Abstract

VISINTINE, BETH. An Investigation of Various Percentages of Reclaimed Asphalt Pavement on the Performance of Asphalt Pavements. (Under the direction of Dr. N. Paul Khosla.)

With the increasing cost of asphalt binder and the growing concern over the availability of quality aggregates, the use of higher percentages of reclaimed asphalt pavements (RAP) has become of much interest across the country. Research has shown that the RAP recovered from construction sites still contains usable materials, both in the recycled aggregates and recycled binder. However, since the RAP binder has been aged during its service life, the use of RAP in new pavement construction