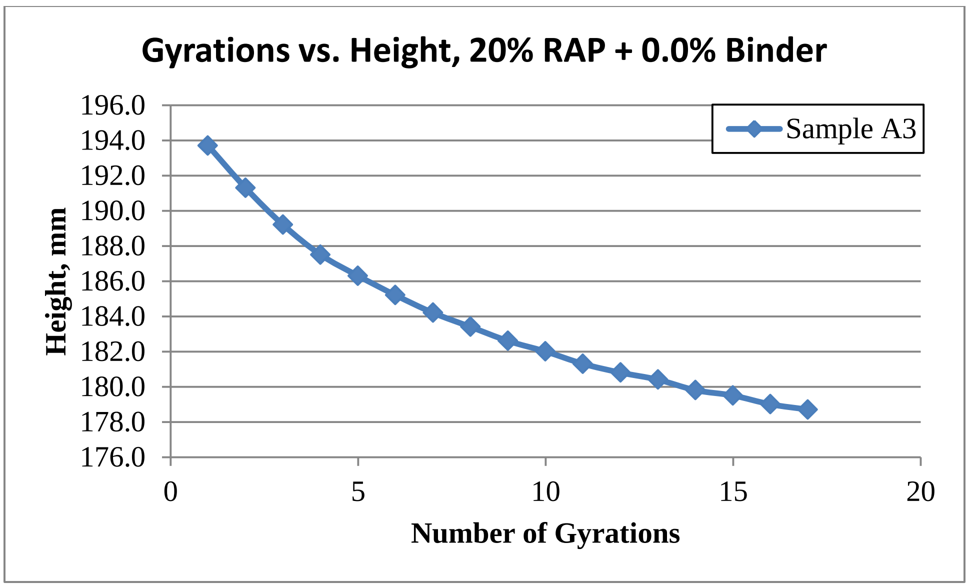

Figure A2. Gyrations vs. Height Plot for Sample A3

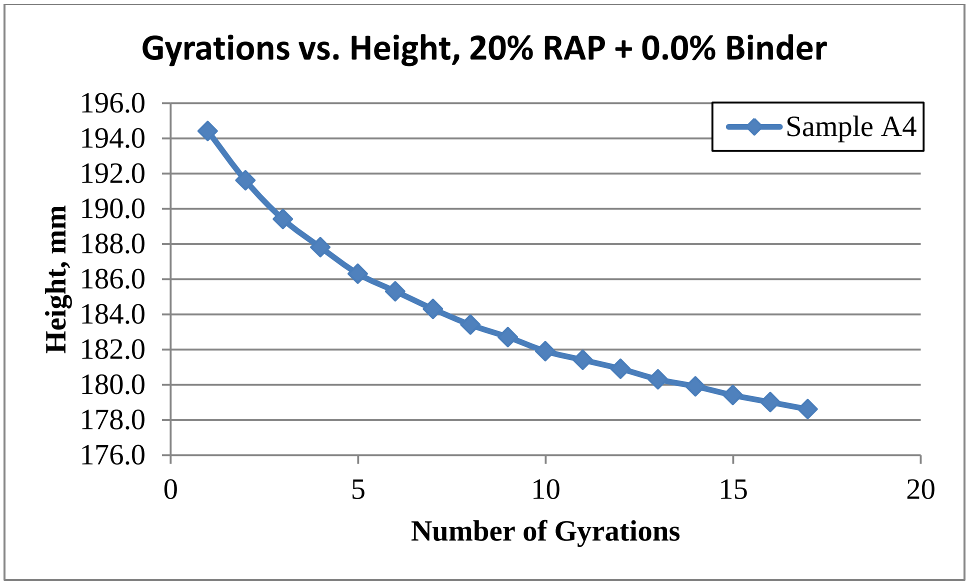

Figure A3. Gyrations vs. Height Plot for Sample A4

20% RAP + 0.5% Asphalt Binder

Table A2. Gyrations vs. Height Raw Data for 20% RAP + 0.5% Binder Samples

Sample C2		Sample C1		Sample C3	
Gyrations	**Height (mm)**	**Gyrations**	**Height (mm)**	**Gyrations**	**Height (mm)**
1	190.2	1	188.4	1	190.0
2	187.9	2	186.2	2	187.7
3	185.7	3	184.1	3	185.6
4	184.2	4	182.4	4	184.1
5	182.8	5	181.2	5	182.7
6	181.8	6	180.0	6	181.6
7	180.7	7	179.1	7	180.6
8	179.9			8	179.8
9	179.2			9	179.0

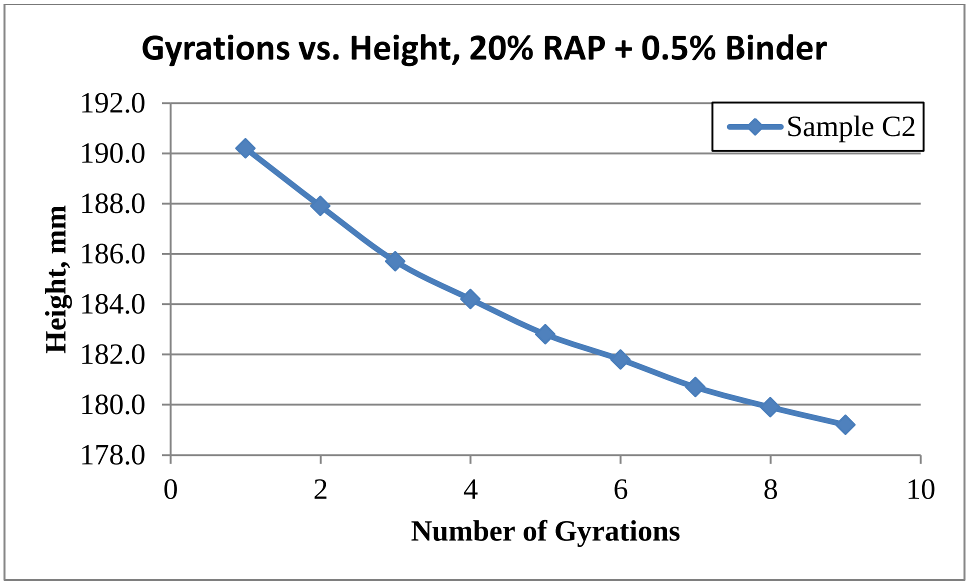

Figure A4. Gyrations vs. Height Plot for Sample C2

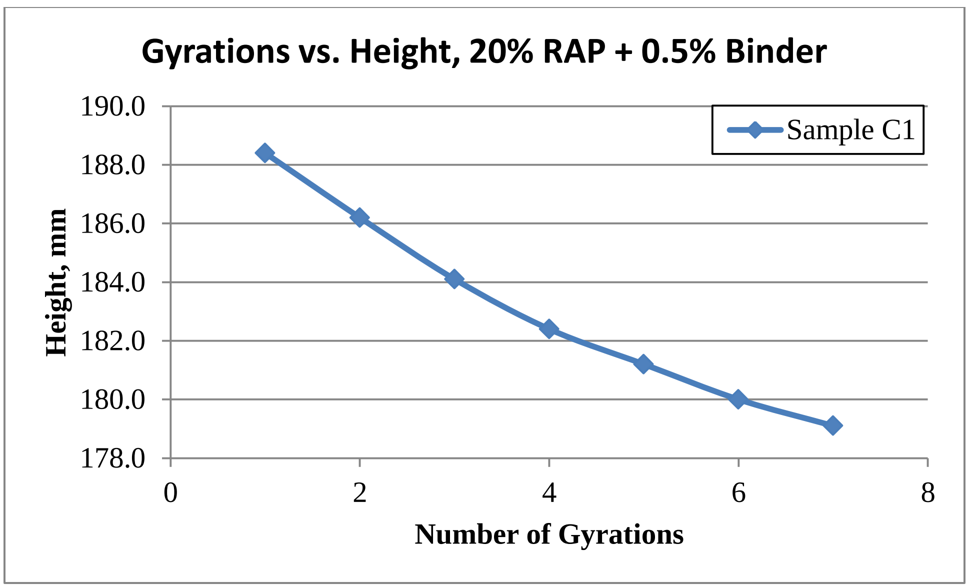

Figure A5. Gyrations vs. Height Plot for Sample C1

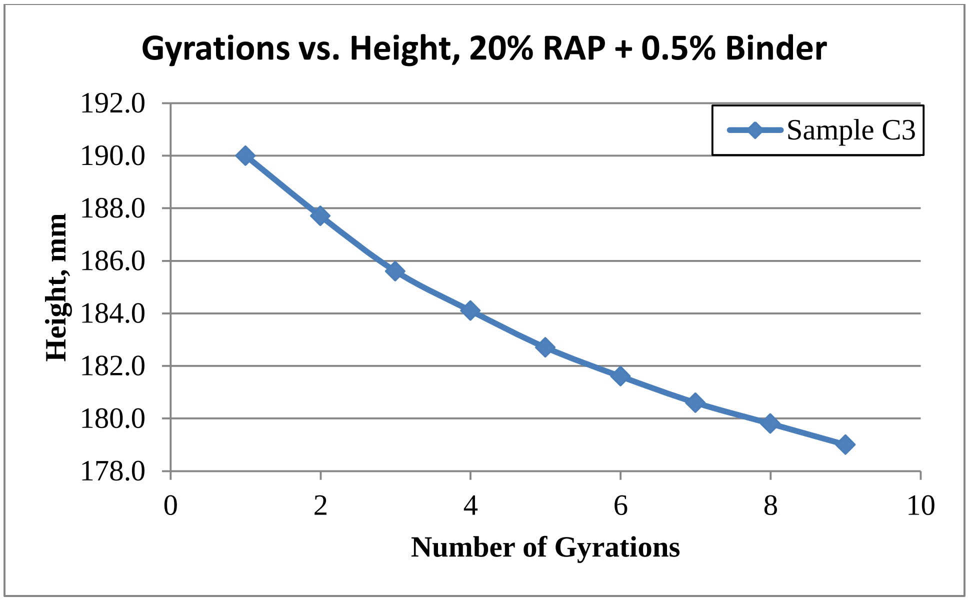

Figure A6. Gyrations vs. Height Plot for Sample C3

20% RAP + 1.0% Asphalt Binder

Table A3. Gyrations vs. Height Raw Data for 20% RAP + 1.0% Binder Samples

Sample E1		Sample E3		Sample E2	
Gyrations	Height (mm)	Gyrations	Height (mm)	Gyrations	Height (mm)
1	188.2	1	190.6	1	190.2
2	185.6	2	188.2	2	187.4
3	183.6	3	185.9	3	185.3
4	182.0	4	184.1	4	183.7
5	180.5	5	182.7	5	182.2
6	179.5	6	181.6	6	181.1
7	178.4	7	180.5	7	180.0
		8	179.6	8	179.1
		9	178.7		

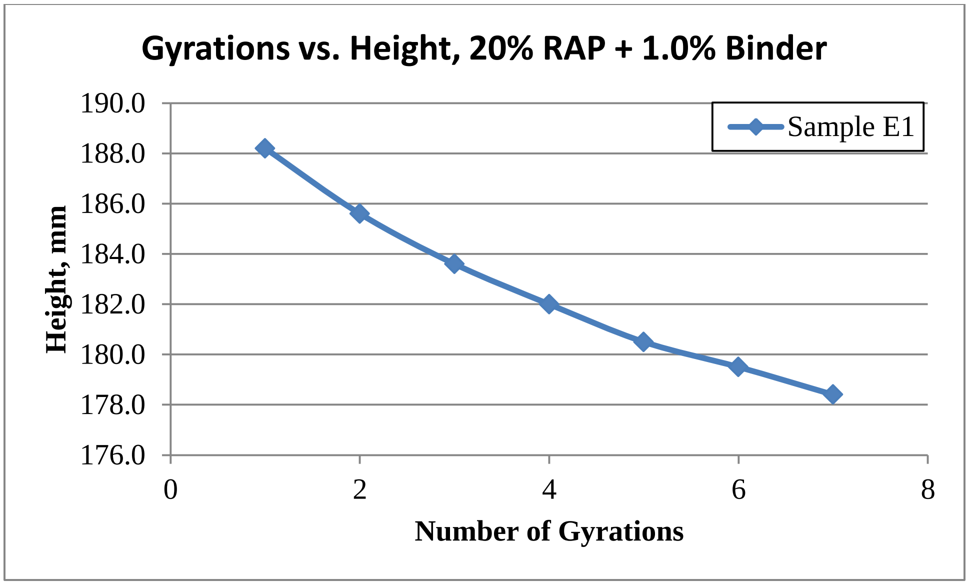

Figure A7. Gyrations vs. Height Plot for Sample E1

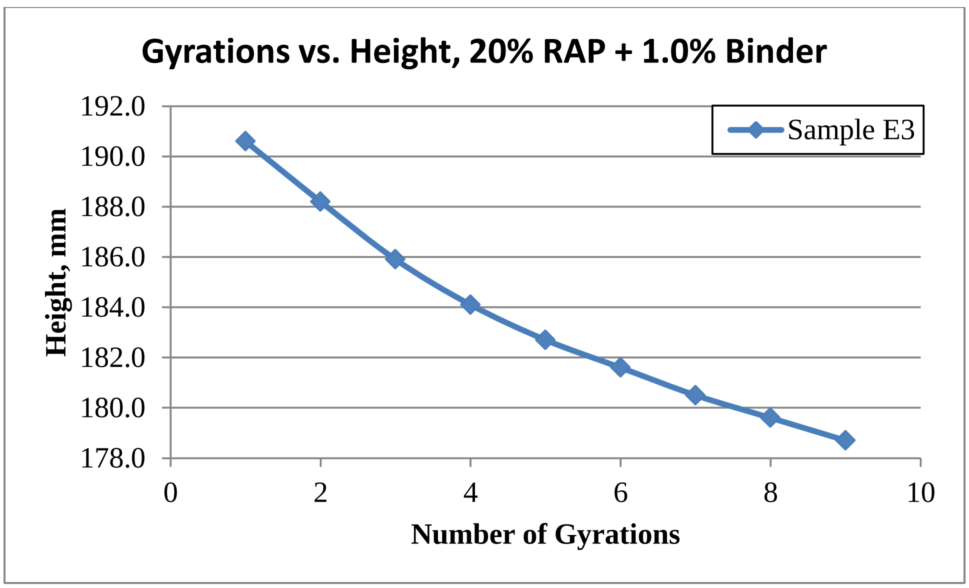

Figure A8. Gyrations vs. Height Plot for Sample E3

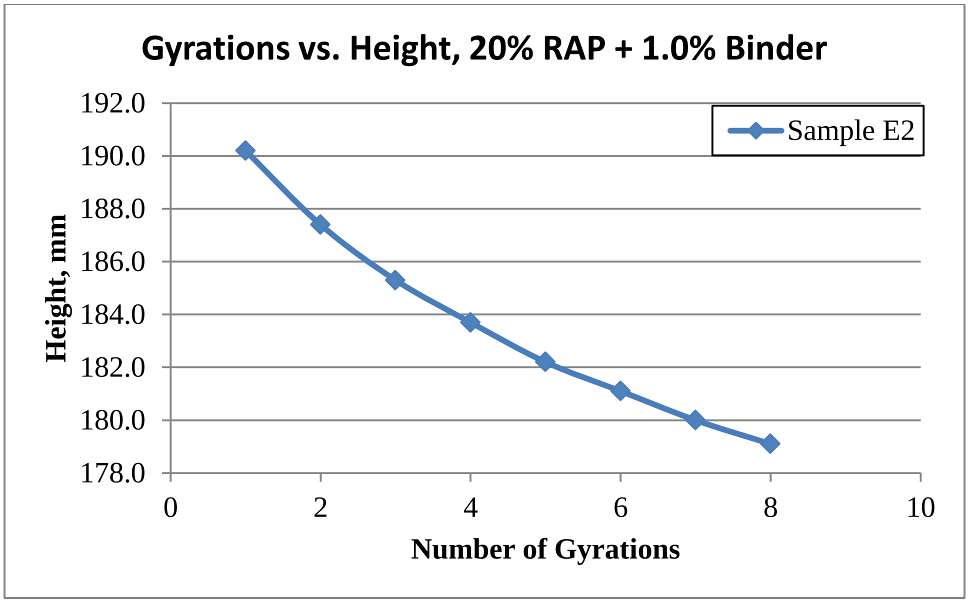

Figure A9. Gyrations vs. Height Plot for Sample E2

40% RAP + 0.0% Asphalt Binder

Table A4. Gyrations vs. Height Raw Data for 40% RAP + 0.0% Binder Samples

Sample B1		Sample B3		Sample B2	
Gyrations	**Height (mm)**	**Gyrations**	**Height (mm)**	**Gyrations**	**Height (mm)**
1	191.7	1	192.2	1	192.4
2	189.1	2	189.8	2	190.0
3	187.2	3	187.7	3	187.7
4	185.6	4	185.9	4	186.2
5	184.3	5	184.7	5	184.7
6	183.1	6	183.5	6	183.5
7	182.3	7	182.6	7	182.5
8	181.5	8	181.8	8	181.7
9	180.6	9	180.9	9	180.8
10	180.0	10	180.3	10	180.2
11	179.4	11	179.7	11	179.6
12	178.9	12	179.2	12	179.0
		13	178.7	13	178.6

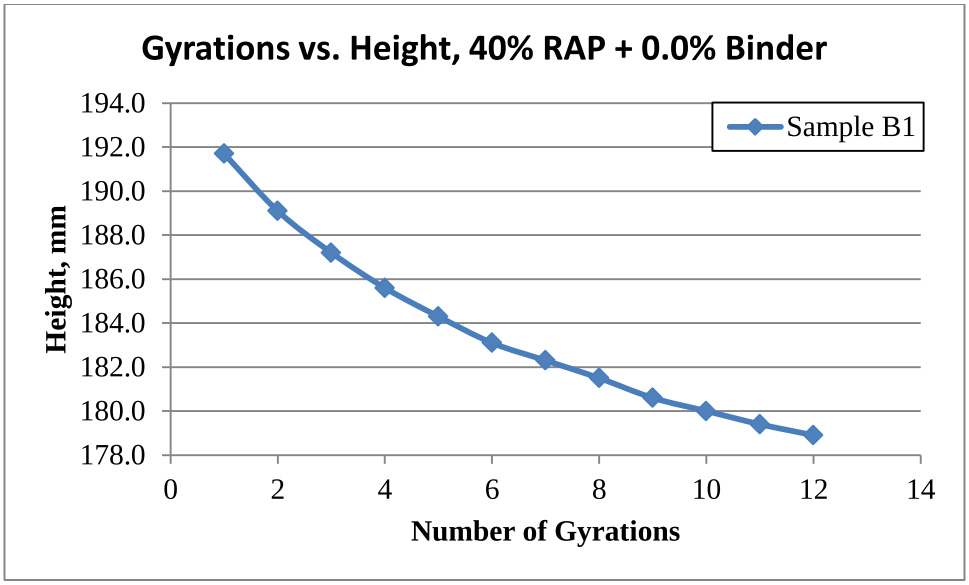

Figure A10. Gyrations vs. Height Plot for Sample B1

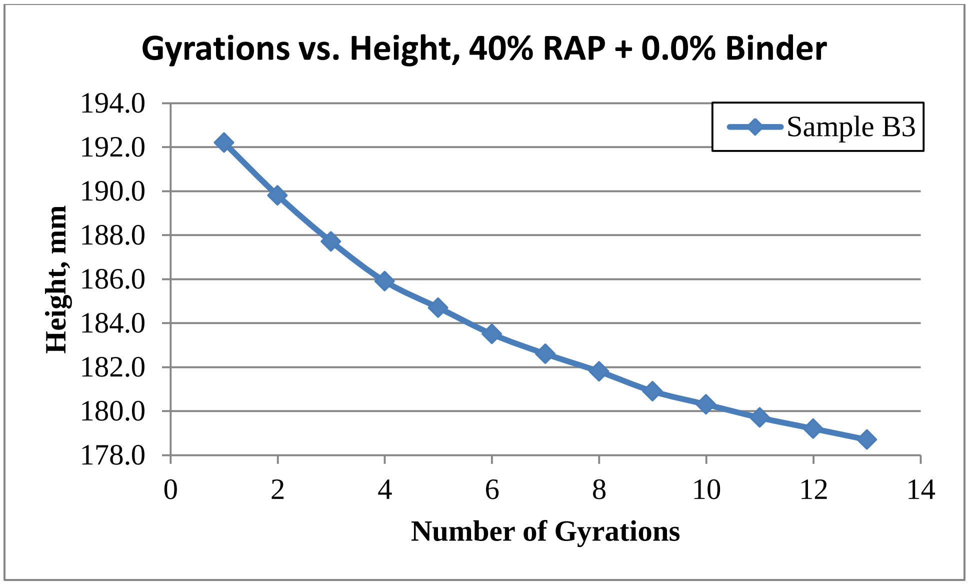

Figure A11. Gyrations vs. Height Plot for Sample B3

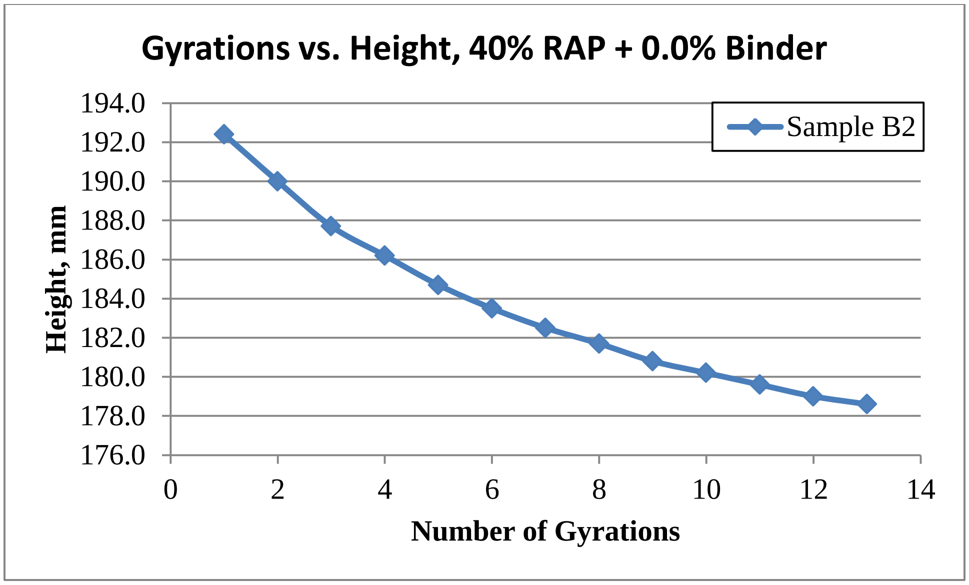

Figure A12. Gyrations vs. Height Plot for Sample B2

40% RAP + 0.5% Asphalt Binder

Table A5. Gyrations vs. Height Raw Data for 40% RAP + 0.5% Binder Samples

Sample D1		Sample D3		Sample D4	
Gyrations	**Height (mm)**	**Gyrations**	**Height (mm)**	**Gyrations**	**Height (mm)**
1	187.3	1	186.4	1	187.0
2	185.0	2	184.1	2	184.7
3	182.7	3	182.0	3	182.6
4	181.1	4	180.3	4	180.9
5	179.8	5	179.1	5	179.6
6	178.8			6	178.6

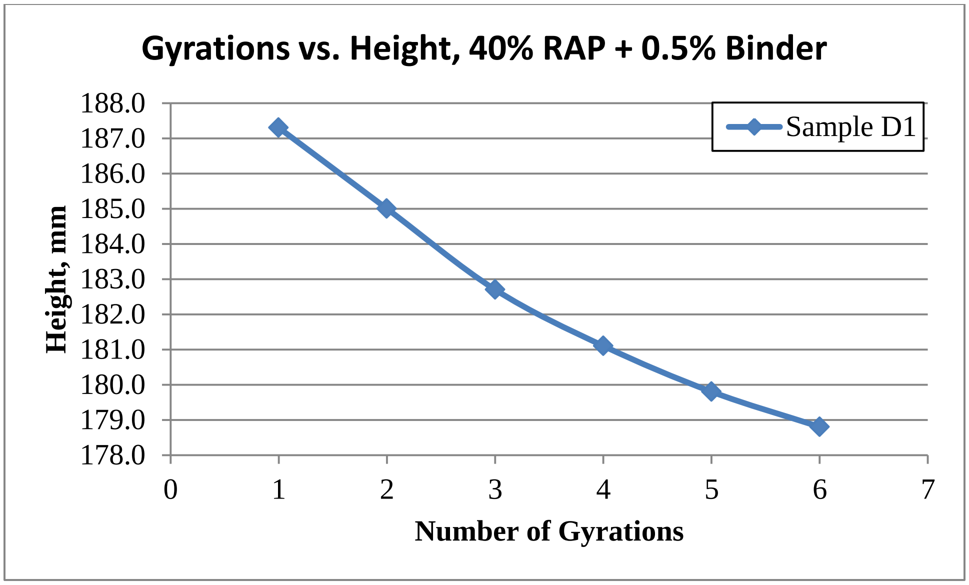

Figure A13. Gyrations vs. Height Plot for Sample D1

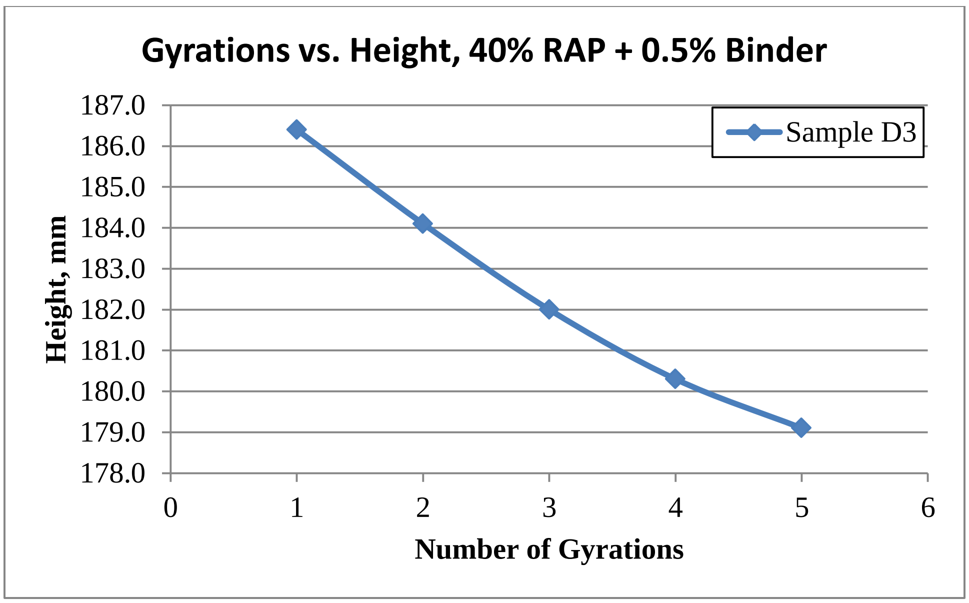

Figure A14. Gyrations vs. Height Plot for Sample D3

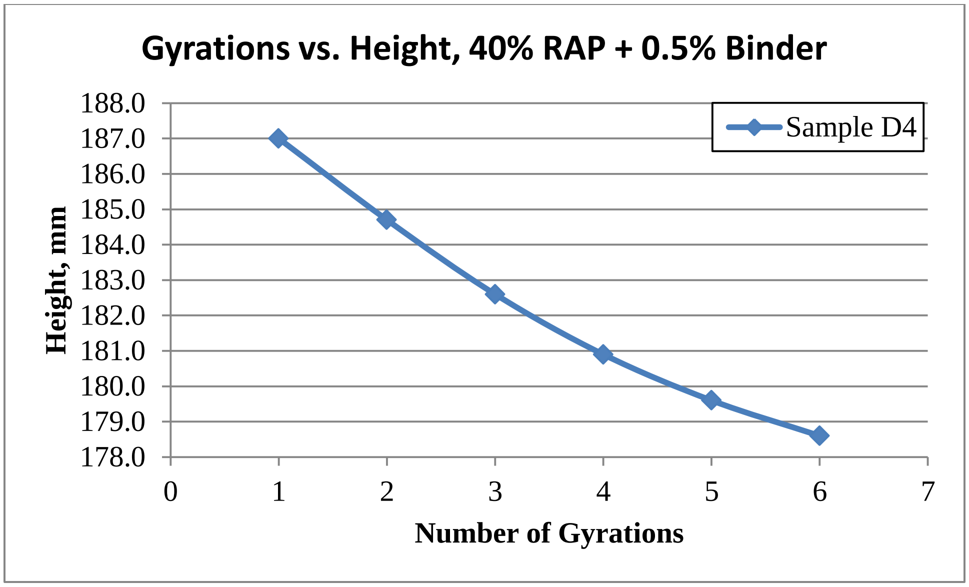

Figure A15. Gyrations vs. Height Plot for Sample D4

40% RAP + 1.0% Asphalt Binder

Table A6. Gyrations vs. Height Raw Data for 40% RAP + 1.0% Binder Samples

Sample F10		**Sample F11**		**Sample F5**	
Gyrations	**Height (mm)**	**Gyrations**	**Height (mm)**	**Gyrations**	**Height (mm)**
1	184.9	1	185.3	1	186.5
2	182.5	2	183.0	2	183.7
3	180.4	3	180.9	3	181.8
4	178.9	4	179.4	4	180.1
				5	178.8

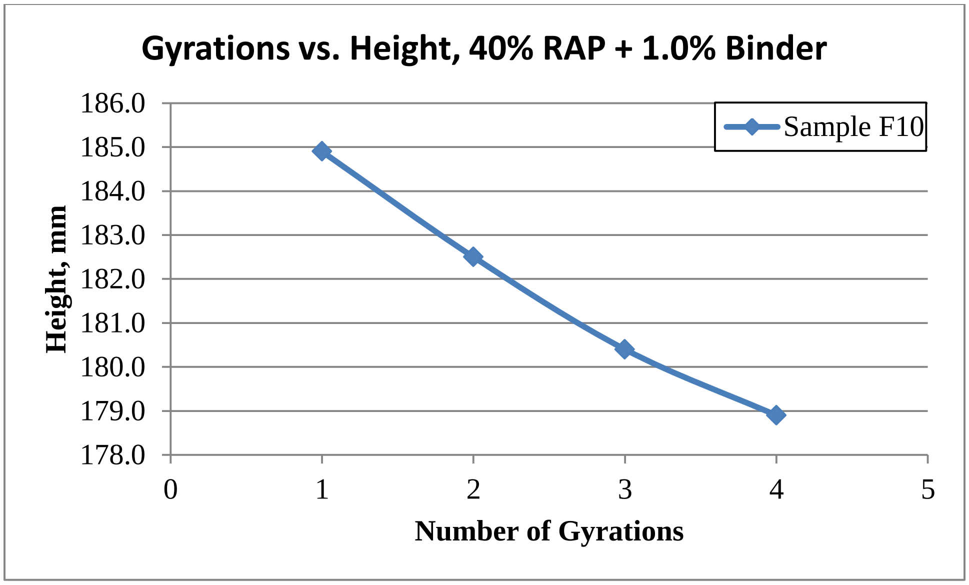

Figure A16. Gyrations vs. Height Plot for Sample F10

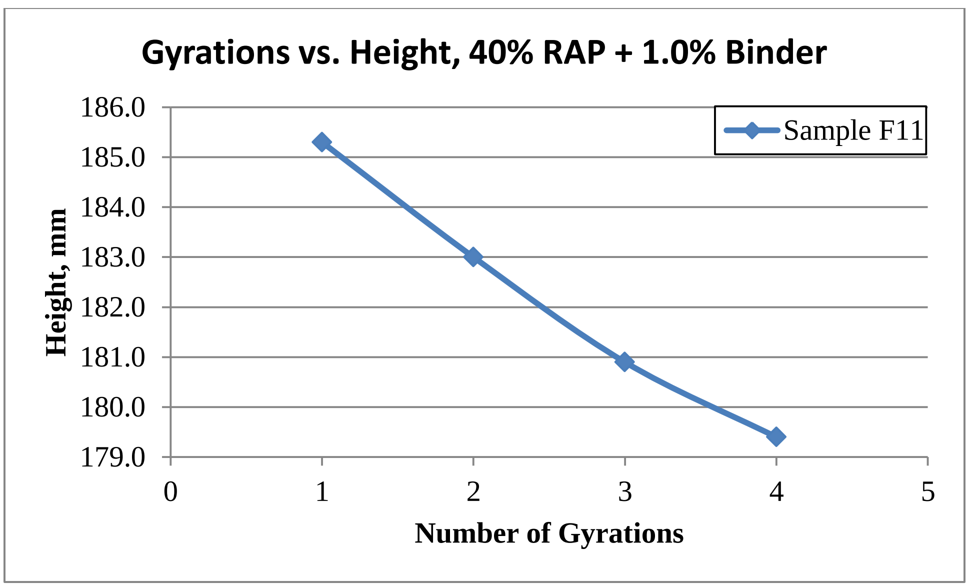

Figure A17. Gyrations vs. Height Plot for Sample F11

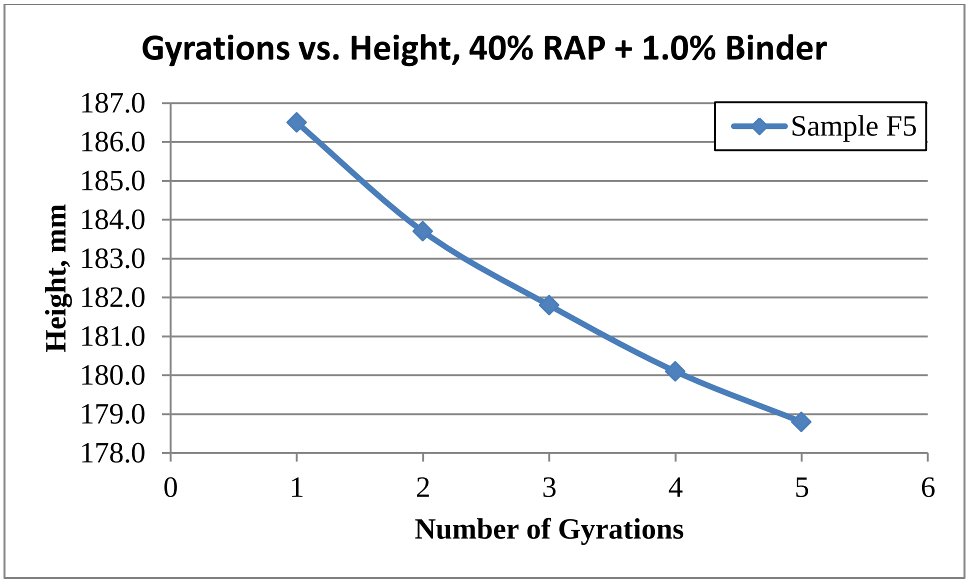

Figure A18. Gyrations vs. Height Plot for Sample F5

APPENDIX B –GMB RAW DATA

DYNAMIC MODULUS SAMPLES

20% RAP + 0.0% Asphalt Binder

Table B1. Dynamic Modulus Gmb Results for 20% RAP + 0.0% Binder

Project:	High RAP, High Binder						
Sample:	20% RAP + 0.00% Binder						
Operator:	Billy Hobbs, Chris Tomlinson, Akyiaa Hosten						
						Rice SG	**2.614**
Sample	**Weight in Air, g**	**Weight in Water, g**	**SSD in Air, g**	**% Water Absorbed**	**Volume (cm^3)**	**Gmb**	**Voids**
	1	2	3	((3-1)/(3-2))*100	3-2 = 4	1/4	6
20% - 1	7437.8	4401.5	7530.5	2.963	3129.0	2.377	9.049
20% - 2	7468.5	4416.6	7541.8	2.345	3125.2	2.390	8.563
20% - 3	7485.2	4437.3	7554.8	2.233	3117.5	2.401	8.132
20% - 1A	2928.2	1726.9	2936.1	0.653	1209.2	2.422	7.345
20% - 2A	2958.8	1743.3	2961.6	0.230	1218.3	2.429	7.076
20% - 3A	2962.6	1750.9	2965.7	0.255	1214.8	2.439	6.688
A1	7469.1	4413.9	7542.2	2.337	3128.3	2.388	8.646
A2	7468.6	4420.2	7538.6	2.245	3118.4	2.395	8.362
A3	7468.4	4419.3	7537.5	2.216	3118.2	2.395	8.359
A4	7464.4	4421.9	7535.8	2.293	3113.9	2.397	8.281
A5	7468.4	4426.0	7545.4	2.468	3119.4	2.394	8.394
A6	7470.4	4416.7	7543.6	2.341	3126.9	2.389	8.589
A7	7469.8	4418.0	7544.7	2.395	3126.7	2.389	8.591
A8	7468.1	4414.0	7539.0	2.269	3125.0	2.390	8.562
A9	7468.3	4418.7	7536.8	2.197	3118.1	2.395	8.357
A1-A	2947.2	1736.9	2952.9	0.469	1216.0	2.424	7.265
A2-A	2959.1	1747.2	2965.9	0.558	1218.7	2.428	7.097
A3-A	2952.1	1743.5	2957.9	0.478	1214.4	2.431	6.988
A4-A	2958.7	1750.0	2965.8	0.584	1215.8	2.434	6.888
A5-A	2952.1	1744.9	2957.3	0.429	1212.4	2.435	6.835
A6-A	2974.2	1757.1	2978.9	0.385	1221.8	2.434	6.860
A7-A	2939.7	1731.6	2944.9	0.429	1213.3	2.423	7.295
A8-A	2955.3	1741.3	2960.2	0.402	1218.9	2.425	7.231
A9-A	2955.2	1744.5	2962.1	0.567	1217.6	2.427	7.135

20% RAP + 0.5% Asphalt Binder

Table B2. Dynamic Modulus Gmb Results for 20% RAP + 0.5% Binder

Project:	High RAP, High Binder						
Sample:	20% RAP + 0.50% Binder						
Operator:	Billy Hobbs, Chris Tomlinson						
						Rice SG	**2.595**
Sample	**Weight in Air, g**	**Weight in Water, g**	**SSD in Air, g**	**% Water Absorbed**	**Volume (cm^3)**	**Gmb**	**Voids**
	1	2	3	((3-1)/(3-2))*100	3-2 = 4	1/4	6
C1	7410.3	4376.0	7490.0	2.559	3114.0	2.380	8.298
C2	7413.1	4381.2	7489.5	2.458	3108.3	2.385	8.095
C4	7410.7	4369.9	7487.8	2.473	3117.9	2.377	8.408
C4	7411.3	4365.6	7485.2	2.369	3119.6	2.376	8.450
C1-A	2930.5	1721.6	2937.3	0.559	1215.7	2.411	7.108
C2-A	2956.8	1743.0	2969.3	1.019	1226.3	2.411	7.085
C3-A	2926.1	1718.6	2934.2	0.666	1215.6	2.407	7.240
C4-A	2912.7	1710.9	2923.6	0.899	1212.7	2.402	7.444

20% RAP + 1.0% Asphalt Binder

Table B3. Dynamic Modulus Gmb Results for 20% RAP + 1.0% Binder

Project:	High RAP, High Binder						
Sample:	20% RAP + 1.00% Binder						
Operator:	Billy Hobbs, Chris Tomlinson						
						Rice SG	**2.576**
Sample	**Weight in Air, g**	**Weight in Water, g**	**SSD in Air, g**	**% Water Absorbed**	**Volume (cm^3)**	**Gmb**	**Voids**
	1	2	3	((3-1)/(3-2))*100	3-2 = 4	1/4	6
E1	7348.6	4300.0	7412.0	2.037	3112.0	2.361	8.332
E2	7373.1	4320.2	7446.0	2.332	3125.8	2.359	8.432
E3	7375.3	4331.7	7448.0	2.333	3116.3	2.367	8.126
E4	7419.8	4346.5	7456.2	1.171	3109.7	2.386	7.375
E5	7422.0	4356.3	7467.0	1.447	3110.7	2.386	7.377
E1-A	2897.6	1693.1	2904.2	0.545	1211.1	2.393	7.122
E2-A	2912.7	1700.4	2920.3	0.623	1219.9	2.388	7.312
E3-A	2925.3	1712.4	2931.3	0.492	1218.9	2.400	6.834
E4-A	2934.9	1720.5	2939.1	0.345	1218.6	2.408	6.505
E5-A	2951.3	1729.8	2955.9	0.375	1226.1	2.407	6.558

40% RAP + 0.0% Asphalt Binder

Table B4. Dynamic Modulus Gmb Results for 40% RAP + 0.0% Binder

Project:	High RAP, High Binder						
Sample:	40% RAP + 0.00% Binder						
Operator:	Billy Hobbs, Chris Tomlinson, Akyiaa Hosten						
						Rice SG	**2.603**
Sample	**Weight in Air, g**	**Weight in Water, g**	**SSD in Air, g**	**% Water Absorbed**	**Volume (cm^3)**	**Gmb**	**Voids**
	1	2	3	((3-1)/(3-2))*100	3-2 = 4	1/4	6
B1	7435.0	4385.5	7499.4	2.068	3113.9	2.388	8.272
B2	7426.3	4383.8	7485.3	1.902	3101.5	2.394	8.013
B3	7446.4	4397.1	7508.5	1.996	3111.4	2.393	8.057
B4	7437.3	4388.8	7496.8	1.914	3108.0	2.393	8.069
B1-A	2955.8	1738.5	2959.3	0.287	1220.8	2.421	6.984
B2-A	2940.4	1732.8	2943.7	0.273	1210.9	2.428	6.712
B3-A	2944.6	1732.7	2947.9	0.272	1215.2	2.423	6.910
B4-A	2966.9	1749.4	2970.6	0.303	1221.2	2.429	6.666

40% RAP + 0.5% Asphalt Binder

Table B5. Dynamic Modulus Gmb Results for 40% RAP + 0.5% Binder

Project:	High RAP, High Binder						
Sample:	40% RAP + 0.50% Binder						
Operator:	Billy Hobbs, Chris Tomlinson						
						Rice SG	**2.584**
Sample	**Weight in Air, g**	**Weight in Water, g**	**SSD in Air, g**	**% Water Absorbed**	**Volume (cm^3)**	**Gmb**	**Voids**
	1	2	3	((3-1)/(3-2))*100	3-2 = 4	1/4	6
D1	7385.9	4343.9	7444.5	1.890	3100.6	2.382	7.814
D2	7406.2	4360.9	7462.4	1.812	3101.5	2.388	7.587
D3	7371.2	4332.38	7436.3	2.097	3103.9	2.375	8.096
D4	7373.7	4327.2	7431.6	1.865	3104.4	2.375	8.079
D1-A	2927.2	1718.3	2935.6	0.690	1217.3	2.405	6.940
D2-A	2924.9	1718.7	2931.5	0.544	1212.8	2.412	6.668
D3-A	2906.9	1706.0	2918.4	0.949	1212.4	2.398	7.212
D4-A	2930.6	1713.9	2937.1	0.531	1223.2	2.396	7.281

40% RAP + 1.0% Asphalt Binder

Table B6. Dynamic Modulus Gmb Results for 40% RAP + 1.0% Binder

Project:	High RAP, High Binder						
Sample:	40% RAP + 1.00% Binder						
Operator:	Billy Hobbs, Chris Tomlinson						
						Rice SG	**2.565**
Sample	**Weight in Air, g**	**Weight in Water, g**	**SSD in Air, g**	**% Water Absorbed**	**Volume (cm^3)**	**Gmb**	**Voids**
	1	2	3	((3-1)/(3-2))*100	3-2 = 4	1/4	6
F1	7302.4	4267.5	7364.8	2.015	3097.3	2.358	8.083
F2	7287.3	4258.0	7354.6	2.173	3096.6	2.353	8.253
F3	7287.8	4255.0	7365.1	2.485	3110.1	2.343	8.644
F4	7292.8	4235.1	7361.9	2.210	3126.8	2.332	9.070
F5	7334.8	4278.7	7396.8	1.988	3118.1	2.352	8.291
F6	7336.4	4280.4	7400.3	2.048	3119.9	2.351	8.324
F1-A	2882.0	1678.2	2889.4	0.611	1211.2	2.379	7.234
F2-A	2874.2	1668.5	2882.8	0.708	1214.3	2.367	7.721
F3-A	2854.5	1652.9	2865.1	0.874	1212.2	2.355	8.195
F4-A	2847.9	1638.3	2855.6	0.633	1217.3	2.340	8.791
F5-A	2896.0	1686.0	2902.4	0.526	1216.4	2.381	7.181
F6-A	2894.3	1680.8	2901.8	0.614	1221.0	2.370	7.585
F7	7340.8	4273.4	7402.2	1.962	3128.8	2.346	8.530
F8	7343.6	4284.2	7412.3	2.196	3128.1	2.348	8.475
F9	7339.0	4272.1	7401.2	1.988	3129.1	2.345	8.561
F7-A	2873.0	1663.3	2880.4	0.608	1217.1	2.361	7.972
F8-A	2870.7	1664.9	2879.8	0.749	1214.9	2.363	7.879
F9-A	2876.1	1669.9	2884.4	0.683	1214.5	2.368	7.675
F10	7350.8	4282.8	7385.9	1.131	3103.1	2.369	7.647
F11	7373.4	4304.9	7420.8	1.521	3115.9	2.366	7.744
F12	7391.0	4320.4	7438.8	1.533	3118.4	2.370	7.597
F10-A	2904.1	1689.7	2907.9	0.312	1218.2	2.384	7.059
F11-A	2905.2	1690.1	2909.5	0.353	1219.4	2.382	7.116
F12-A	2909.7	1701.4	2913.4	0.305	1212.0	2.401	6.404

FATIGUE BEAM SAMPLES

20% RAP + 0.0% Asphalt Binder

Table B7. Fatigue Beam Gmb Results for 20% RAP + 0.0% Binder

Project:	High RAP, High Binder						
Sample:	20% RAP + 0.00% Binder						
Operator:	Billy Hobbs, Chris Tomlinson						
						Rice SG	**2.614**
Sample	**Weight in Air, g**	**Weight in Water, g**	**SSD in Air, g**	**% Water Absorbed**	**Volume (cm^3)**	**Gmb**	**Voids**
	1	2	3	((3-1)/(3-2))*100	3-2 = 4	1/4	6
A1	3214.0	1904.4	3220.5	0.494	1316.1	2.442	6.562
A2	3264.2	1935.0	3269.8	0.420	1334.8	2.445	6.432
A3	3313.0	1960.3	3323.2	0.748	1362.9	2.431	6.991
A4	BROKEN	BROKEN	BROKEN	BROKEN	BROKEN	BROKEN	BROKEN
A5	3237.1	1914.8	3246.8	0.728	1332.0	2.430	7.013
A6	3217.2	1899.7	3239.2	1.642	1339.5	2.402	8.103
A7	3216.4	1904.7	3238.6	1.664	1333.9	2.411	7.740
A8	3239.6	1910.5	3256.4	1.248	1345.9	2.407	7.903
A9	3243.5	1918.6	3258.3	1.105	1339.7	2.421	7.365
A10	3232.1	1897.4	3250.7	1.374	1353.3	2.388	8.618
A11	3235.4	1917.5	3246.5	0.835	1329.0	2.434	6.852
A12	3234.5	1902.3	3255.4	1.545	1353.1	2.390	8.537
A13	3246.0	1912.3	3262.4	1.215	1350.1	2.404	8.008
A14	3246.7	1926.5	3263.4	1.249	1336.9	2.429	7.080

20% RAP + 0.5% Asphalt Binder

Table B8. Fatigue Beam Gmb Results for 20% RAP + 0.5% Binder

Project:	High RAP, High Binder						
Sample:	20% RAP + 0.5% Binder						
Operator:	Billy Hobbs, Chris Tomlinson						
						Rice SG	**2.595**
Sample	**Weight in Air, g**	**Weight in Water, g**	**SSD in Air, g**	**% Water Absorbed**	**Volume (cm^3)**	**Gmb**	**Voids**
	1	2	3	((3-1)/(3-2))*100	3-2 = 4	1/4	6
C1	3036.7	1790.6	3051.8	1.197	1261.2	2.408	7.214
C2	3046.7	1820.1	3053.3	0.535	1233.2	2.471	4.795
C3	3038.6	1790.0	3054.2	1.234	1264.2	2.404	7.377
C4	3042.0	1806.2	3051.3	0.747	1245.1	2.443	5.851
C5	3033.8	1791.0	3047.2	1.067	1256.2	2.415	6.934
C6	3038.5	1811.9	3046.2	0.624	1234.3	2.462	5.136
C7	3039.6	1800.8	3054.3	1.173	1253.5	2.425	6.555

20% RAP + 1.0% Asphalt Binder

Table B9. Fatigue Beam Gmb Results for 20% RAP + 1.0% Binder

Project:	High RAP, High Binder						
Sample:	20% RAP + 1.00% Binder						
Operator:	Billy Hobbs, Chris Tomlinson						
						Rice SG	**2.576**
Sample	**Weight in Air, g**	**Weight in Water, g**	**SSD in Air, g**	**% Water Absorbed**	**Volume (cm^3)**	**Gmb**	**Voids**
	1	2	3	((3-1)/(3-2))*100	3-2 = 4	1/4	6
E1	2904.0	1696.9	2920.7	1.365	1223.8	2.373	7.883
E2	2901.3	1707.7	2912.4	0.921	1204.7	2.408	6.509
E3	2903.0	1696.1	2921.7	1.526	1225.6	2.369	8.050
E4	2911.7	1697.4	2928.9	1.397	1231.5	2.364	8.216
E5	2909.1	1714.0	2920.9	0.978	1206.9	2.410	6.429
E6	2911.7	1703.0	2937.7	2.106	1234.7	2.358	8.454
E7	2920.6	1704.3	2938.5	1.450	1234.2	2.366	8.137
E8	2922.8	1725.8	2933.0	0.845	1207.2	2.421	6.012
E9	2922.6	1728.1	2937.7	1.248	1209.6	2.416	6.205
E10	2924.4	1722.8	2935.4	0.907	1212.6	2.412	6.379
E11	2925.1	1720.8	2935.8	0.881	1215.0	2.407	6.542
E12	2923.8	1702.2	2941.7	1.444	1239.5	2.359	8.430
E13	2924.3	1721.2	2935.6	0.931	1214.4	2.408	6.521
E14	2925.9	1712.6	2950.5	1.987	1237.9	2.364	8.245

40% RAP + 0.0% Asphalt Binder

Table B10. Fatigue Beam Gmb Results for 40% RAP + 0.0% Binder

Project:	High RAP, High Binder						
Sample:	40% RAP + 0.00% Binder						
Operator:	Billy Hobbs, Chris Tomlinson						
						Rice SG	**2.603**
Sample	**Weight in Air, g**	**Weight in Water, g**	**SSD in Air, g**	**% Water Absorbed**	**Volume (cm^3)**	**Gmb**	**Voids**
	1	2	3	((3-1)/(3-2))*100	3-2 = 4	1/4	6
B1	3211.0	1910.1	3216.2	0.398	1306.1	2.458	5.553
B2	3262.3	1934.4	3269.3	0.524	1334.9	2.444	6.114
B3	3309.4	1966.9	3318.9	0.703	1352.0	2.448	5.963
B4	3173.0	1873.0	3181.9	0.680	1308.9	2.424	6.870
B5	3174.6	1867.2	3188.4	1.045	1321.2	2.403	7.691
B6	3175.9	1868.0	3194.0	1.365	1326.0	2.395	7.987
B7	3206.8	1902.9	3215.0	0.625	1312.1	2.444	6.108
B8	3202.8	1899.2	3212.6	0.746	1313.4	2.439	6.317
B9	3205.5	1905.0	3214.7	0.702	1309.7	2.448	5.974
B10	3204.4	1892.0	3214.6	0.771	1322.6	2.423	6.923
B11	3195.6	1900.0	3202.0	0.492	1302.0	2.454	5.710
B12	3196.9	1894.8	3209.3	0.943	1314.5	2.432	6.568

40% RAP + 0.5% Asphalt Binder

Table B11. Fatigue Beam Gmb Results for 40% RAP + 0.5% Binder

Project:	High RAP, High Binder						
Sample:	40% RAP + 0.50% Binder						
Operator:	Billy Hobbs, Chris Tomlinson						
						Rice SG	**2.584**
Sample	**Weight in Air, g**	**Weight in Water, g**	**SSD in Air, g**	**% Water Absorbed**	**Volume (cm^3)**	**Gmb**	**Voids**
	1	2	3	((3-1)/(3-2))*100	3-2 = 4	1/4	6
D1	3169.3	1906.9	3172.4	0.245	1265.5	2.504	3.081
D2	3174.5	1901.8	3180.2	0.446	1278.4	2.483	3.902
D3	3175.2	1911.6	3179.6	0.347	1268.0	2.504	3.092
D4	3097.7	1862.5	3101.0	0.266	1238.5	2.501	3.205
D5	3100.5	1843.8	3106.6	0.483	1262.8	2.455	4.982
D6	3028.7	1812.5	3033.6	0.401	1221.1	2.480	4.013
D7	3029.4	1787.5	3041.6	0.973	1254.1	2.416	6.517
D8	2978.6	1751.8	2986.5	0.640	1234.7	2.412	6.641
D9	2978.4	1771.8	2987.9	0.781	1216.1	2.449	5.219
D10	2978.7	1752.7	2996.5	1.431	1243.8	2.395	7.320
D11	2974.5	1749.7	2987.0	1.010	1237.3	2.404	6.965
D12	2968.1	1768.4	2975.5	0.613	1207.1	2.459	4.843
D13	2968.5	1745.1	2980.4	0.963	1235.3	2.403	7.002

40% RAP + 1.0% Asphalt Binder

Table B12. Fatigue Beam Gmb Results for 40% RAP + 1.0% Binder

Project:	High RAP, High Binder						
Sample:	40% RAP + 1.00% Binder						
Operator:	Billy Hobbs, Chris Tomlinson						
						Rice SG	**2.565**
Sample	**Weight in Air, g**	**Weight in Water, g**	**SSD in Air, g**	**% Water Absorbed**	**Volume (cm^3)**	**Gmb**	**Voids**
	1	2	3	((3-1)/(3-2))*100	3-2 = 4	1/4	6
F1	2776.3	1611.7	2799.2	1.928	1187.5	2.338	8.852
F2	2778.0	1610.1	2796.0	1.518	1185.9	2.343	8.674
F3	2840.8	1669.5	2850.5	0.821	1181.0	2.405	6.221
F4	2841.2	1657.0	2858.3	1.423	1201.3	2.365	7.793
F5	2845.6	1656.5	2856.2	0.884	1199.7	2.372	7.527
F6	2842.9	1667.9	2853.3	0.877	1185.4	2.398	6.500
F7	2843.3	1650.0	2856.4	1.086	1206.4	2.357	8.115
F8	2832.6	1658.9	2846.1	1.137	1187.2	2.386	6.981
F9	2844.0	1667.6	2853.7	0.818	1186.1	2.398	6.520

APPENDIX C – DYNAMIC MODULUS DATA

DYNAMIC MODULUS TEST RAW DATA

20% RAP + 0.0% Asphalt Binder

Table C1. Dynamic Modulus Raw Data for 20% RAP + 0.0% Binder Samples

Temperature	Frequency	Sample A2	Sample A3	Sample A4	Average
°C	Hz	kPa	kPa	kPa	kPa
4.4	25	15203560	14814600	14474900	14831020
	10	13807400	13722180	13362660	13630747
	5	12775390	12793180	12428200	12665590
	1	10421700	10632990	10346950	10467213
	0.5	9491330	9689905	9449068	9543434
	0.1	7663377	7617999	7448538	7576638
21.1	25	7476950	7760770	7621622	7619781
	10	6338979	6551294	6471606	6453960
	5	5501687	5698855	5652243	5617595
	1	3768255	3908530	3929402	3868729
	0.5	3117140	3226646	3266322	3203369
	0.1	2049077	2117885	2167422	2111461
37.8	25	3023102	3117885	3010382	3050456
	10	2466335	2553380	2463424	2494380
	5	1956014	2009930	1965983	1977309
	1	1193350	1218493	1217936	1209926
	0.5	890772	896418	913154	900115
	0.1	479878	471563	494431	481957
54.4	25	1067756	1075473	1089014	1077414
	10	798662	814346	828598	813869
	5	617971	631599	644874	631482
	1	406948	421036	432433	420139
	0.5	308328	317029	330172	318509
	0.1	178826	178288	195084	184066

Table C2. Phase Angles for 20% RAP + 0.0% Binder Samples

Temperature	Frequency	Sample A2	Sample A3	Sample A4	Average
°C	Hz	deg	deg	deg	deg
4.4	25	7.76	8.68	8.07	8.17
	10	9.60	9.28	9.00	9.29
	5	10.54	10.10	9.66	10.10
	1	12.63	12.14	11.51	12.09
	0.5	13.76	13.11	12.56	13.14
	0.1	16.32	15.64	14.45	15.47
21.1	25	17.08	16.68	15.91	16.56
	10	18.43	18.33	17.66	18.14
	5	19.78	19.74	19.00	19.51
	1	23.85	23.95	23.06	23.62
	0.5	25.62	25.86	24.91	25.46
	0.1	28.79	29.07	28.23	28.70
37.8	25	27.17	27.47	26.53	27.06
	10	26.64	26.93	25.87	26.48
	5	27.64	28.09	26.94	27.56
	1	29.50	29.92	28.90	29.44
	0.5	30.57	31.23	30.04	30.61
	0.1	31.20	31.87	30.91	31.33
54.4	25	30.28	30.50	29.52	30.10
	10	27.53	27.45	27.15	27.38
	5	26.64	26.52	26.31	26.49
	1	23.78	23.47	23.42	23.56
	0.5	22.95	22.84	22.67	22.82
	0.1	19.92	20.49	20.09	20.17

Table C3. Dynamic Modulus Coefficient of Variation Between 20% RAP + 0.0% Binder Samples

	4.4°C	21.1°C	37.8°C	54.4°C
25 Hz	2.46	1.86	1.93	1.00
10 Hz	1.73	1.66	2.05	1.84
5 Hz	1.62	1.83	1.45	2.13
1 Hz	1.42	2.27	1.19	3.04
0.5 Hz	1.35	2.41	1.29	3.45
0.1 Hz	1.49	2.81	2.40	5.19

20% RAP + 0.5% Asphalt Binder

Table C4. Dynamic Modulus Raw Data for 20% RAP + 0.5% Binder Samples

Temperature	Frequency	Sample C1	Sample C2	Sample C3	Average
°C	Hz	kPa	kPa	kPa	kPa
4.4	25	16233230	13909860	14250290	14797793
	10	14727320	12655280	12951350	13444650
	5	13737560	11760210	12069340	12522370
	1	11493530	9724723	10067890	10428714
	0.5	10538160	8876894	9191868	9535641
	0.1	8375242	7121070	7230280	7575531
21.1	25	8286523	6821028	7417692	7508414
	10	6933731	5845539	6206578	6328616
	5	6045691	5106825	5405295	5519270
	1	4235075	3570992	3735240	3847102
	0.5	3553843	2962841	3118449	3211711
	0.1	2345705	2018302	2029072	2131026
37.8	25	3233444	2973642	2921710	3042932
	10	2611278	2446290	2389959	2482509
	5	2101016	1961020	1907652	1989896
	1	1273394	1205847	1149804	1209682
	0.5	955171	904506	855169	904948
	0.1	520485	492080	450285	487617
54.4	25	1268354	1098130	1003809	1123431
	10	987407	836931	774787	866375
	5	770076	653337	596647	673353
	1	498858	420430	381640	433642
	0.5	373450	317554	286298	325767
	0.1	217309	175669	163035	185338

Table C5. Phase Angles for 20% RAP + 0.5% Binder Samples

Temperature	Frequency	Sample C1	Sample C2	Sample C3	Average
°C	Hz	deg	deg	deg	deg
4.4	25	8.20	8.71	7.59	8.17
	10	8.82	9.55	9.07	9.15
	5	9.39	10.30	9.51	9.73
	1	11.05	12.07	11.32	11.48
	0.5	11.96	12.92	12.16	12.35
	0.1	13.83	14.71	13.92	14.15
21.1	25	16.05	16.68	16.19	16.31
	10	17.23	17.88	17.67	17.59
	5	18.49	19.07	19.00	18.85
	1	22.21	22.68	23.06	22.65
	0.5	24.00	24.46	24.84	24.43
	0.1	27.43	27.46	28.35	27.75
37.8	25	26.44	26.17	26.96	26.52
	10	26.19	25.79	26.57	26.18
	5	27.47	26.78	27.75	27.33
	1	30.38	29.33	30.52	30.08
	0.5	32.06	30.69	31.98	31.58
	0.1	33.58	31.51	33.50	32.86
54.4	25	29.31	29.76	30.99	30.02
	10	26.85	27.61	28.29	27.58
	5	26.45	27.04	27.66	27.05
	1	24.18	25.25	25.74	25.06
	0.5	24.17	24.75	25.08	24.67
	0.1	21.78	22.74	22.61	22.38

Table C6. Dynamic Modulus Coefficient of Variation Between 20% RAP + 0.5% Binder Samples

	4.4°C	21.1°C	37.8°C	54.4°C
25 Hz	8.48	9.81	5.49	11.93
10 Hz	8.34	8.76	4.63	12.62
5 Hz	8.49	8.69	5.02	13.13
1 Hz	8.99	8.99	5.12	13.77
0.5 Hz	9.25	9.54	5.53	13.55
0.1 Hz	9.17	8.73	7.24	15.32

20% RAP + 1.0% Asphalt Binder

Table C7. Dynamic Modulus Raw Data for 20% RAP + 1.0% Binder Samples

Temperature	Frequency	Sample E1	Sample E2	Sample E3	Average
°C	Hz	kPa	kPa	kPa	kPa
4.4	25	15316110	14446980	14594950	14786013
	10	13730180	12962240	12760940	13151120
	5	12670840	12036710	11770750	12159433
	1	10342550	9961510	9627110	9977057
	0.5	9373985	9075603	8774351	9074646
	0.1	7421304	6957047	7059234	7145862
21.1	25	6850845	6600622	6844171	6765213
	10	5695608	5631166	5839750	5722175
	5	4921223	4906886	5077053	4968387
	1	3350821	3363928	3519724	3411491
	0.5	2774065	2779026	2918894	2823995
	0.1	1788773	1824152	1934183	1849036
37.8	25	2508677	2552442	2690257	2583792
	10	2041658	2096828	2174512	2104333
	5	1608504	1652664	1730249	1663806
	1	975405	1007533	1060270	1014403
	0.5	722109	749477	793867	755151
	0.1	386512	401384	435480	407792
54.4	25	897668	1002181	944340	948063
	10	684436	764829	728146	725804
	5	534770	599611	569305	567895
	1	357989	403156	378192	379779
	0.5	271233	309281	288535	289683
	0.1	153740	183791	164856	167462

Table C8. Phase Angles for 20% RAP + 1.0% Binder Samples

Temperature	Frequency	Sample E1	Sample E2	Sample E3	Average
°C	Hz	deg	deg	deg	deg
4.4	25	8.67	7.98	8.36	8.34
	10	9.87	9.65	9.42	9.65
	5	10.44	10.59	10.15	10.39
	1	12.49	12.60	11.94	12.34
	0.5	13.50	13.56	12.84	13.30
	0.1	15.59	16.13	15.34	15.69
21.1	25	17.13	17.55	16.81	17.16
	10	18.55	18.58	18.08	18.40
	5	20.01	19.84	19.37	19.74
	1	24.01	23.82	23.18	23.67
	0.5	25.74	25.55	24.93	25.41
	0.1	29.10	28.66	28.23	28.66
37.8	25	27.73	27.38	27.14	27.42
	10	27.06	26.62	26.59	26.76
	5	27.95	27.52	27.55	27.67
	1	29.75	29.70	29.57	29.67
	0.5	30.83	30.57	30.78	30.73
	0.1	30.96	30.96	31.41	31.11
54.4	25	29.24	27.99	29.81	29.01
	10	26.57	25.77	27.14	26.49
	5	25.49	24.91	26.30	25.57
	1	22.62	22.27	23.93	22.94
	0.5	21.70	21.75	23.10	22.18
	0.1	19.08	19.36	20.63	19.69

Table C9. Dynamic Modulus Coefficient of Variation Between 20% RAP + 1.0% Binder Samples

	4.4°C	21.1°C	37.8°C	54.4°C
25 Hz	3.14	2.11	3.67	5.52
10 Hz	3.89	1.87	3.17	5.55
5 Hz	3.80	1.90	3.70	5.71
1 Hz	3.59	2.75	4.22	5.96
0.5 Hz	3.30	2.91	4.80	6.58
0.1 Hz	3.41	4.10	6.16	9.07

40% RAP + 0.0% Asphalt Binder

Table C10. Dynamic Modulus Raw Data for 40% RAP + 0.0% Binder Samples

Temperature	Frequency	Sample B1	Sample B2	Sample B3	Average
°C	Hz	kPa	kPa	kPa	kPa
4.4	25	15477100	18915240	16150780	16847707
	10	14098200	17646290	14965780	15570090
	5	13212440	16624270	14140280	14658997
	1	11144940	14084150	12102770	12443953
	0.5	10259970	13007360	11221460	11496263
	0.1	8287945	10385280	9087435	9253553
21.1	25	8030882	9708535	9480426	9073281
	10	7019919	8489806	8384277	7964667
	5	6165654	7488101	7443254	7032336
	1	4373991	5352878	5396112	5040994
	0.5	3630094	4455481	4546514	4210696
	0.1	2397416	2984683	3073492	2818530
37.8	25	3493310	4364432	4223784	4027175
	10	2786261	3470013	3439699	3231991
	5	2189222	2745969	2749137	2561443
	1	1292676	1619180	1651602	1521153
	0.5	943384	1194503	1230717	1122868
	0.1	475359	620670	648427	581485
54.4	25	1119026	1370637	1368021	1285895
	10	809056	993937	998715	933903
	5	607219	757038	756270	706842
	1	374525	484260	619568	492784
	0.5	277541	363096	514725	385121
	0.1	152771	198652	272486	207970

Table C11. Phase Angles for 40% RAP + 0.0% Binder Samples

Temperature	Frequency	Sample B1	Sample B2	Sample B3	Average
°C	Hz	deg	deg	deg	deg
4.4	25	6.44	7.49	5.94	6.62
	10	7.92	8.02	7.81	7.92
	5	8.37	8.70	8.75	8.61
	1	10.30	10.37	10.71	10.46
	0.5	11.23	11.42	11.46	11.37
	0.1	13.32	13.65	13.55	13.51
21.1	25	14.32	14.65	14.76	14.58
	10	16.65	16.27	15.98	16.30
	5	18.12	17.51	17.26	17.63
	1	22.57	21.67	21.38	21.87
	0.5	24.63	23.76	23.25	23.88
	0.1	28.75	27.80	27.34	27.96
37.8	25	26.69	26.49	25.93	26.37
	10	27.34	26.77	26.28	26.80
	5	28.81	28.22	27.82	28.28
	1	31.58	30.85	30.89	31.11
	0.5	32.89	32.15	32.38	32.47
	0.1	33.22	32.26	33.13	32.87
54.4	25	32.60	31.86	31.94	32.13
	10	30.50	29.43	29.74	29.89
	5	29.70	28.36	29.03	29.03
	1	26.14	24.08	26.83	25.68
	0.5	24.98	23.11	25.93	24.67
	0.1	21.92	20.69	22.46	21.69

Table C12. Dynamic Modulus Coefficient of Variation Between 40% RAP + 0.0% Binder Samples

	4.4°C	21.1°C	37.8°C	54.4°C
25 Hz	10.81	10.03	11.61	11.24
10 Hz	11.88	10.29	11.95	11.58
5 Hz	12.03	10.68	12.58	12.21
1 Hz	12.05	11.47	13.05	24.91
0.5 Hz	12.13	11.99	13.94	31.19
0.1 Hz	11.44	13.03	15.98	29.04

40% RAP + 0.5% Asphalt Binder

Table C13. Dynamic Modulus Raw Data for 40% RAP + 0.5% Binder Samples

Temperature	Frequency	Sample D1	Sample D3	Sample D4	Average
°C	Hz	kPa	kPa	kPa	kPa
4.4	25	15100220	14773540	16783790	15552517
	10	14061870	13918850	15458530	14479750
	5	13183500	13153940	14547420	13628287
	1	11235030	11255200	12363910	11618047
	0.5	10400930	10404880	11412360	10739390
	0.1	8452107	8272175	9238208	8654163
21.1	25	8924171	8915632	9689014	9176272
	10	8128123	7615568	8345093	8029595
	5	7165611	6694374	7317507	7059164
	1	5120797	4759560	5139790	5006716
	0.5	4278306	3996445	4295665	4190139
	0.1	2840326	2681281	2771017	2764208
37.8	25	3865241	3744486	3776680	3795469
	10	3056461	3046660	3006151	3036424
	5	2426134	2429156	2380441	2411910
	1	1437342	1438780	1391326	1422483
	0.5	1076392	1074068	1040495	1063652
	0.1	564679	557242	542188	554703
54.4	25	1251182	1250688	1259999	1253956
	10	916329	902312	917273	911971
	5	700057	680426	699546	693343
	1	442929	412615	448962	434835
	0.5	330633	305863	339587	325361
	0.1	175439	167460	189330	177409

Table C14. Phase Angles for 40% RAP + 0.5% Binder Samples

Temperature	Frequency	Sample D1	Sample D3	Sample D4	Average
°C	Hz	deg	deg	deg	deg
4.4	25	5.76	5.58	5.73	5.69
	10	7.75	7.67	7.98	7.80
	5	8.42	8.41	8.82	8.55
	1	10.10	10.08	10.43	10.20
	0.5	11.02	10.87	11.33	11.07
	0.1	12.54	12.68	13.04	12.75
21.1	25	14.58	14.26	15.37	14.74
	10	16.06	16.19	16.75	16.33
	5	17.44	17.56	18.34	17.78
	1	21.47	21.70	22.69	21.95
	0.5	23.43	23.70	24.84	23.99
	0.1	27.67	27.79	29.18	28.21
37.8	25	26.22	26.50	27.07	26.60
	10	26.53	26.77	27.31	26.87
	5	27.96	28.32	28.71	28.33
	1	30.90	31.66	31.50	31.35
	0.5	32.10	32.96	32.26	32.44
	0.1	32.65	34.09	32.33	33.02
54.4	25	31.98	33.11	31.13	32.07
	10	29.63	30.90	28.74	29.76
	5	28.69	30.18	27.84	28.90
	1	25.18	27.17	23.29	25.21
	0.5	24.17	26.14	22.27	24.19
	0.1	22.14	22.90	19.26	21.43

Table C15. Dynamic Modulus Coefficient of Variation Between 40% RAP + 0.5% Binder Samples

	4.4°C	21.1°C	37.8°C	54.4°C
25 Hz	6.94	4.84	1.65	0.42
10 Hz	5.87	4.67	0.88	0.92
5 Hz	5.84	4.60	1.13	1.61
1 Hz	5.56	4.28	1.90	4.48
0.5 Hz	5.43	4.01	1.89	5.37
0.1 Hz	5.94	2.88	2.07	6.24

40% RAP + 1.0% Asphalt Binder

Table C16. Dynamic Modulus Raw Data for 40% RAP + 1.0% Binder Samples

Temperature	Frequency	Sample F5	Sample F10	Sample F11	Average
°C	Hz	kPa	kPa	kPa	kPa
4.4	25	14577700	13483690	13890890	13984093
	10	13404830	12421330	12673960	12833373
	5	12488940	11598060	11779510	11955503
	1	10446810	9624933	9751983	9941242
	0.5	9549629	8761047	8887397	9066024
	0.1	7626732	6741554	6979866	7116051
21.1	25	8139616	7559781	7334794	7678064
	10	6861174	6526069	6233135	6540126
	5	6005289	5649490	5401681	5685487
	1	4194261	3807209	3678859	3893443
	0.5	3497647	3103064	3011772	3204161
	0.1	2257587	1922810	1898187	2026195
37.8	25	3207291	3018493	2800959	3008914
	10	2561096	2270850	2195396	2342447
	5	2021989	1718123	1690374	1810162
	1	1189432	989568	1090093	1089698
	0.5	887871	712414	1013508	871264
	0.1	466250	363428	530233	453303
54.4	25	1077506	876914	861321	938580
	10	786507	622169	627480	678719
	5	598410	468998	474205	513871
	1	377977	303639	310981	330866
	0.5	281482	229142	233231	247952
	0.1	154440	137500	134771	142237

Table C17. Phase Angles for 40% RAP + 1.0% Binder Samples

Temperature	Frequency	Sample F5	Sample F10	Sample F11	Average
°C	Hz	deg	deg	deg	deg
4.4	25	8.00	7.66	8.14	7.93
	10	8.88	9.19	9.21	9.09
	5	9.52	9.88	10.00	9.80
	1	11.33	11.97	11.91	11.74
	0.5	12.17	13.01	13.14	12.77
	0.1	14.26	15.87	16.07	15.40
21.1	25	15.70	16.96	17.08	16.58
	10	17.17	18.77	18.40	18.11
	5	18.56	20.33	19.96	19.62
	1	22.70	25.17	24.48	24.12
	0.5	24.66	27.28	26.65	26.20
	0.1	29.05	31.74	31.06	30.62
37.8	25	27.24	28.78	29.51	28.51
	10	27.31	28.89	29.05	28.42
	5	28.62	30.41	30.28	29.77
	1	31.35	30.32	32.73	31.47
	0.5	32.17	30.83	33.57	32.19
	0.1	32.13	29.13	30.85	30.70
54.4	25	31.74	32.52	31.56	31.94
	10	29.28	29.53	28.78	29.20
	5	28.50	28.10	27.37	27.99
	1	24.64	22.70	22.41	23.25
	0.5	23.87	21.32	21.16	22.12
	0.1	20.58	17.25	17.55	18.46

Table C18. Dynamic Modulus Coefficient of Variation Between 40% RAP + 1.0% Binder Samples

	4.4°C	21.1°C	37.8°C	54.4°C
25 Hz	3.95	5.41	6.76	12.85
10 Hz	3.98	4.81	8.24	13.76
5 Hz	3.94	5.34	10.16	14.26
1 Hz	4.45	6.89	9.17	12.38
0.5 Hz	4.67	8.06	17.36	11.74
0.1 Hz	6.44	9.91	18.56	7.49

DYNAMIC MODULUS MASTER CURVES

20% RAP + 0.0% Asphalt Binder

Table C19. Variables Used to Construct Master Curve for 20% RAP + 0.0% Binder

Temp	Log(Shift)	Freq	Log(Shift Freq)	Log(A2)	Log(A3)	Log(A4)	Sigmoid
°C	#	Hz	#	kPa	kPa	kPa	kPa
4.4	2.326	25	3.723	7.182	7.171	7.161	7.163
	2.326	10	3.326	7.140	7.137	7.126	7.131
	2.326	5	3.025	7.106	7.107	7.094	7.104
	2.326	1	2.326	7.018	7.027	7.015	7.026
	2.326	0.5	2.025	6.977	6.986	6.975	6.986
	2.326	0.1	1.326	6.884	6.882	6.872	6.875
21.1	0.000	25	1.398	6.874	6.890	6.882	6.887
	0.000	10	1.000	6.802	6.816	6.811	6.814
	0.000	5	0.699	6.740	6.756	6.752	6.753
	0.000	1	0.000	6.576	6.592	6.594	6.590
	0.000	0.5	-0.301	6.494	6.509	6.514	6.511
	0.000	0.1	-1.000	6.312	6.326	6.336	6.309
37.8	-1.780	25	-0.382	6.480	6.494	6.479	6.489
	-1.780	10	-0.780	6.392	6.407	6.392	6.376
	-1.780	5	-1.081	6.291	6.303	6.294	6.285
	-1.780	1	-1.780	6.077	6.086	6.086	6.060
	-1.780	0.5	-2.081	5.950	5.953	5.961	5.960
	-1.780	0.1	-2.780	5.681	5.674	5.694	5.724
54.4	-3.202	25	-1.804	6.028	6.032	6.037	6.052
	-3.202	10	-2.202	5.902	5.911	5.918	5.919
	-3.202	5	-2.503	5.791	5.800	5.809	5.818
	-3.202	1	-3.202	5.610	5.624	5.636	5.584
	-3.202	0.5	-3.503	5.489	5.501	5.519	5.487
	-3.202	0.1	-4.202	5.252	5.251	5.290	5.274

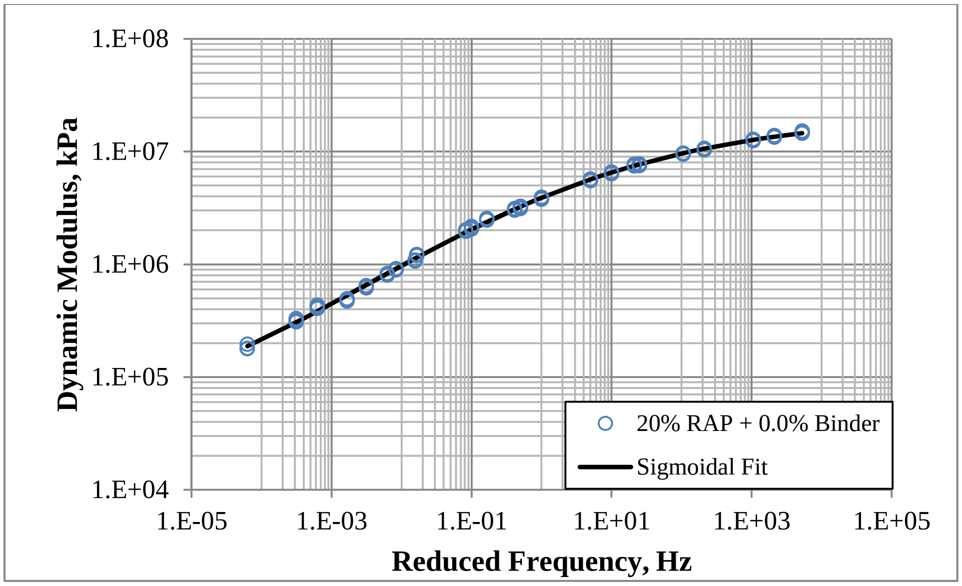

Figure C1. Dynamic Modulus Master Curve for Samples Containing 20% RAP + 0.0% Binder

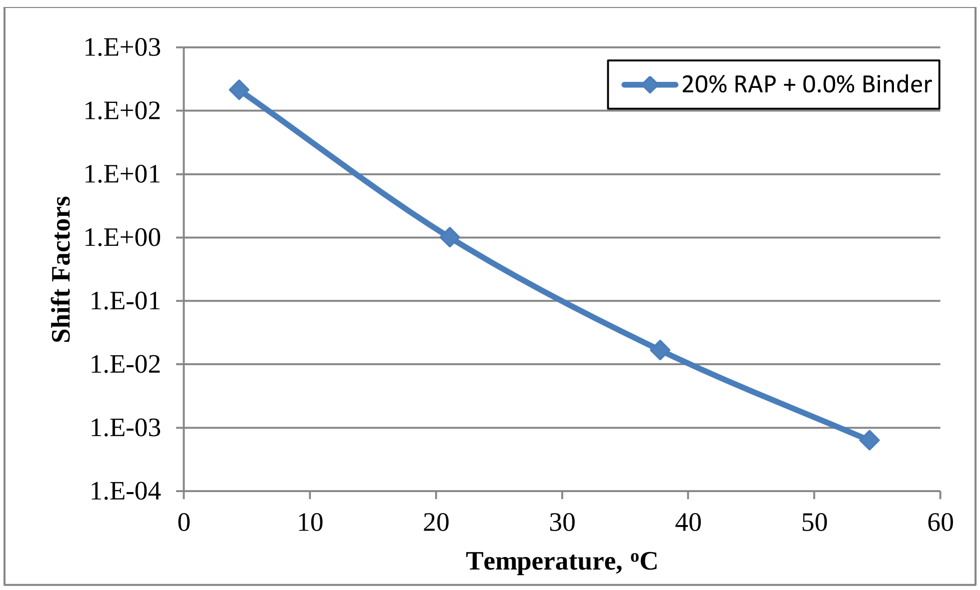

Figure C2. Shift Factors for 20% RAP + 0.0% Binder Master Curve

20% RAP + 0.5% Asphalt Binder

Table C20. Variables Used to Construct Master Curve for 20% RAP + 0.5% Binder

Temp	Log(Shift)	Freq	Log(Shift Freq)	Log(C1)	Log(C2)	Log(C3)	Sigmoid
°C	#	Hz	#	kPa	kPa	kPa	kPa
4.4	2.377	25	3.774	7.210	7.143	7.154	7.159
	2.377	10	3.377	7.168	7.102	7.112	7.127
	2.377	5	3.076	7.138	7.070	7.082	7.099
	2.377	1	2.377	7.060	6.988	7.003	7.022
	2.377	0.5	2.076	7.023	6.948	6.963	6.982
	2.377	0.1	1.377	6.923	6.853	6.859	6.874
21.1	0.000	25	1.398	6.918	6.834	6.870	6.878
	0.000	10	1.000	6.841	6.767	6.793	6.806
	0.000	5	0.699	6.781	6.708	6.733	6.746
	0.000	1	0.000	6.627	6.553	6.572	6.586
	0.000	0.5	-0.301	6.551	6.472	6.494	6.509
	0.000	0.1	-1.000	6.370	6.305	6.307	6.312
37.8	-1.790	25	-0.392	6.510	6.473	6.466	6.485
	-1.790	10	-0.790	6.417	6.389	6.378	6.374
	-1.790	5	-1.091	6.322	6.292	6.280	6.285
	-1.790	1	-1.790	6.105	6.081	6.061	6.064
	-1.790	0.5	-2.091	5.980	5.956	5.932	5.963
	-1.790	0.1	-2.790	5.716	5.692	5.653	5.726
54.4	-3.159	25	-1.761	6.103	6.041	6.002	6.073
	-3.159	10	-2.159	5.994	5.923	5.889	5.941
	-3.159	5	-2.460	5.887	5.815	5.776	5.838
	-3.159	1	-3.159	5.698	5.624	5.582	5.600
	-3.159	0.5	-3.460	5.572	5.502	5.457	5.498
	-3.159	0.1	-4.159	5.337	5.245	5.212	5.271

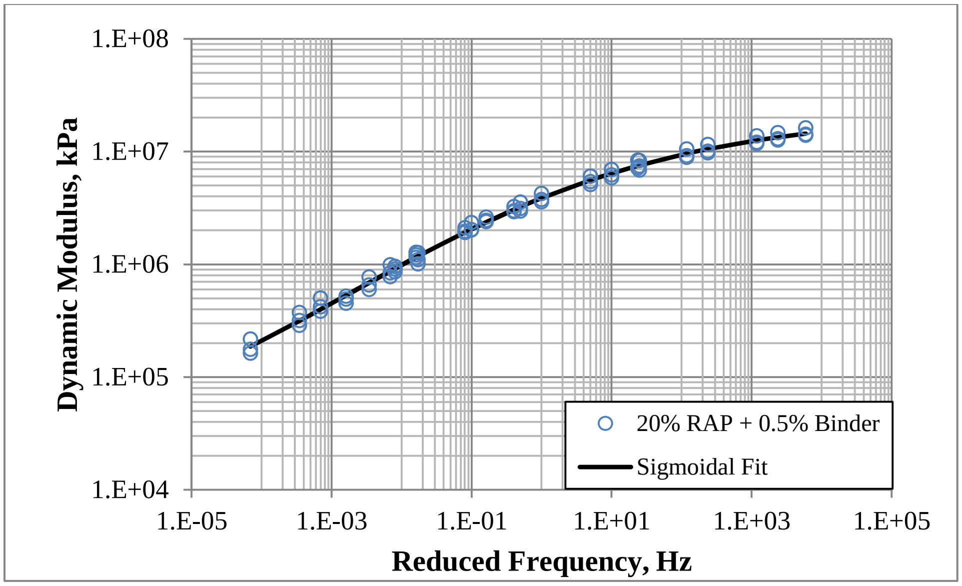

Figure C3. Dynamic Modulus Master Curve for Samples Containing 20% RAP + 0.5% Binder

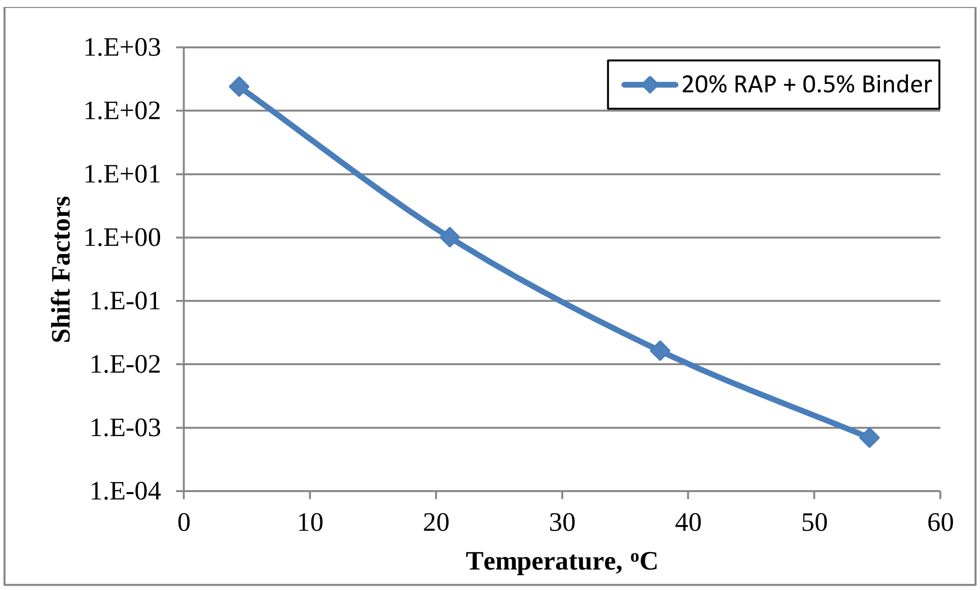

Figure C4. Shift Factors for 20% RAP + 0.5% Binder Master Curve

20% RAP + 1.0% Asphalt Binder

Table C21. Variables Used to Construct Master Curve for 20% RAP + 1.0% Binder

Temp	Log(Shift)	Freq	Log(Shift Freq)	Log(E1)	Log(E2)	Log(E3)	Sigmoid
°C	#	Hz	#	kPa	kPa	kPa	kPa
4.4	2.442	25	3.840	7.185	7.160	7.164	7.155
	2.442	10	3.442	7.138	7.113	7.106	7.119
	2.442	5	3.141	7.103	7.081	7.071	7.089
	2.442	1	2.442	7.015	6.998	6.983	7.005
	2.442	0.5	2.141	6.972	6.958	6.943	6.963
	2.442	0.1	1.442	6.870	6.842	6.849	6.849
21.1	0.000	25	1.398	6.836	6.820	6.835	6.841
	0.000	10	1.000	6.756	6.751	6.766	6.763
	0.000	5	0.699	6.692	6.691	6.706	6.700
	0.000	1	0.000	6.525	6.527	6.547	6.533
	0.000	0.5	-0.301	6.443	6.444	6.465	6.453
	0.000	0.1	-1.000	6.253	6.261	6.286	6.252
37.8	-1.844	25	-0.446	6.399	6.407	6.430	6.413
	-1.844	10	-0.844	6.310	6.322	6.337	6.299
	-1.844	5	-1.145	6.206	6.218	6.238	6.208
	-1.844	1	-1.844	5.989	6.003	6.025	5.985
	-1.844	0.5	-2.145	5.859	5.875	5.900	5.887
	-1.844	0.1	-2.844	5.587	5.604	5.639	5.655
54.4	-3.196	25	-1.798	5.953	6.001	5.975	6.000
	-3.196	10	-2.196	5.835	5.884	5.862	5.870
	-3.196	5	-2.497	5.728	5.778	5.755	5.770
	-3.196	1	-3.196	5.554	5.605	5.578	5.540
	-3.196	0.5	-3.497	5.433	5.490	5.460	5.443
	-3.196	0.1	-4.196	5.187	5.264	5.217	5.230

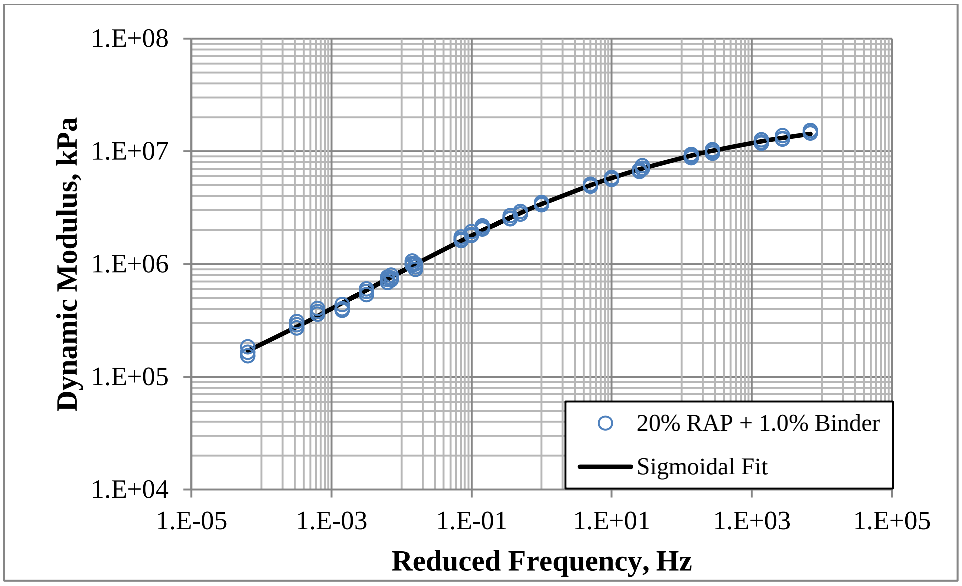

Figure C5. Dynamic Modulus Master Curve for Samples Containing 20% RAP + 1.0% Binder

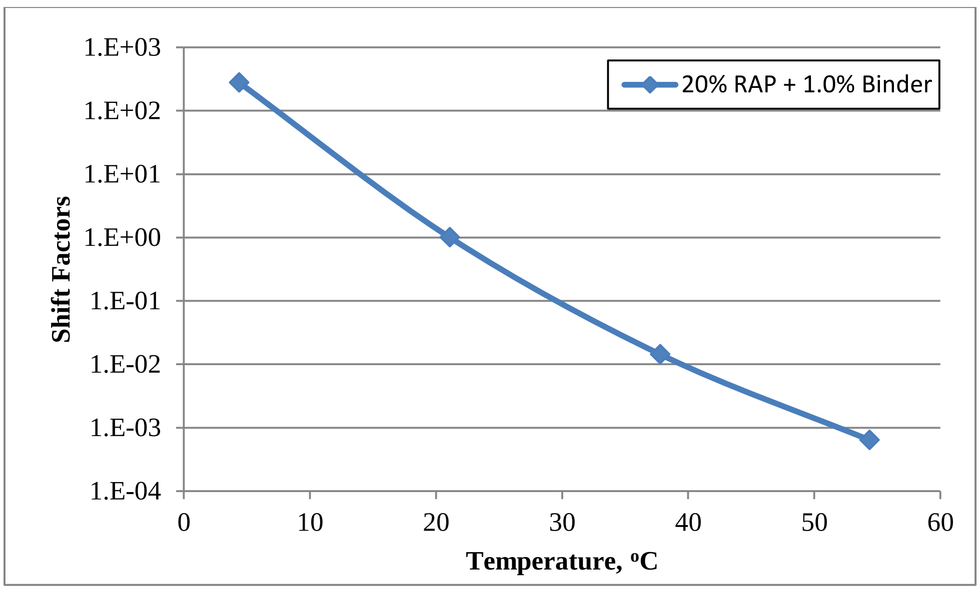

Figure C6. Shift Factors for 20% RAP + 1.0% Binder Master Curve

40% RAP + 0.0% Asphalt Binder

Table C22. Variables Used to Construct Master Curve for 40% RAP + 0.0% Binder

Temp	Log(Shift)	Freq	Log(Shift Freq)	Log(B1)	Log(B2)	Log(B3)	Sigmoid
^{o}C	#	Hz	#	kPa	kPa	kPa	kPa
4.4	2.323	25	3.721	7.190	7.277	7.208	7.210
	2.323	10	3.323	7.149	7.247	7.175	7.185
	2.323	5	3.022	7.121	7.221	7.150	7.163
	2.323	1	2.323	7.047	7.149	7.083	7.098
	2.323	0.5	2.022	7.011	7.114	7.050	7.063
	2.323	0.1	1.323	6.918	7.016	6.958	6.966
21.1	0.000	25	1.398	6.905	6.987	6.977	6.978
	0.000	10	1.000	6.846	6.929	6.923	6.911
	0.000	5	0.699	6.790	6.874	6.872	6.855
	0.000	1	0.000	6.641	6.729	6.732	6.700
	0.000	0.5	-0.301	6.560	6.649	6.658	6.623
	0.000	0.1	-1.000	6.380	6.475	6.488	6.423
37.8	-1.804	25	-0.406	6.543	6.640	6.626	6.595
	-1.804	10	-0.804	6.445	6.540	6.537	6.482
	-1.804	5	-1.105	6.340	6.439	6.439	6.390
	-1.804	1	-1.804	6.111	6.209	6.218	6.161
	-1.804	0.5	-2.105	5.975	6.077	6.090	6.057
	-1.804	0.1	-2.804	5.677	5.793	5.812	5.812
54.4	-3.312	25	-1.914	6.049	6.137	6.136	6.123
	-3.312	10	-2.312	5.908	5.997	5.999	5.984
	-3.312	5	-2.613	5.783	5.879	5.879	5.878
	-3.312	1	-3.312	5.573	5.685	5.792	5.637
	-3.312	0.5	-3.613	5.443	5.560	5.712	5.537
	-3.312	0.1	-4.312	5.184	5.298	5.435	5.323

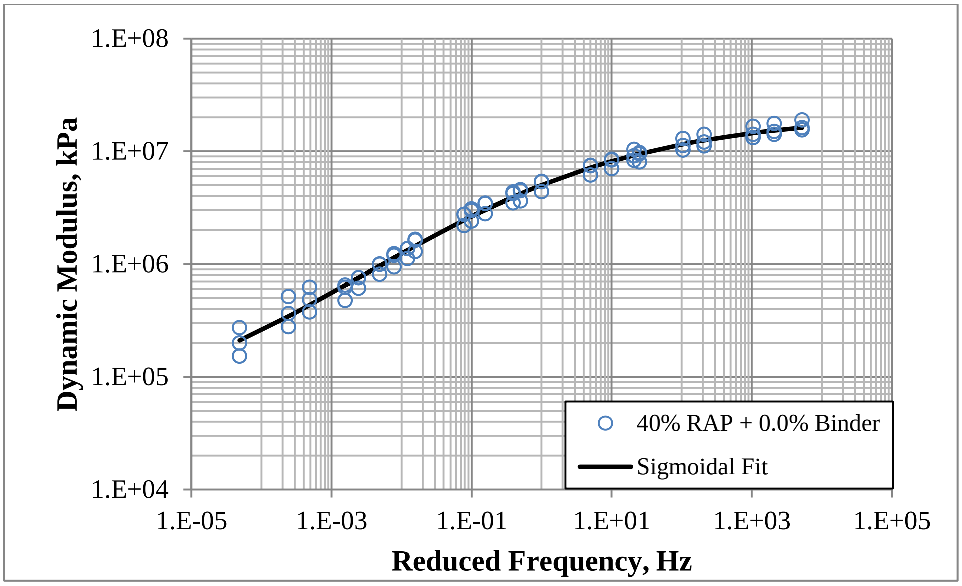

Figure C7. Dynamic Modulus Master Curve for Samples Containing 40% RAP + 0.0% Binder

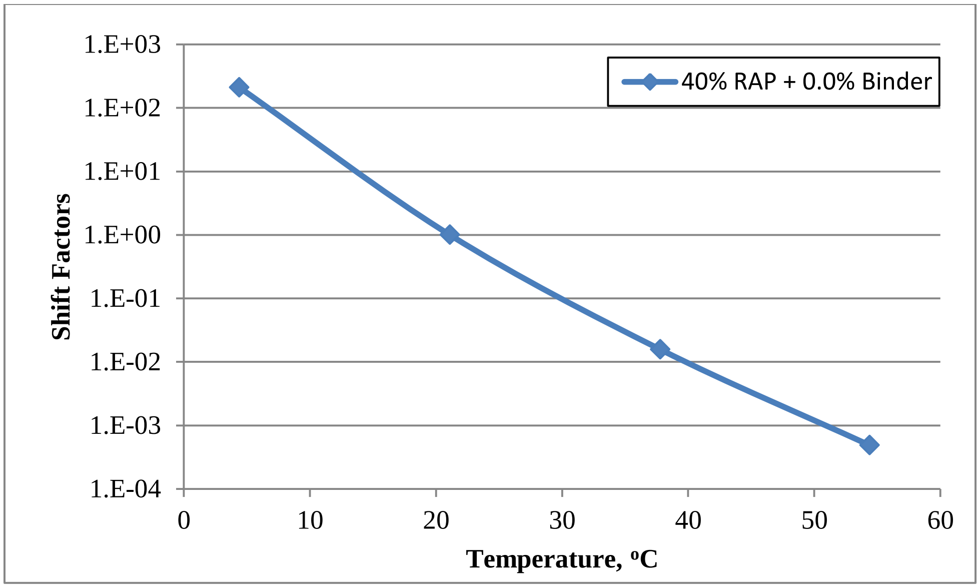

Figure C8. Shift Factors for 40% RAP + 0.0% Binder Master Curve

40% RAP + 0.5% Asphalt Binder

Table C23. Variables Used to Construct Master Curve for 40% RAP + 0.5% Binder

Temp	Log(Shift)	Freq	Log(Shift Freq)	Log(D1)	Log(D3)	Log(D4)	Sigmoid
°C	#	Hz	#	kPa	kPa	kPa	kPa
4.4	2.169	25	3.567	7.179	7.169	7.225	7.184
	2.169	10	3.169	7.148	7.144	7.189	7.158
	2.169	5	2.868	7.120	7.119	7.163	7.135
	2.169	1	2.169	7.051	7.051	7.092	7.069
	2.169	0.5	1.868	7.017	7.017	7.057	7.034
	2.169	0.1	1.169	6.927	6.918	6.966	6.935
21.1	0.000	25	1.398	6.951	6.950	6.986	6.970
	0.000	10	1.000	6.910	6.882	6.921	6.907
	0.000	5	0.699	6.855	6.826	6.864	6.852
	0.000	1	0.000	6.709	6.678	6.711	6.702
	0.000	0.5	-0.301	6.631	6.602	6.633	6.627
	0.000	0.1	-1.000	6.453	6.428	6.443	6.428
37.8	-1.876	25	-0.478	6.587	6.573	6.577	6.580
	-1.876	10	-0.876	6.485	6.484	6.478	6.466
	-1.876	5	-1.177	6.385	6.385	6.377	6.373
	-1.876	1	-1.876	6.158	6.158	6.143	6.138
	-1.876	0.5	-2.177	6.032	6.031	6.017	6.031
	-1.876	0.1	-2.876	5.752	5.746	5.734	5.775
54.4	-3.347	25	-1.949	6.097	6.097	6.100	6.113
	-3.347	10	-2.347	5.962	5.955	5.962	5.969
	-3.347	5	-2.648	5.845	5.833	5.845	5.859
	-3.347	1	-3.347	5.646	5.616	5.652	5.602
	-3.347	0.5	-3.648	5.519	5.486	5.531	5.495
	-3.347	0.1	-4.347	5.244	5.224	5.277	5.260

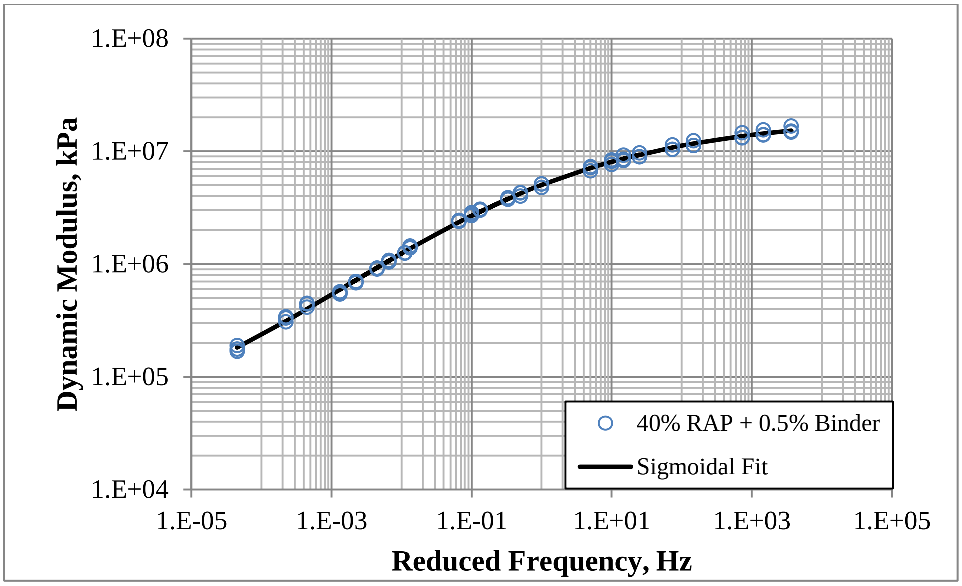

Figure C9. Dynamic Modulus Master Curve for Samples Containing 40% RAP + 0.5% Binder

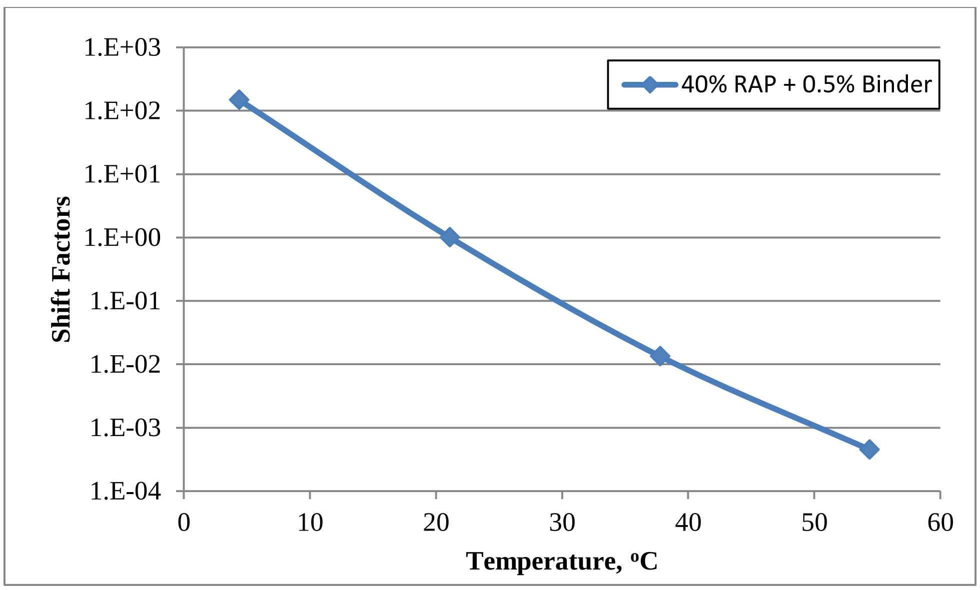

Figure C10. Shift Factors for 40% RAP + 0.5% Binder Master Curve

40% RAP + 1.0% Asphalt Binder

Table C24. Variables Used to Construct Master Curve for 40% RAP + 1.0% Binder

Temp	Log(Shift)	Freq	Log(Shift Freq)	Log(F5)	Log(F10)	Log(F11)	Sigmoid
°C	#	Hz	#	kPa	kPa	kPa	kPa
4.4	2.168	25	3.566	7.164	7.130	7.143	7.140
	2.168	10	3.168	7.127	7.094	7.103	7.108
	2.168	5	2.867	7.097	7.064	7.071	7.080
	2.168	1	2.168	7.019	6.983	6.989	7.001
	2.168	0.5	1.867	6.980	6.943	6.949	6.960
	2.168	0.1	1.168	6.882	6.829	6.844	6.846
21.1	0.000	25	1.398	6.911	6.879	6.865	6.887
	0.000	10	1.000	6.836	6.815	6.795	6.815
	0.000	5	0.699	6.779	6.752	6.733	6.754
	0.000	1	0.000	6.623	6.581	6.566	6.589
	0.000	0.5	-0.301	6.544	6.492	6.479	6.509
	0.000	0.1	-1.000	6.354	6.284	6.278	6.302
37.8	-1.818	25	-0.420	6.506	6.480	6.447	6.476
	-1.818	10	-0.818	6.408	6.356	6.342	6.358
	-1.818	5	-1.119	6.306	6.235	6.228	6.264
	-1.818	1	-1.818	6.075	5.995	6.037	6.029
	-1.818	0.5	-2.119	5.948	5.853	6.006	5.923
	-1.818	0.1	-2.818	5.669	5.560	5.724	5.675
54.4	-3.367	25	-1.969	6.032	5.943	5.935	5.976
	-3.367	10	-2.367	5.896	5.794	5.798	5.835
	-3.367	5	-2.668	5.777	5.671	5.676	5.728
	-3.367	1	-3.367	5.577	5.482	5.493	5.484
	-3.367	0.5	-3.668	5.449	5.360	5.368	5.382
	-3.367	0.1	-4.367	5.189	5.138	5.130	5.164

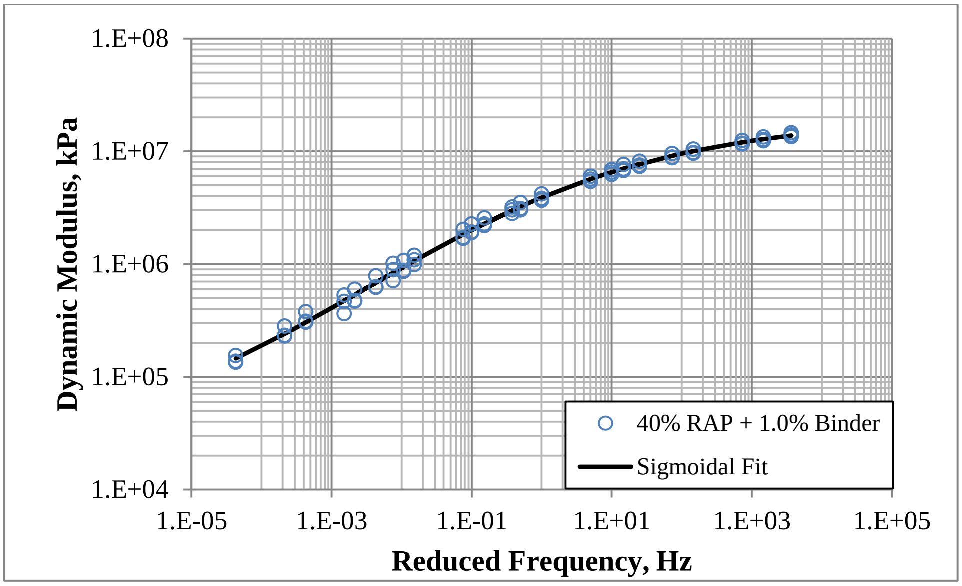

Figure C11. Dynamic Modulus Master Curve for Samples Containing 40% RAP + 1.0% Binder

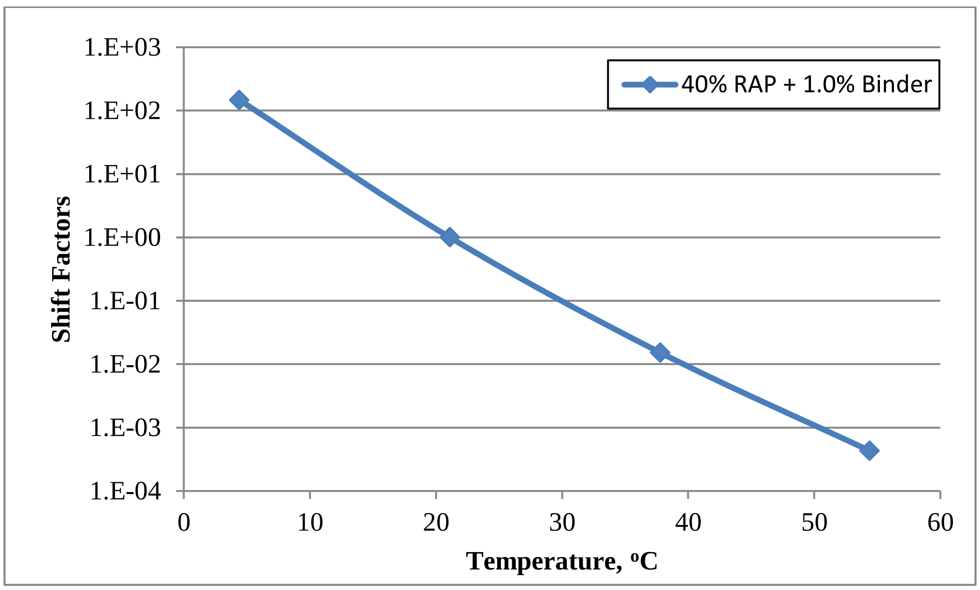

Figure C12. Shift Factors for 40% RAP + 1.0% Binder Master Curve

APPENDIX D – THIRD-POINT FATIGUE TESTING DATA

STIFFNESS VERSUS CYCLES CURVES

20% RAP + 0.0% Asphalt Binder

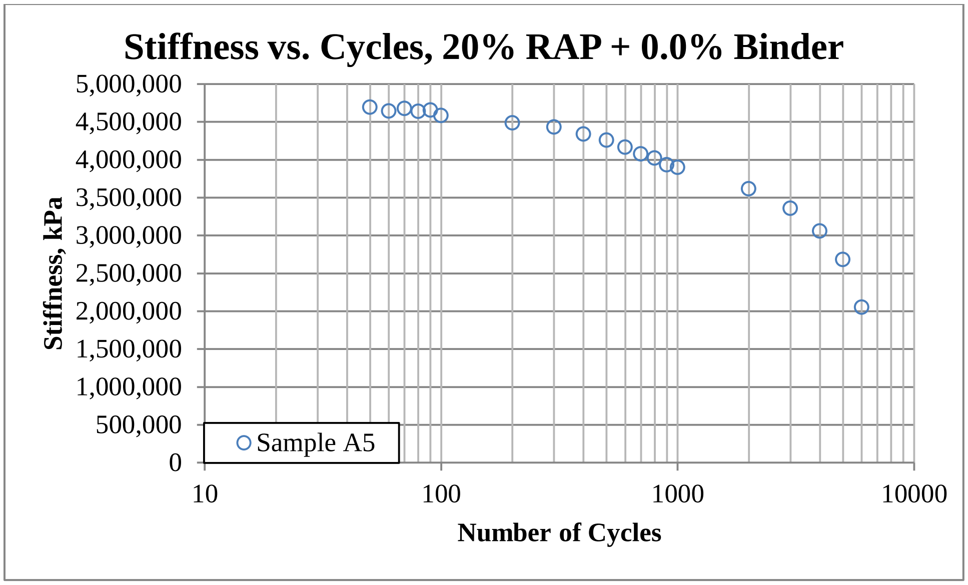

Figure D1. Fatigue Resistance Curve for Sample A5

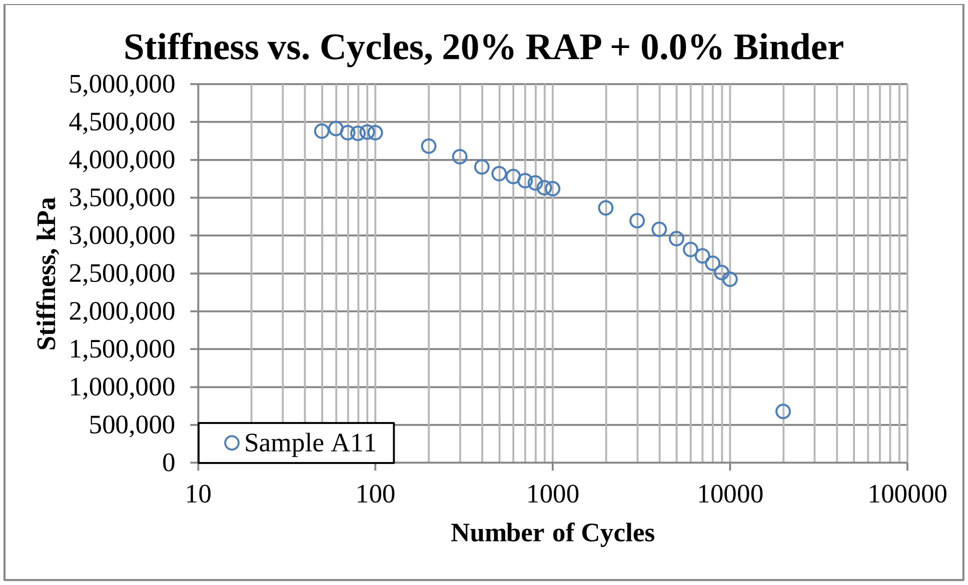

Figure D2. Fatigue Resistance Curve for Sample A11

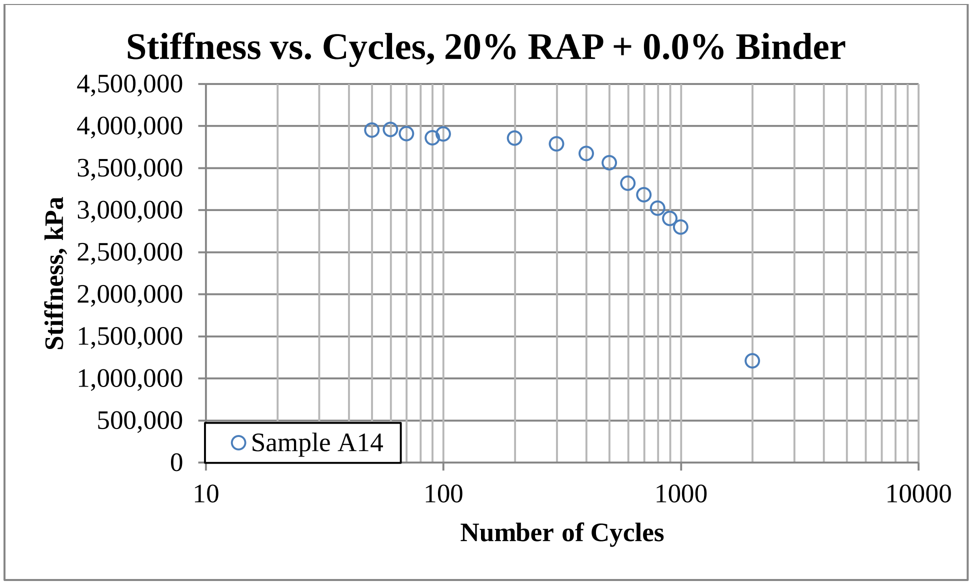

Figure D3. Fatigue Resistance Curve for Sample A14

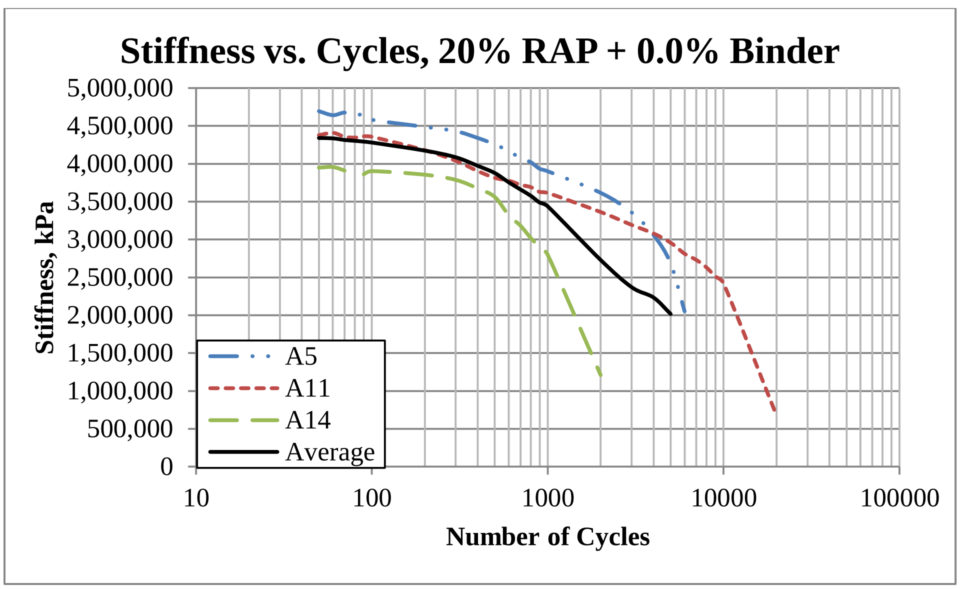

Figure D4. Fatigue Resistance Curve Summary for 20% RAP + 0.0% Binder

20% RAP + 0.5% Asphalt Binder

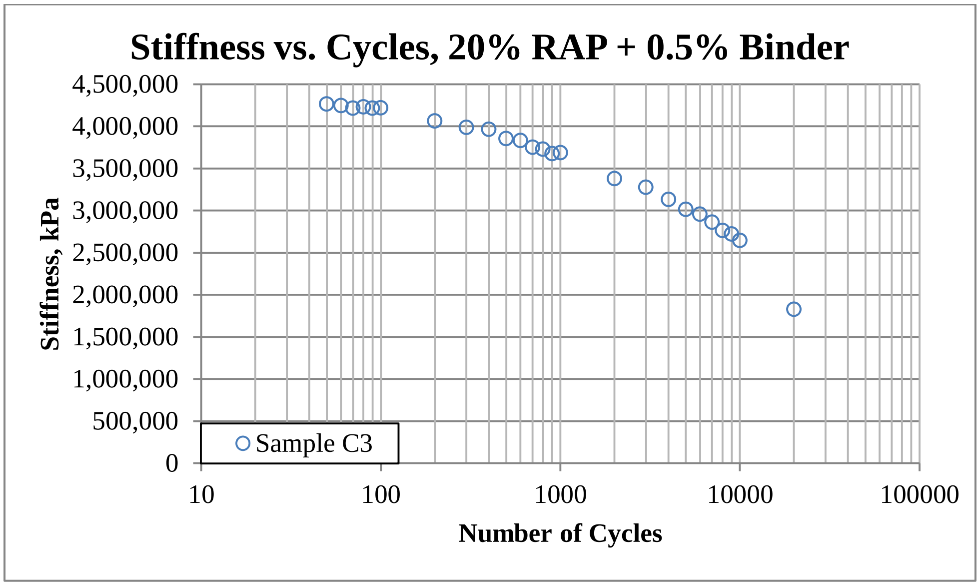

Figure D5. Fatigue Resistance Curve for Sample C3

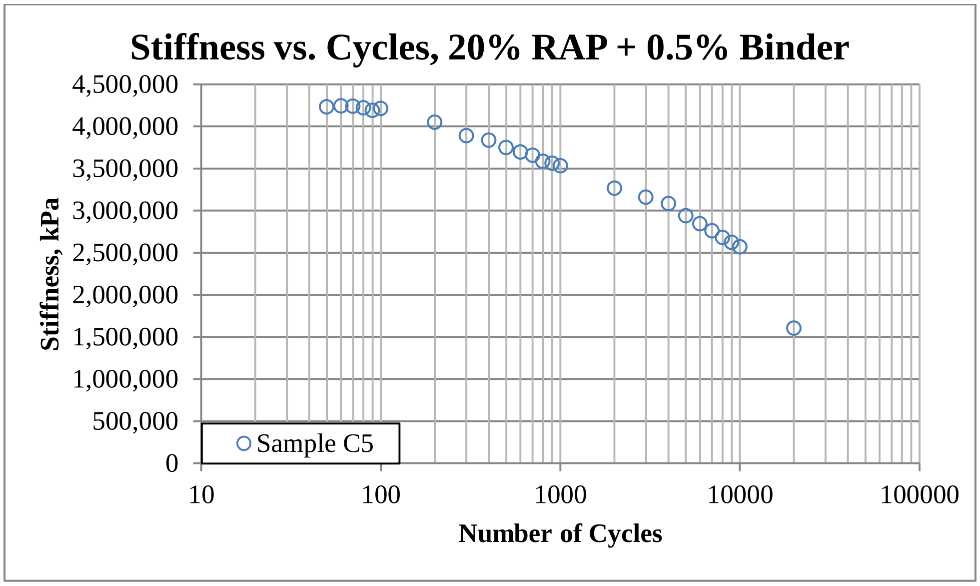

Figure D6. Fatigue Resistance Curve for Sample C5

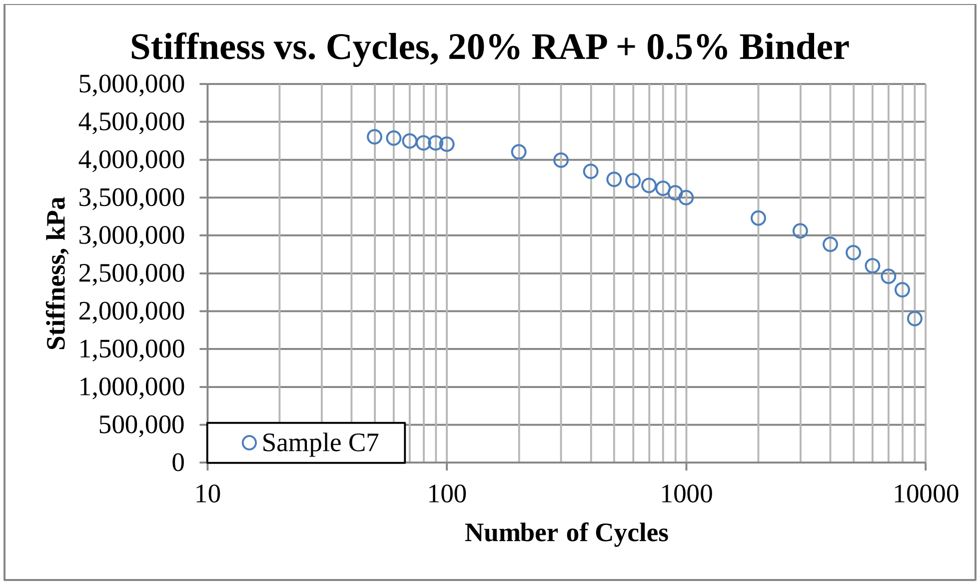

Figure D7. Fatigue Resistance Curve for Sample C7

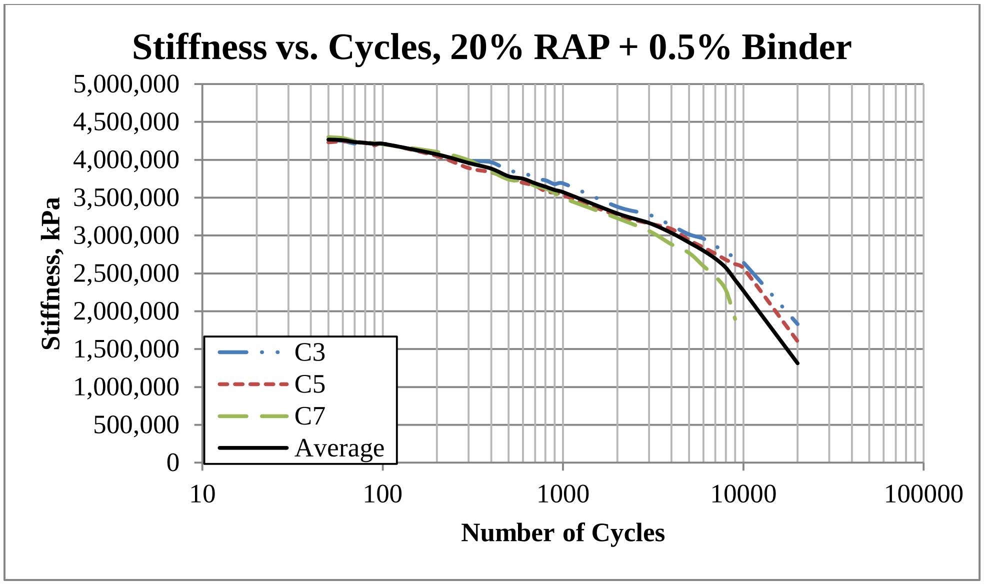

Figure D8. Fatigue Resistance Curve Summary for 20% RAP + 0.5% Binder

20% RAP + 1.0% Asphalt Binder

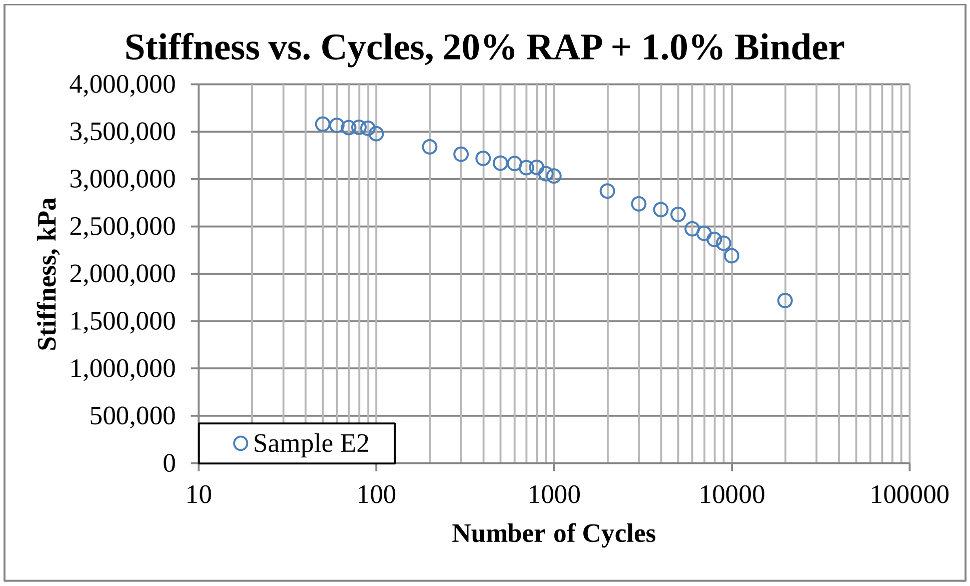

Figure D9. Fatigue Resistance Curve for Sample E2

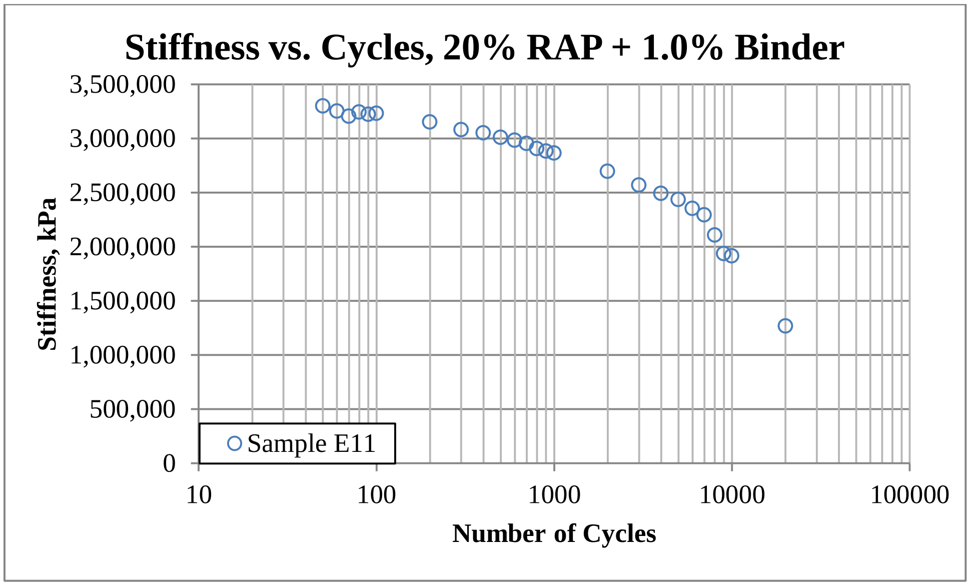

Figure D10. Fatigue Resistance Curve for Sample E11

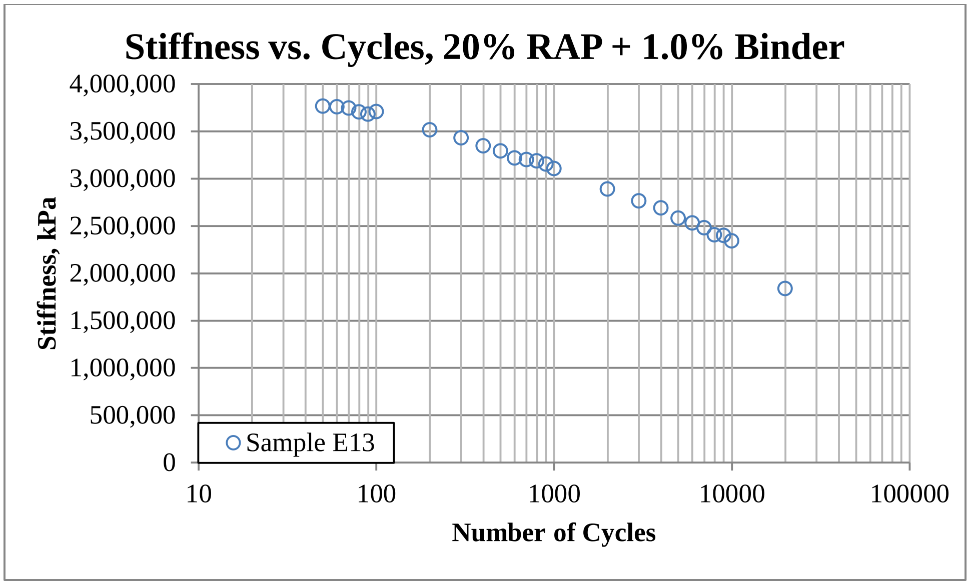

Figure D11. Fatigue Resistance Curve for Sample E13

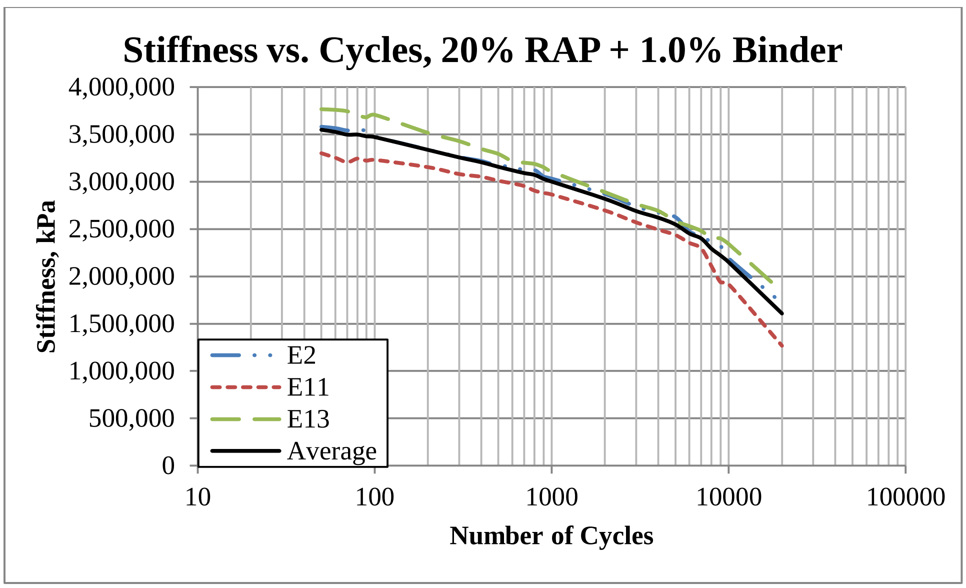

Figure D12. Fatigue Resistance Curve Summary for 20% RAP + 1.0% Binder

40% RAP + 0.0% Asphalt Binder

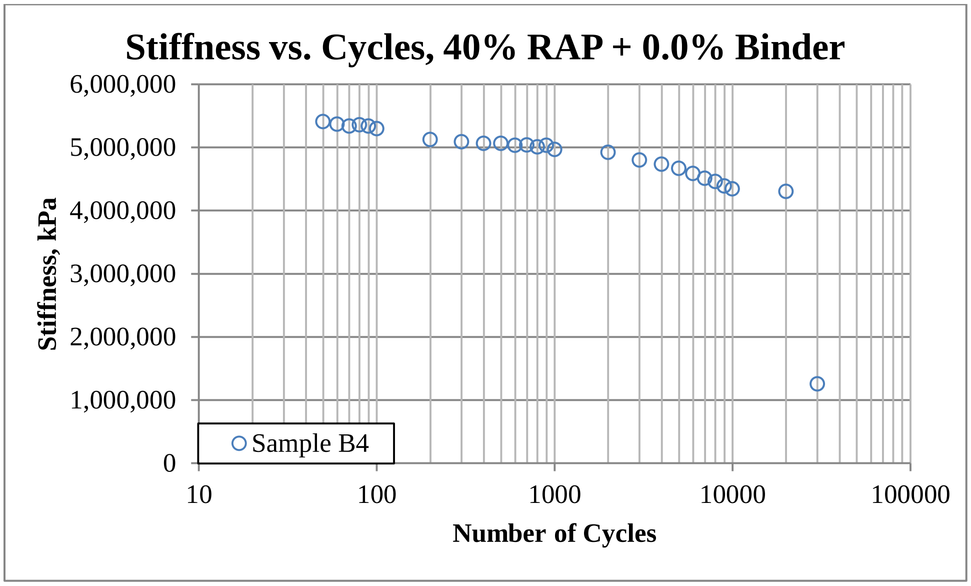

Figure D13. Fatigue Resistance Curve for Sample B4

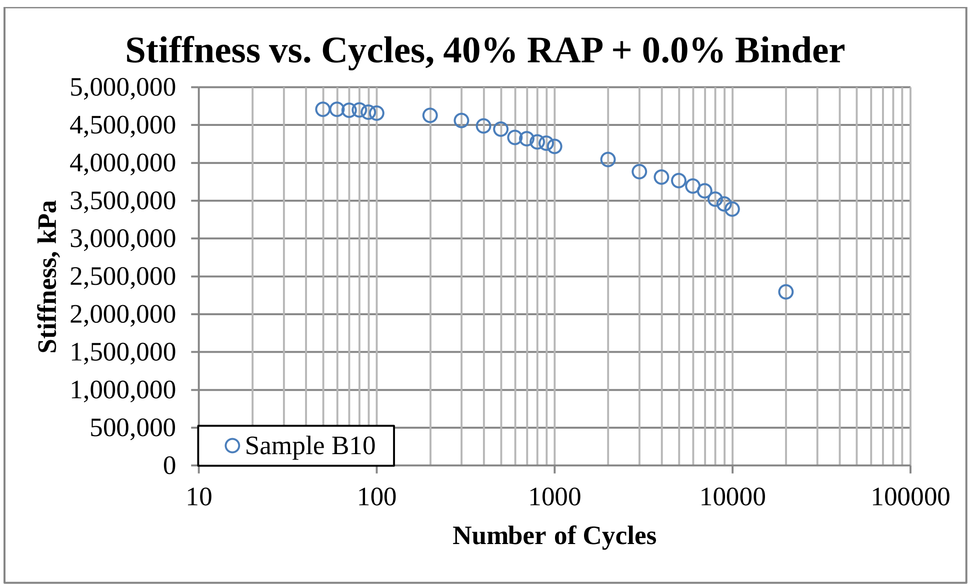

Figure D14. Fatigue Resistance Curve for Sample B10

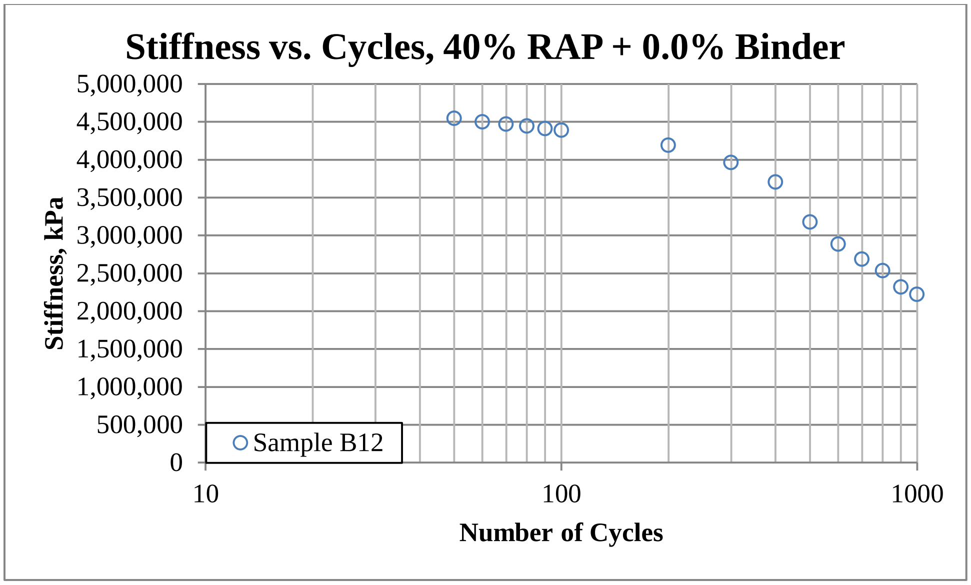

Figure D15. Fatigue Resistance Curve for Sample B12

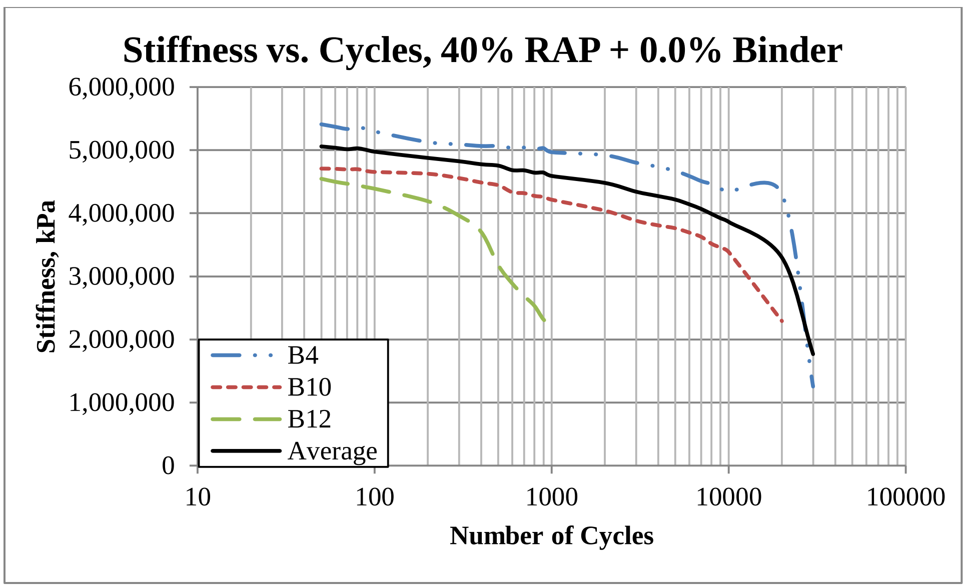

Figure D16. Fatigue Resistance Curve Summary for 40% RAP + 0.0% Binder

40% RAP + 0.5% Asphalt Binder

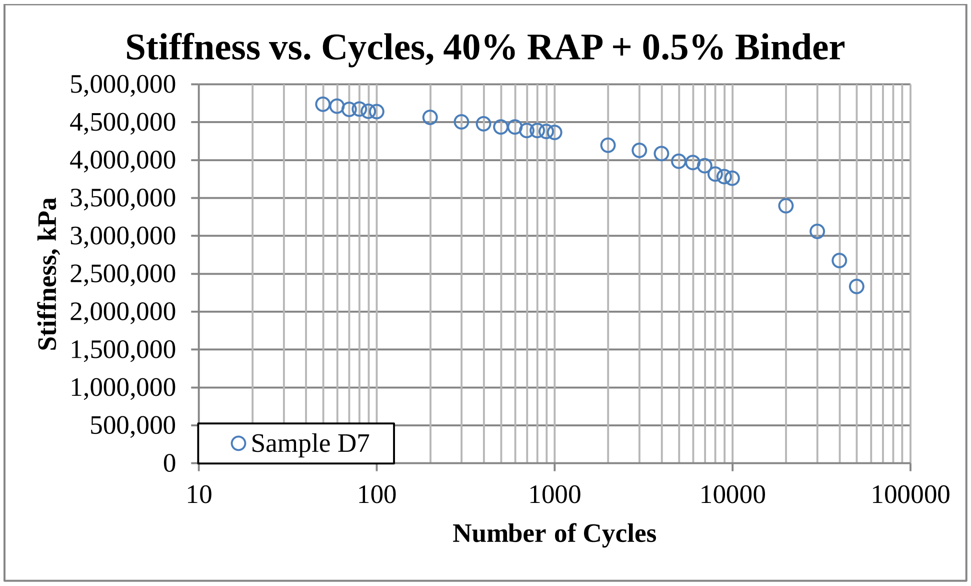

Figure D17. Fatigue Resistance Curve for Sample D7

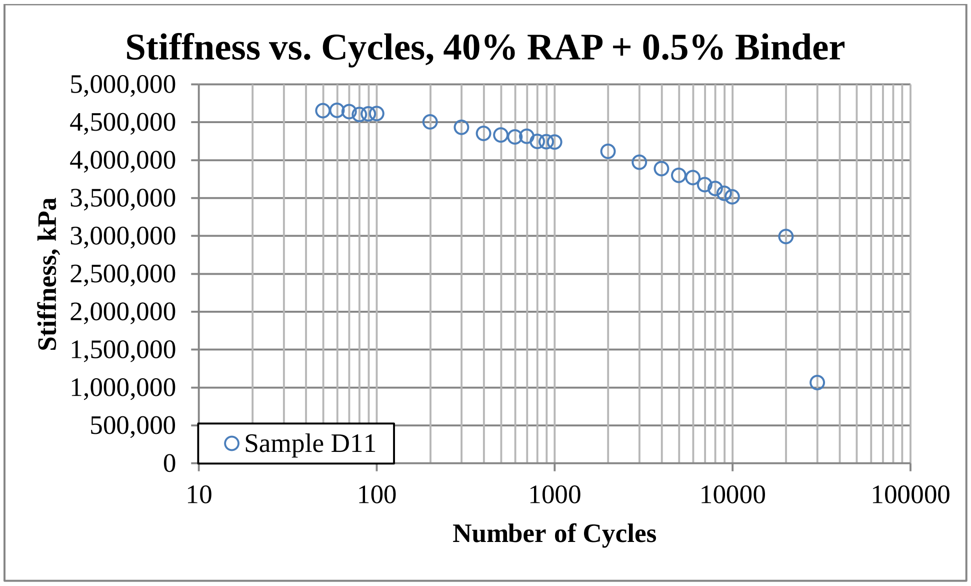

Figure D18. Fatigue Resistance Curve for Sample D11

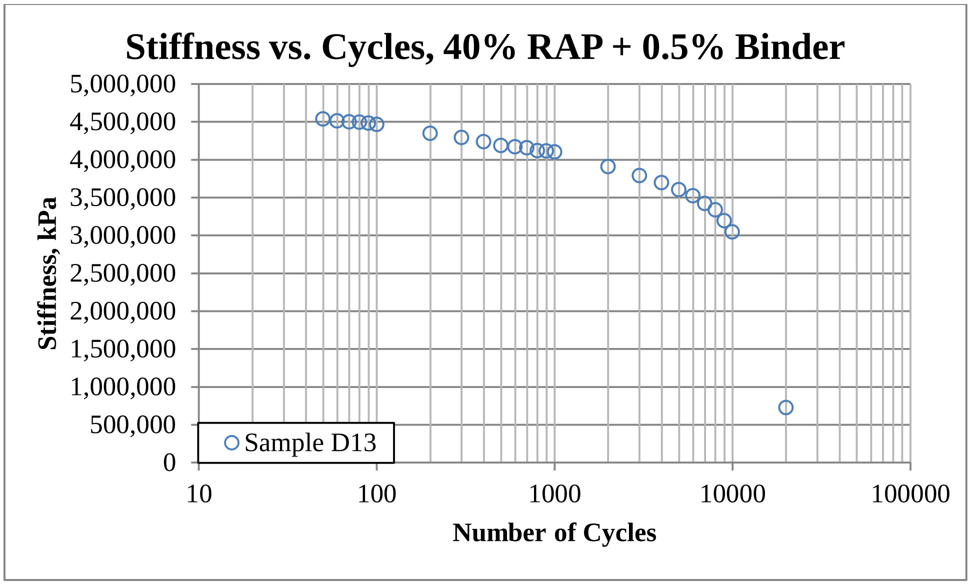

Figure D19. Fatigue Resistance Curve for Sample D13

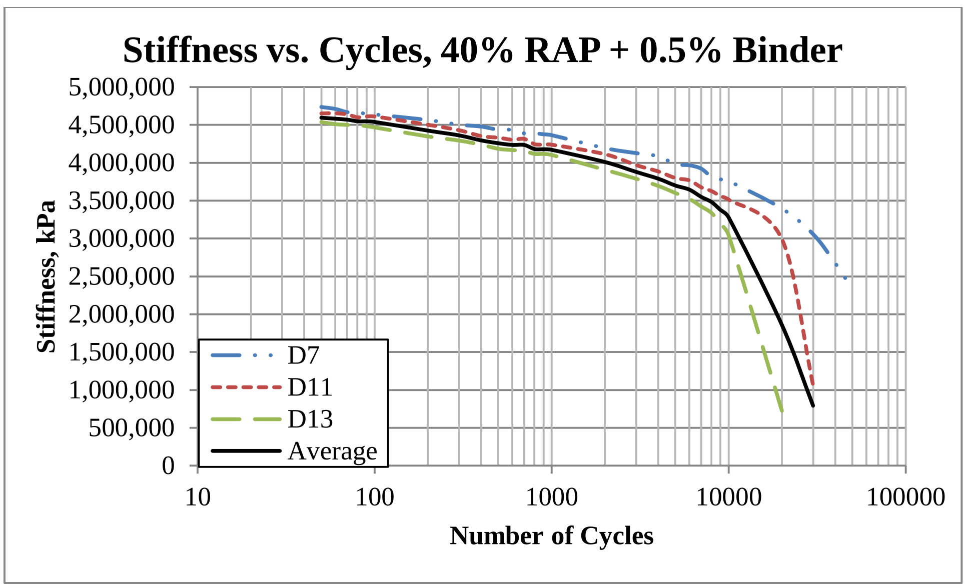

Figure D20. Fatigue Resistance Curve Summary for 40% RAP + 0.5% Binder

40% RAP + 1.0% Asphalt Binder

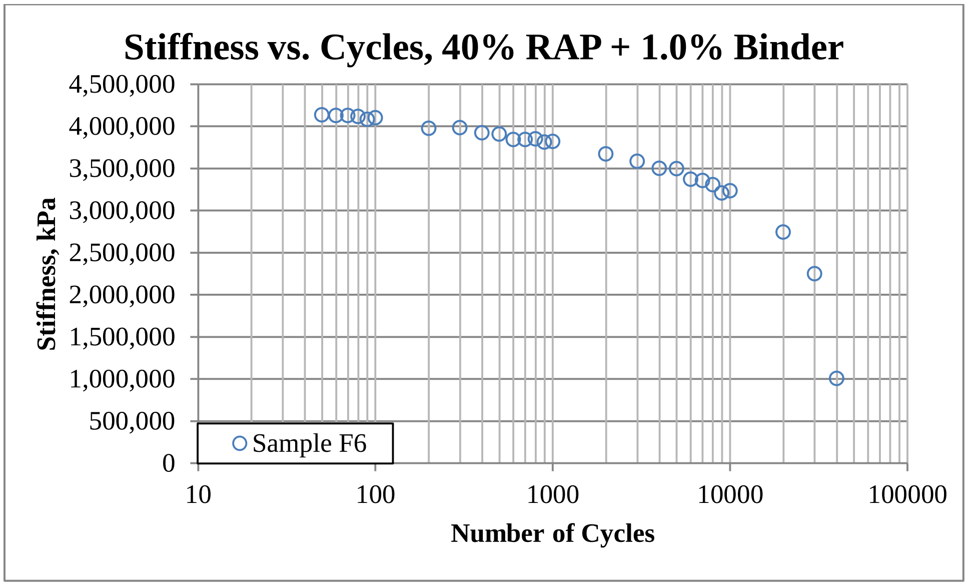

Figure D21. Fatigue Resistance Curve for Sample F6

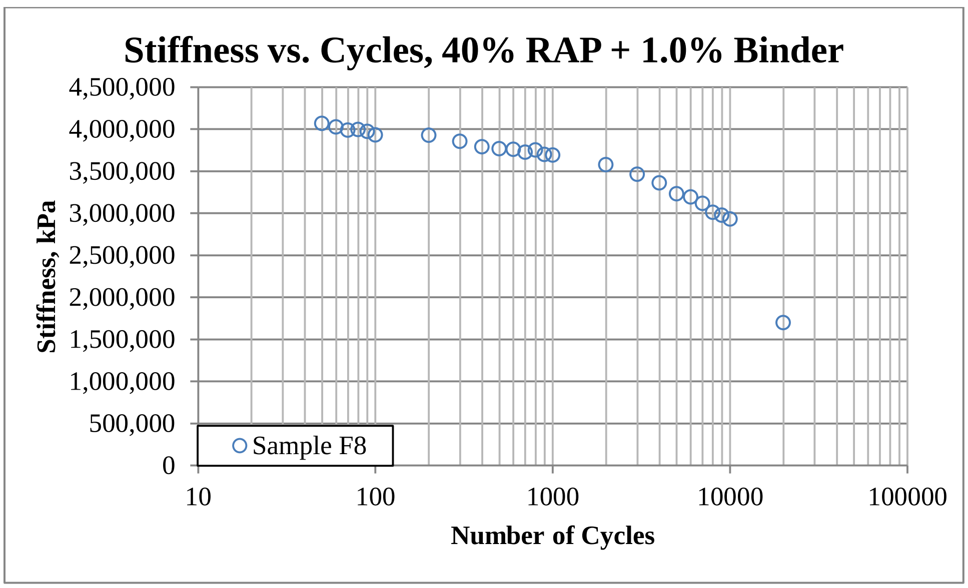

Figure D22. Fatigue Resistance Curve for Sample F8

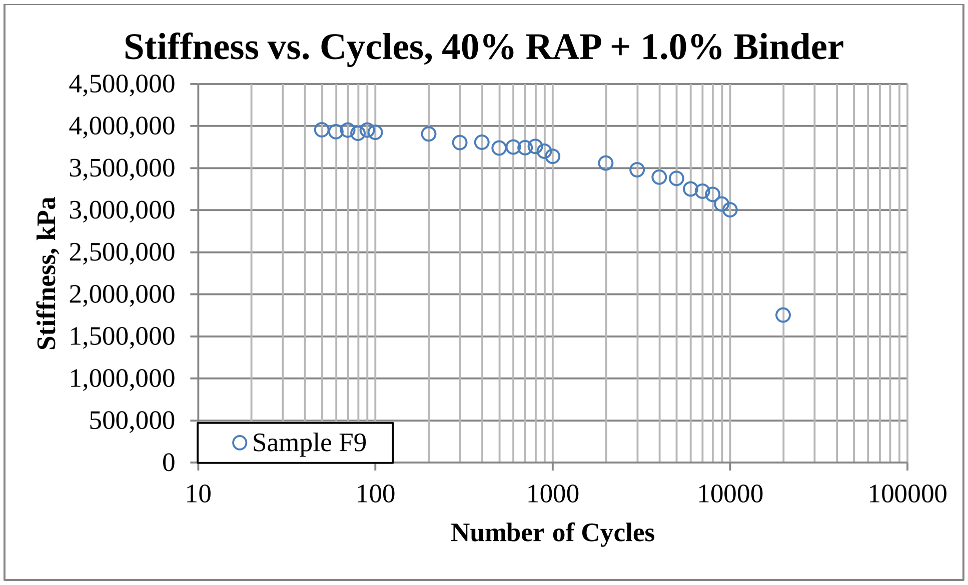

Figure D23. Fatigue Resistance Curve for Sample F9

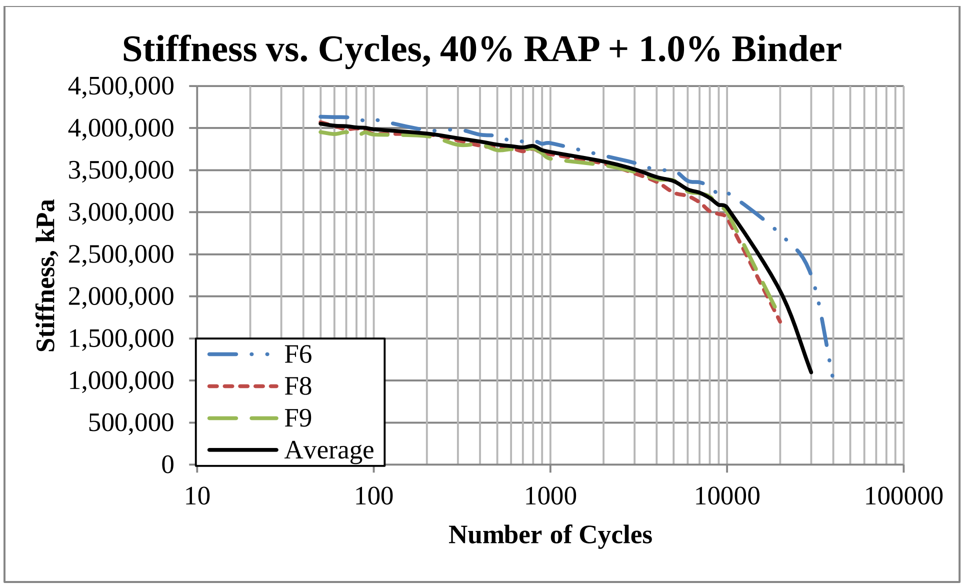

Figure D24. Fatigue Resistance Curve Summary for 40% RAP + 1.0% Binder

APPENDIX E – CODE FOR ANOVA MODELS GENERATED IN SAS

DYNAMIC MODULUS MODEL 1 – ALL VARIABLES INCLUDED

```
data chris;
input RAP Binder AV Temp Freq Dynamic;
lines;
20    0.0   7.097 4.4   25    15203560
20    0.0   7.097 4.4   10    13807400
20    0.0   7.097 4.4   5     12775390
20    0.0   7.097 4.4   1     10421700
20    0.0   7.097 4.4   0.5   9491330
20    0.0   7.097 4.4   0.1   7663377
20    0.0   7.097 21.1  25    7476950
20    0.0   7.097 21.1  10    6338979
20    0.0   7.097 21.1  5     5501687
20    0.0   7.097 21.1  1     3768255
20    0.0   7.097 21.1  0.5   3117140
20    0.0   7.097 21.1  0.1   2049077
20    0.0   7.097 37.8  25    3023102
20    0.0   7.097 37.8  10    2466335
20    0.0   7.097 37.8  5     1956014
20    0.0   7.097 37.8  1     1193350
20    0.0   7.097 37.8  0.5   890772
20    0.0   7.097 37.8  0.1   479878.3
20    0.0   7.097 54.4  25    1067756
20    0.0   7.097 54.4  10    798661.8
20    0.0   7.097 54.4  5     617971.3
20    0.0   7.097 54.4  1     406948.3
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20    0.0   7.097 54.4  0.1   178825.6
20    0.0   6.988 4.4   25    14814600
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20    0.0   6.988 21.1  5     5698855
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20    0.0   6.988 37.8  25    3117885
20    0.0   6.988 37.8  10    2553380
20    0.0   6.988 37.8  5     2009930
20    0.0   6.988 37.8  1     1218493
20    0.0   6.988 37.8  0.5   896417.7
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20    0.0   6.988 54.4  25    1075473
20    0.0   6.988 54.4  10    814346.4
20    0.0   6.988 54.4  5     631599.4
20    0.0   6.988 54.4  1     421035.9
20    0.0   6.988 54.4  0.5   317029
20    0.0   6.988 54.4  0.1   178287.7
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```

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40	0.0	6.984	37.8	1	1292676
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40	0.0	6.984	54.4	1	374525.3
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40	0.0	6.712	4.4	1	14084150
40	0.0	6.712	4.4	0.5	13007360
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40	0.0	6.712	21.1	10	8489806
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40	0.0	6.712	21.1	1	5352878

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40	0.0	6.910	21.1	10	8384277
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40	0.0	6.910	37.8	1	1651602
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20	0.5	7.108	21.1	10	6933731
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20	0.5	7.108	21.1	1	4235075
20	0.5	7.108	21.1	0.5	3553843
20	0.5	7.108	21.1	0.1	2345705
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20	0.5	7.108	37.8	1	1273394
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20	0.5	7.085	54.4	0.1	175669.4
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20	0.5	7.240	4.4	5	12069340
20	0.5	7.240	4.4	1	10067890
20	0.5	7.240	4.4	0.5	9191868
20	0.5	7.240	4.4	0.1	7230280
20	0.5	7.240	21.1	25	7417692
20	0.5	7.240	21.1	10	6206578
20	0.5	7.240	21.1	5	5405295
20	0.5	7.240	21.1	1	3735240
20	0.5	7.240	21.1	0.5	3118449
20	0.5	7.240	21.1	0.1	2029072
20	0.5	7.240	37.8	25	2921710
20	0.5	7.240	37.8	10	2389959
20	0.5	7.240	37.8	5	1907652
20	0.5	7.240	37.8	1	1149804
20	0.5	7.240	37.8	0.5	855168.9
20	0.5	7.240	37.8	0.1	450285.3
20	0.5	7.240	54.4	25	1003809
20	0.5	7.240	54.4	10	774787.3
20	0.5	7.240	54.4	5	596646.5
20	0.5	7.240	54.4	1	381639.6
20	0.5	7.240	54.4	0.5	286298.3
20	0.5	7.240	54.4	0.1	163035.3
40	0.5	6.940	4.4	25	15100220
40	0.5	6.940	4.4	10	14061870
40	0.5	6.940	4.4	5	13183500
40	0.5	6.940	4.4	1	11235030

40	0.5	6.940	4.4	0.5	10400930
40	0.5	6.940	4.4	0.1	8452107
40	0.5	6.940	21.1	25	8924171
40	0.5	6.940	21.1	10	8128123
40	0.5	6.940	21.1	5	7165611
40	0.5	6.940	21.1	1	5120797
40	0.5	6.940	21.1	0.5	4278306
40	0.5	6.940	21.1	0.1	2840326
40	0.5	6.940	37.8	25	3865241
40	0.5	6.940	37.8	10	3056461
40	0.5	6.940	37.8	5	2426134
40	0.5	6.940	37.8	1	1437342
40	0.5	6.940	37.8	0.5	1076392
40	0.5	6.940	37.8	0.1	564678.6
40	0.5	6.940	54.4	25	1251182
40	0.5	6.940	54.4	10	916329.3
40	0.5	6.940	54.4	5	700057
40	0.5	6.940	54.4	1	442929.4
40	0.5	6.940	54.4	0.5	330632.8
40	0.5	6.940	54.4	0.1	175438.8
40	0.5	7.212	4.4	25	14773540
40	0.5	7.212	4.4	10	13918850
40	0.5	7.212	4.4	5	13153940
40	0.5	7.212	4.4	1	11255200
40	0.5	7.212	4.4	0.5	10404880
40	0.5	7.212	4.4	0.1	8272175
40	0.5	7.212	21.1	25	8915632
40	0.5	7.212	21.1	10	7615568
40	0.5	7.212	21.1	5	6694374
40	0.5	7.212	21.1	1	4759560
40	0.5	7.212	21.1	0.5	3996445
40	0.5	7.212	21.1	0.1	2681281
40	0.5	7.212	37.8	25	3744486
40	0.5	7.212	37.8	10	3046660
40	0.5	7.212	37.8	5	2429156
40	0.5	7.212	37.8	1	1438780
40	0.5	7.212	37.8	0.5	1074068
40	0.5	7.212	37.8	0.1	557242.4
40	0.5	7.212	54.4	25	1250688
40	0.5	7.212	54.4	10	902311.8
40	0.5	7.212	54.4	5	680426.1
40	0.5	7.212	54.4	1	412614.5
40	0.5	7.212	54.4	0.5	305863.1
40	0.5	7.212	54.4	0.1	167459.9
40	0.5	7.281	4.4	25	16783790
40	0.5	7.281	4.4	10	15458530
40	0.5	7.281	4.4	5	14547420
40	0.5	7.281	4.4	1	12363910
40	0.5	7.281	4.4	0.5	11412360
40	0.5	7.281	4.4	0.1	9238208
40	0.5	7.281	21.1	25	9689014
40	0.5	7.281	21.1	10	8345093
40	0.5	7.281	21.1	5	7317507
40	0.5	7.281	21.1	1	5139790
40	0.5	7.281	21.1	0.5	4295665
40	0.5	7.281	21.1	0.1	2771017
40	0.5	7.281	37.8	25	3776680

40	0.5	7.281	37.8	10	3006151
40	0.5	7.281	37.8	5	2380441
40	0.5	7.281	37.8	1	1391326
40	0.5	7.281	37.8	0.5	1040495
40	0.5	7.281	37.8	0.1	542187.6
40	0.5	7.281	54.4	25	1259999
40	0.5	7.281	54.4	10	917272.9
40	0.5	7.281	54.4	5	699545.9
40	0.5	7.281	54.4	1	448962.1
40	0.5	7.281	54.4	0.5	339586.8
40	0.5	7.281	54.4	0.1	189329.6
20	1.0	7.122	4.4	25	15316110
20	1.0	7.122	4.4	10	13730180
20	1.0	7.122	4.4	5	12670840
20	1.0	7.122	4.4	1	10342550
20	1.0	7.122	4.4	0.5	9373985
20	1.0	7.122	4.4	0.1	7421304
20	1.0	7.122	21.1	25	6850845
20	1.0	7.122	21.1	10	5695608
20	1.0	7.122	21.1	5	4921223
20	1.0	7.122	21.1	1	3350821
20	1.0	7.122	21.1	0.5	2774065
20	1.0	7.122	21.1	0.1	1788773
20	1.0	7.122	37.8	25	2508677
20	1.0	7.122	37.8	10	2041658
20	1.0	7.122	37.8	5	1608504
20	1.0	7.122	37.8	1	975404.9
20	1.0	7.122	37.8	0.5	722109.3
20	1.0	7.122	37.8	0.1	386511.8
20	1.0	7.122	54.4	25	897667.5
20	1.0	7.122	54.4	10	684436.3
20	1.0	7.122	54.4	5	534769.8
20	1.0	7.122	54.4	1	357989.2
20	1.0	7.122	54.4	0.5	271232.9
20	1.0	7.122	54.4	0.1	153739.7
20	1.0	7.312	4.4	25	14446980
20	1.0	7.312	4.4	10	12962240
20	1.0	7.312	4.4	5	12036710
20	1.0	7.312	4.4	1	9961510
20	1.0	7.312	4.4	0.5	9075603
20	1.0	7.312	4.4	0.1	6957047
20	1.0	7.312	21.1	25	6600622
20	1.0	7.312	21.1	10	5631166
20	1.0	7.312	21.1	5	4906886
20	1.0	7.312	21.1	1	3363928
20	1.0	7.312	21.1	0.5	2779026
20	1.0	7.312	21.1	0.1	1824152
20	1.0	7.312	37.8	25	2552442
20	1.0	7.312	37.8	10	2096828
20	1.0	7.312	37.8	5	1652664
20	1.0	7.312	37.8	1	1007533
20	1.0	7.312	37.8	0.5	749476.5
20	1.0	7.312	37.8	0.1	401383.8
20	1.0	7.312	54.4	25	1002181
20	1.0	7.312	54.4	10	764829.4
20	1.0	7.312	54.4	5	599610.7
20	1.0	7.312	54.4	1	403156

20	1.0	7.312	54.4	0.5	309281
20	1.0	7.312	54.4	0.1	183791.3
20	1.0	6.834	4.4	25	14594950
20	1.0	6.834	4.4	10	12760940
20	1.0	6.834	4.4	5	11770750
20	1.0	6.834	4.4	1	9627110
20	1.0	6.834	4.4	0.5	8774351
20	1.0	6.834	4.4	0.1	7059234
20	1.0	6.834	21.1	25	6844171
20	1.0	6.834	21.1	10	5839750
20	1.0	6.834	21.1	5	5077053
20	1.0	6.834	21.1	1	3519724
20	1.0	6.834	21.1	0.5	2918894
20	1.0	6.834	21.1	0.1	1934183
20	1.0	6.834	37.8	25	2690257
20	1.0	6.834	37.8	10	2174512
20	1.0	6.834	37.8	5	1730249
20	1.0	6.834	37.8	1	1060270
20	1.0	6.834	37.8	0.5	793866.6
20	1.0	6.834	37.8	0.1	435479.9
20	1.0	6.834	54.4	25	944339.8
20	1.0	6.834	54.4	10	728146.2
20	1.0	6.834	54.4	5	569305.1
20	1.0	6.834	54.4	1	378191.7
20	1.0	6.834	54.4	0.5	288534.7
20	1.0	6.834	54.4	0.1	164856.3
40	1.0	7.181	4.4	25	14577700
40	1.0	7.181	4.4	10	13404830
40	1.0	7.181	4.4	5	12488940
40	1.0	7.181	4.4	1	10446810
40	1.0	7.181	4.4	0.5	9549629
40	1.0	7.181	4.4	0.1	7626732
40	1.0	7.181	21.1	25	8139616
40	1.0	7.181	21.1	10	6861174
40	1.0	7.181	21.1	5	6005289
40	1.0	7.181	21.1	1	4194261
40	1.0	7.181	21.1	0.5	3497647
40	1.0	7.181	21.1	0.1	2257587
40	1.0	7.181	37.8	25	3207291
40	1.0	7.181	37.8	10	2561096
40	1.0	7.181	37.8	5	2021989
40	1.0	7.181	37.8	1	1189432
40	1.0	7.181	37.8	0.5	887870.6
40	1.0	7.181	37.8	0.1	466249.6
40	1.0	7.181	54.4	25	1077506
40	1.0	7.181	54.4	10	786506.7
40	1.0	7.181	54.4	5	598409.6
40	1.0	7.181	54.4	1	377976.7
40	1.0	7.181	54.4	0.5	281482.4
40	1.0	7.181	54.4	0.1	154439.7
40	1.0	7.059	4.4	25	13483690
40	1.0	7.059	4.4	10	12421330
40	1.0	7.059	4.4	5	11598060
40	1.0	7.059	4.4	1	9624933
40	1.0	7.059	4.4	0.5	8761047
40	1.0	7.059	4.4	0.1	6741554
40	1.0	7.059	21.1	25	7559781

```
40    1.0   7.059 21.1  10    6526069
40    1.0   7.059 21.1  5     5649490
40    1.0   7.059 21.1  1     3807209
40    1.0   7.059 21.1  0.5   3103064
40    1.0   7.059 21.1  0.1   1922810
40    1.0   7.059 37.8  25    3018493
40    1.0   7.059 37.8  10    2270850
40    1.0   7.059 37.8  5     1718123
40    1.0   7.059 37.8  1     989568.1
40    1.0   7.059 37.8  0.5   712413.8
40    1.0   7.059 37.8  0.1   363428
40    1.0   7.059 54.4  25    876913.7
40    1.0   7.059 54.4  10    622168.6
40    1.0   7.059 54.4  5     468998.2
40    1.0   7.059 54.4  1     303639.3
40    1.0   7.059 54.4  0.5   229141.5
40    1.0   7.059 54.4  0.1   137500.3
40    1.0   7.116 4.4   25    13890890
40    1.0   7.116 4.4   10    12673960
40    1.0   7.116 4.4   5     11779510
40    1.0   7.116 4.4   1     9751983
40    1.0   7.116 4.4   0.5   8887397
40    1.0   7.116 4.4   0.1   6979866
40    1.0   7.116 21.1  25    7334794
40    1.0   7.116 21.1  10    6233135
40    1.0   7.116 21.1  5     5401681
40    1.0   7.116 21.1  1     3678859
40    1.0   7.116 21.1  0.5   3011772
40    1.0   7.116 21.1  0.1   1898187
40    1.0   7.116 37.8  25    2800959
40    1.0   7.116 37.8  10    2195396
40    1.0   7.116 37.8  5     1690374
40    1.0   7.116 37.8  1     1090093
40    1.0   7.116 37.8  0.5   1013508
40    1.0   7.116 37.8  0.1   530232.8
40    1.0   7.116 54.4  25    861320.6
40    1.0   7.116 54.4  10    627480.4
40    1.0   7.116 54.4  5     474204.7
40    1.0   7.116 54.4  1     310980.6
40    1.0   7.116 54.4  0.5   233230.6
40    1.0   7.116 54.4  0.1   134770.7
;
run;
proc reg data= chris;
model Dynamic = RAP Binder AV Temp Freq/clb clm cli;
plot npp.*predicted. rstudent.*predicted. rstudent.*RAP rstudent.*Binder
rstudent.*AV rstudent.*Temp rstudent.*Freq;
run;
```

DYNAMIC MODULUS MODEL 2 – AV CONTENT EXCLUDED

```
data chris;
input RAP Binder AV Temp Freq Dynamic;
lines;
20    0.0   7.097 4.4   25    15203560
20    0.0   7.097 4.4   10    13807400
20    0.0   7.097 4.4   5     12775390
```

20	0.0	7.097	4.4	1	10421700
20	0.0	7.097	4.4	0.5	9491330
20	0.0	7.097	4.4	0.1	7663377
20	0.0	7.097	21.1	25	7476950
20	0.0	7.097	21.1	10	6338979
20	0.0	7.097	21.1	5	5501687
20	0.0	7.097	21.1	1	3768255
20	0.0	7.097	21.1	0.5	3117140
20	0.0	7.097	21.1	0.1	2049077
20	0.0	7.097	37.8	25	3023102
20	0.0	7.097	37.8	10	2466335
20	0.0	7.097	37.8	5	1956014
20	0.0	7.097	37.8	1	1193350
20	0.0	7.097	37.8	0.5	890772
20	0.0	7.097	37.8	0.1	479878.3
20	0.0	7.097	54.4	25	1067756
20	0.0	7.097	54.4	10	798661.8
20	0.0	7.097	54.4	5	617971.3
20	0.0	7.097	54.4	1	406948.3
20	0.0	7.097	54.4	0.5	308327.8
20	0.0	7.097	54.4	0.1	178825.6
20	0.0	6.988	4.4	25	14814600
20	0.0	6.988	4.4	10	13722180
20	0.0	6.988	4.4	5	12793180
20	0.0	6.988	4.4	1	10632990
20	0.0	6.988	4.4	0.5	9689905
20	0.0	6.988	4.4	0.1	7617999
20	0.0	6.988	21.1	25	7760770
20	0.0	6.988	21.1	10	6551294
20	0.0	6.988	21.1	5	5698855
20	0.0	6.988	21.1	1	3908530
20	0.0	6.988	21.1	0.5	3226646
20	0.0	6.988	21.1	0.1	2117885
20	0.0	6.988	37.8	25	3117885
20	0.0	6.988	37.8	10	2553380
20	0.0	6.988	37.8	5	2009930
20	0.0	6.988	37.8	1	1218493
20	0.0	6.988	37.8	0.5	896417.7
20	0.0	6.988	37.8	0.1	471563.1
20	0.0	6.988	54.4	25	1075473
20	0.0	6.988	54.4	10	814346.4
20	0.0	6.988	54.4	5	631599.4
20	0.0	6.988	54.4	1	421035.9
20	0.0	6.988	54.4	0.5	317029
20	0.0	6.988	54.4	0.1	178287.7
20	0.0	6.888	4.4	25	14474900
20	0.0	6.888	4.4	10	13362660
20	0.0	6.888	4.4	5	12428200
20	0.0	6.888	4.4	1	10346950
20	0.0	6.888	4.4	0.5	9449068
20	0.0	6.888	4.4	0.1	7448538
20	0.0	6.888	21.1	25	7621622
20	0.0	6.888	21.1	10	6471606
20	0.0	6.888	21.1	5	5652243
20	0.0	6.888	21.1	1	3929402
20	0.0	6.888	21.1	0.5	3266322
20	0.0	6.888	21.1	0.1	2167422

20	0.0	6.888	37.8	25	3010382
20	0.0	6.888	37.8	10	2463424
20	0.0	6.888	37.8	5	1965983
20	0.0	6.888	37.8	1	1217936
20	0.0	6.888	37.8	0.5	913153.9
20	0.0	6.888	37.8	0.1	494431
20	0.0	6.888	54.4	25	1089014
20	0.0	6.888	54.4	10	828598.3
20	0.0	6.888	54.4	5	644874
20	0.0	6.888	54.4	1	432432.9
20	0.0	6.888	54.4	0.5	330171.6
20	0.0	6.888	54.4	0.1	195084.3
40	0.0	6.984	4.4	25	15477100
40	0.0	6.984	4.4	10	14098200
40	0.0	6.984	4.4	5	13212440
40	0.0	6.984	4.4	1	11144940
40	0.0	6.984	4.4	0.5	10259970
40	0.0	6.984	4.4	0.1	8287945
40	0.0	6.984	21.1	25	8030882
40	0.0	6.984	21.1	10	7019919
40	0.0	6.984	21.1	5	6165654
40	0.0	6.984	21.1	1	4373991
40	0.0	6.984	21.1	0.5	3630094
40	0.0	6.984	21.1	0.1	2397416
40	0.0	6.984	37.8	25	3493310
40	0.0	6.984	37.8	10	2786261
40	0.0	6.984	37.8	5	2189222
40	0.0	6.984	37.8	1	1292676
40	0.0	6.984	37.8	0.5	943384.4
40	0.0	6.984	37.8	0.1	475358.5
40	0.0	6.984	54.4	25	1119026
40	0.0	6.984	54.4	10	809056.2
40	0.0	6.984	54.4	5	607219.3
40	0.0	6.984	54.4	1	374525.3
40	0.0	6.984	54.4	0.5	277541
40	0.0	6.984	54.4	0.1	152770.7
40	0.0	6.712	4.4	25	18915240
40	0.0	6.712	4.4	10	17646290
40	0.0	6.712	4.4	5	16624270
40	0.0	6.712	4.4	1	14084150
40	0.0	6.712	4.4	0.5	13007360
40	0.0	6.712	4.4	0.1	10385280
40	0.0	6.712	21.1	25	9708535
40	0.0	6.712	21.1	10	8489806
40	0.0	6.712	21.1	5	7488101
40	0.0	6.712	21.1	1	5352878
40	0.0	6.712	21.1	0.5	4455481
40	0.0	6.712	21.1	0.1	2984683
40	0.0	6.712	37.8	25	4364432
40	0.0	6.712	37.8	10	3470013
40	0.0	6.712	37.8	5	2745969
40	0.0	6.712	37.8	1	1619180
40	0.0	6.712	37.8	0.5	1194503
40	0.0	6.712	37.8	0.1	620670
40	0.0	6.712	54.4	25	1370637
40	0.0	6.712	54.4	10	993937.3
40	0.0	6.712	54.4	5	757037.5

40	0.0	6.712	54.4	1	484259.9
40	0.0	6.712	54.4	0.5	363096.2
40	0.0	6.712	54.4	0.1	198652.2
40	0.0	6.910	4.4	25	16150780
40	0.0	6.910	4.4	10	14965780
40	0.0	6.910	4.4	5	14140280
40	0.0	6.910	4.4	1	12102770
40	0.0	6.910	4.4	0.5	11221460
40	0.0	6.910	4.4	0.1	9087435
40	0.0	6.910	21.1	25	9480426
40	0.0	6.910	21.1	10	8384277
40	0.0	6.910	21.1	5	7443254
40	0.0	6.910	21.1	1	5396112
40	0.0	6.910	21.1	0.5	4546514
40	0.0	6.910	21.1	0.1	3073492
40	0.0	6.910	37.8	25	4223784
40	0.0	6.910	37.8	10	3439699
40	0.0	6.910	37.8	5	2749137
40	0.0	6.910	37.8	1	1651602
40	0.0	6.910	37.8	0.5	1230717
40	0.0	6.910	37.8	0.1	648426.8
40	0.0	6.910	54.4	25	1368021
40	0.0	6.910	54.4	10	998715.1
40	0.0	6.910	54.4	5	756270.1
40	0.0	6.910	54.4	1	619567.8
40	0.0	6.910	54.4	0.5	514725.1
40	0.0	6.910	54.4	0.1	272485.6
20	0.5	7.108	4.4	25	16233230
20	0.5	7.108	4.4	10	14727320
20	0.5	7.108	4.4	5	13737560
20	0.5	7.108	4.4	1	11493530
20	0.5	7.108	4.4	0.5	10538160
20	0.5	7.108	4.4	0.1	8375242
20	0.5	7.108	21.1	25	8286523
20	0.5	7.108	21.1	10	6933731
20	0.5	7.108	21.1	5	6045691
20	0.5	7.108	21.1	1	4235075
20	0.5	7.108	21.1	0.5	3553843
20	0.5	7.108	21.1	0.1	2345705
20	0.5	7.108	37.8	25	3233444
20	0.5	7.108	37.8	10	2611278
20	0.5	7.108	37.8	5	2101016
20	0.5	7.108	37.8	1	1273394
20	0.5	7.108	37.8	0.5	955170.6
20	0.5	7.108	37.8	0.1	520484.7
20	0.5	7.108	54.4	25	1268354
20	0.5	7.108	54.4	10	987407.1
20	0.5	7.108	54.4	5	770075.8
20	0.5	7.108	54.4	1	498857.5
20	0.5	7.108	54.4	0.5	373450.3
20	0.5	7.108	54.4	0.1	217309.2
20	0.5	7.085	4.4	25	13909860
20	0.5	7.085	4.4	10	12655280
20	0.5	7.085	4.4	5	11760210
20	0.5	7.085	4.4	1	9724723
20	0.5	7.085	4.4	0.5	8876894
20	0.5	7.085	4.4	0.1	7121070

20	0.5	7.085	21.1	25	6821028
20	0.5	7.085	21.1	10	5845539
20	0.5	7.085	21.1	5	5106825
20	0.5	7.085	21.1	1	3570992
20	0.5	7.085	21.1	0.5	2962841
20	0.5	7.085	21.1	0.1	2018302
20	0.5	7.085	37.8	25	2973642
20	0.5	7.085	37.8	10	2446290
20	0.5	7.085	37.8	5	1961020
20	0.5	7.085	37.8	1	1205847
20	0.5	7.085	37.8	0.5	904505.9
20	0.5	7.085	37.8	0.1	492080.3
20	0.5	7.085	54.4	25	1098130
20	0.5	7.085	54.4	10	836930.9
20	0.5	7.085	54.4	5	653337.1
20	0.5	7.085	54.4	1	420429.8
20	0.5	7.085	54.4	0.5	317553.7
20	0.5	7.085	54.4	0.1	175669.4
20	0.5	7.240	4.4	25	14250290
20	0.5	7.240	4.4	10	12951350
20	0.5	7.240	4.4	5	12069340
20	0.5	7.240	4.4	1	10067890
20	0.5	7.240	4.4	0.5	9191868
20	0.5	7.240	4.4	0.1	7230280
20	0.5	7.240	21.1	25	7417692
20	0.5	7.240	21.1	10	6206578
20	0.5	7.240	21.1	5	5405295
20	0.5	7.240	21.1	1	3735240
20	0.5	7.240	21.1	0.5	3118449
20	0.5	7.240	21.1	0.1	2029072
20	0.5	7.240	37.8	25	2921710
20	0.5	7.240	37.8	10	2389959
20	0.5	7.240	37.8	5	1907652
20	0.5	7.240	37.8	1	1149804
20	0.5	7.240	37.8	0.5	855168.9
20	0.5	7.240	37.8	0.1	450285.3
20	0.5	7.240	54.4	25	1003809
20	0.5	7.240	54.4	10	774787.3
20	0.5	7.240	54.4	5	596646.5
20	0.5	7.240	54.4	1	381639.6
20	0.5	7.240	54.4	0.5	286298.3
20	0.5	7.240	54.4	0.1	163035.3
40	0.5	6.940	4.4	25	15100220
40	0.5	6.940	4.4	10	14061870
40	0.5	6.940	4.4	5	13183500
40	0.5	6.940	4.4	1	11235030
40	0.5	6.940	4.4	0.5	10400930
40	0.5	6.940	4.4	0.1	8452107
40	0.5	6.940	21.1	25	8924171
40	0.5	6.940	21.1	10	8128123
40	0.5	6.940	21.1	5	7165611
40	0.5	6.940	21.1	1	5120797
40	0.5	6.940	21.1	0.5	4278306
40	0.5	6.940	21.1	0.1	2840326
40	0.5	6.940	37.8	25	3865241
40	0.5	6.940	37.8	10	3056461
40	0.5	6.940	37.8	5	2426134

40	0.5	6.940	37.8	1	1437342
40	0.5	6.940	37.8	0.5	1076392
40	0.5	6.940	37.8	0.1	564678.6
40	0.5	6.940	54.4	25	1251182
40	0.5	6.940	54.4	10	916329.3
40	0.5	6.940	54.4	5	700057
40	0.5	6.940	54.4	1	442929.4
40	0.5	6.940	54.4	0.5	330632.8
40	0.5	6.940	54.4	0.1	175438.8
40	0.5	7.212	4.4	25	14773540
40	0.5	7.212	4.4	10	13918850
40	0.5	7.212	4.4	5	13153940
40	0.5	7.212	4.4	1	11255200
40	0.5	7.212	4.4	0.5	10404880
40	0.5	7.212	4.4	0.1	8272175
40	0.5	7.212	21.1	25	8915632
40	0.5	7.212	21.1	10	7615568
40	0.5	7.212	21.1	5	6694374
40	0.5	7.212	21.1	1	4759560
40	0.5	7.212	21.1	0.5	3996445
40	0.5	7.212	21.1	0.1	2681281
40	0.5	7.212	37.8	25	3744486
40	0.5	7.212	37.8	10	3046660
40	0.5	7.212	37.8	5	2429156
40	0.5	7.212	37.8	1	1438780
40	0.5	7.212	37.8	0.5	1074068
40	0.5	7.212	37.8	0.1	557242.4
40	0.5	7.212	54.4	25	1250688
40	0.5	7.212	54.4	10	902311.8
40	0.5	7.212	54.4	5	680426.1
40	0.5	7.212	54.4	1	412614.5
40	0.5	7.212	54.4	0.5	305863.1
40	0.5	7.212	54.4	0.1	167459.9
40	0.5	7.281	4.4	25	16783790
40	0.5	7.281	4.4	10	15458530
40	0.5	7.281	4.4	5	14547420
40	0.5	7.281	4.4	1	12363910
40	0.5	7.281	4.4	0.5	11412360
40	0.5	7.281	4.4	0.1	9238208
40	0.5	7.281	21.1	25	9689014
40	0.5	7.281	21.1	10	8345093
40	0.5	7.281	21.1	5	7317507
40	0.5	7.281	21.1	1	5139790
40	0.5	7.281	21.1	0.5	4295665
40	0.5	7.281	21.1	0.1	2771017
40	0.5	7.281	37.8	25	3776680
40	0.5	7.281	37.8	10	3006151
40	0.5	7.281	37.8	5	2380441
40	0.5	7.281	37.8	1	1391326
40	0.5	7.281	37.8	0.5	1040495
40	0.5	7.281	37.8	0.1	542187.6
40	0.5	7.281	54.4	25	1259999
40	0.5	7.281	54.4	10	917272.9
40	0.5	7.281	54.4	5	699545.9
40	0.5	7.281	54.4	1	448962.1
40	0.5	7.281	54.4	0.5	339586.8
40	0.5	7.281	54.4	0.1	189329.6

20	1.0	7.122	4.4	25	15316110
20	1.0	7.122	4.4	10	13730180
20	1.0	7.122	4.4	5	12670840
20	1.0	7.122	4.4	1	10342550
20	1.0	7.122	4.4	0.5	9373985
20	1.0	7.122	4.4	0.1	7421304
20	1.0	7.122	21.1	25	6850845
20	1.0	7.122	21.1	10	5695608
20	1.0	7.122	21.1	5	4921223
20	1.0	7.122	21.1	1	3350821
20	1.0	7.122	21.1	0.5	2774065
20	1.0	7.122	21.1	0.1	1788773
20	1.0	7.122	37.8	25	2508677
20	1.0	7.122	37.8	10	2041658
20	1.0	7.122	37.8	5	1608504
20	1.0	7.122	37.8	1	975404.9
20	1.0	7.122	37.8	0.5	722109.3
20	1.0	7.122	37.8	0.1	386511.8
20	1.0	7.122	54.4	25	897667.5
20	1.0	7.122	54.4	10	684436.3
20	1.0	7.122	54.4	5	534769.8
20	1.0	7.122	54.4	1	357989.2
20	1.0	7.122	54.4	0.5	271232.9
20	1.0	7.122	54.4	0.1	153739.7
20	1.0	7.312	4.4	25	14446980
20	1.0	7.312	4.4	10	12962240
20	1.0	7.312	4.4	5	12036710
20	1.0	7.312	4.4	1	9961510
20	1.0	7.312	4.4	0.5	9075603
20	1.0	7.312	4.4	0.1	6957047
20	1.0	7.312	21.1	25	6600622
20	1.0	7.312	21.1	10	5631166
20	1.0	7.312	21.1	5	4906886
20	1.0	7.312	21.1	1	3363928
20	1.0	7.312	21.1	0.5	2779026
20	1.0	7.312	21.1	0.1	1824152
20	1.0	7.312	37.8	25	2552442
20	1.0	7.312	37.8	10	2096828
20	1.0	7.312	37.8	5	1652664
20	1.0	7.312	37.8	1	1007533
20	1.0	7.312	37.8	0.5	749476.5
20	1.0	7.312	37.8	0.1	401383.8
20	1.0	7.312	54.4	25	1002181
20	1.0	7.312	54.4	10	764829.4
20	1.0	7.312	54.4	5	599610.7
20	1.0	7.312	54.4	1	403156
20	1.0	7.312	54.4	0.5	309281
20	1.0	7.312	54.4	0.1	183791.3
20	1.0	6.834	4.4	25	14594950
20	1.0	6.834	4.4	10	12760940
20	1.0	6.834	4.4	5	11770750
20	1.0	6.834	4.4	1	9627110
20	1.0	6.834	4.4	0.5	8774351
20	1.0	6.834	4.4	0.1	7059234
20	1.0	6.834	21.1	25	6844171
20	1.0	6.834	21.1	10	5839750
20	1.0	6.834	21.1	5	5077053

20	1.0	6.834	21.1	1	3519724
20	1.0	6.834	21.1	0.5	2918894
20	1.0	6.834	21.1	0.1	1934183
20	1.0	6.834	37.8	25	2690257
20	1.0	6.834	37.8	10	2174512
20	1.0	6.834	37.8	5	1730249
20	1.0	6.834	37.8	1	1060270
20	1.0	6.834	37.8	0.5	793866.6
20	1.0	6.834	37.8	0.1	435479.9
20	1.0	6.834	54.4	25	944339.8
20	1.0	6.834	54.4	10	728146.2
20	1.0	6.834	54.4	5	569305.1
20	1.0	6.834	54.4	1	378191.7
20	1.0	6.834	54.4	0.5	288534.7
20	1.0	6.834	54.4	0.1	164856.3
40	1.0	7.181	4.4	25	14577700
40	1.0	7.181	4.4	10	13404830
40	1.0	7.181	4.4	5	12488940
40	1.0	7.181	4.4	1	10446810
40	1.0	7.181	4.4	0.5	9549629
40	1.0	7.181	4.4	0.1	7626732
40	1.0	7.181	21.1	25	8139616
40	1.0	7.181	21.1	10	6861174
40	1.0	7.181	21.1	5	6005289
40	1.0	7.181	21.1	1	4194261
40	1.0	7.181	21.1	0.5	3497647
40	1.0	7.181	21.1	0.1	2257587
40	1.0	7.181	37.8	25	3207291
40	1.0	7.181	37.8	10	2561096
40	1.0	7.181	37.8	5	2021989
40	1.0	7.181	37.8	1	1189432
40	1.0	7.181	37.8	0.5	887870.6
40	1.0	7.181	37.8	0.1	466249.6
40	1.0	7.181	54.4	25	1077506
40	1.0	7.181	54.4	10	786506.7
40	1.0	7.181	54.4	5	598409.6
40	1.0	7.181	54.4	1	377976.7
40	1.0	7.181	54.4	0.5	281482.4
40	1.0	7.181	54.4	0.1	154439.7
40	1.0	7.059	4.4	25	13483690
40	1.0	7.059	4.4	10	12421330
40	1.0	7.059	4.4	5	11598060
40	1.0	7.059	4.4	1	9624933
40	1.0	7.059	4.4	0.5	8761047
40	1.0	7.059	4.4	0.1	6741554
40	1.0	7.059	21.1	25	7559781
40	1.0	7.059	21.1	10	6526069
40	1.0	7.059	21.1	5	5649490
40	1.0	7.059	21.1	1	3807209
40	1.0	7.059	21.1	0.5	3103064
40	1.0	7.059	21.1	0.1	1922810
40	1.0	7.059	37.8	25	3018493
40	1.0	7.059	37.8	10	2270850
40	1.0	7.059	37.8	5	1718123
40	1.0	7.059	37.8	1	989568.1
40	1.0	7.059	37.8	0.5	712413.8
40	1.0	7.059	37.8	0.1	363428

```
40    1.0   7.059 54.4  25    876913.7
40    1.0   7.059 54.4  10    622168.6
40    1.0   7.059 54.4  5     468998.2
40    1.0   7.059 54.4  1     303639.3
40    1.0   7.059 54.4  0.5   229141.5
40    1.0   7.059 54.4  0.1   137500.3
40    1.0   7.116 4.4   25    13890890
40    1.0   7.116 4.4   10    12673960
40    1.0   7.116 4.4   5     11779510
40    1.0   7.116 4.4   1     9751983
40    1.0   7.116 4.4   0.5   8887397
40    1.0   7.116 4.4   0.1   6979866
40    1.0   7.116 21.1  25    7334794
40    1.0   7.116 21.1  10    6233135
40    1.0   7.116 21.1  5     5401681
40    1.0   7.116 21.1  1     3678859
40    1.0   7.116 21.1  0.5   3011772
40    1.0   7.116 21.1  0.1   1898187
40    1.0   7.116 37.8  25    2800959
40    1.0   7.116 37.8  10    2195396
40    1.0   7.116 37.8  5     1690374
40    1.0   7.116 37.8  1     1090093
40    1.0   7.116 37.8  0.5   1013508
40    1.0   7.116 37.8  0.1   530232.8
40    1.0   7.116 54.4  25    861320.6
40    1.0   7.116 54.4  10    627480.4
40    1.0   7.116 54.4  5     474204.7
40    1.0   7.116 54.4  1     310980.6
40    1.0   7.116 54.4  0.5   233230.6
40    1.0   7.116 54.4  0.1   134770.7
;
run;
proc reg data= chris;
model Dynamic = RAP Binder Temp Freq/clb clm cli;
plot npp.*predicted. rstudent.*predicted. rstudent.*RAP rstudent.*Binder
rstudent.*Temp rstudent.*Freq;
run;
```

FATIGUE RESISTANCE MODEL 1 – ALL VARIABLES INCLUDED

```
data chris;
input RAP Binder AV Fatigue Stiffness;
lines;
20    0.0   7.013 5532  4694554
20    0.0   6.852 6127  4377783
20    0.0   7.080 1526  3948662
40    0.0   6.870 25245 5409662
40    0.0   6.923 19434 4707912
40    0.0   6.568 936   4546491
20    0.5   7.377 16271 4330386
20    0.5   6.934 14696 4295519
20    0.5   6.555 8338  4373932
40    0.5   6.517 48978 4745985
40    0.5   6.965 23457 4653756
40    0.5   7.002 13342 4540170
20    1.0   6.509 18451 3612231
20    1.0   6.542 14104 3342464
```

```
20    1.0   6.521 19141 3840349
40    1.0   6.500 31470 4179191
40    1.0   6.981 17279 4070142
40    1.0   6.520 18211 4057044

;
run;
proc reg data= chris;
model Fatigue = RAP Binder AV/clb clm cli;
plot npp.*predicted. rstudent.*predicted. rstudent.*RAP rstudent.*Binder
rstudent.*AV;
run;
```

FATIGUE RESISTANCE MODEL 2 – AV CONTENT AND OUTLIERS EXCLUDED

```
data chris;
input RAP Binder AV Fatigue Stiffness;
lines;
20    0.0   7.013 5532  4694554
20    0.0   6.852 6127  4377783
20    0.0   7.080 1526  3948662
40    0.0   6.870 25245 5409662
40    0.0   6.923 19434 4707912

20    0.5   7.377 16271 4330386
20    0.5   6.934 14696 4295519
20    0.5   6.555 8338  4373932

40    0.5   6.965 23457 4653756
40    0.5   7.002 13342 4540170
20    1.0   6.509 18451 3612231
20    1.0   6.542 14104 3342464
20    1.0   6.521 19141 3840349
40    1.0   6.500 31470 4179191
40    1.0   6.981 17279 4070142
40    1.0   6.520 18211 4057044

;
run;
proc reg data= chris;
model Fatigue = RAP Binder /clb clm cli;
plot npp.*predicted. rstudent.*predicted. rstudent.*RAP rstudent.*Binder;
run;
```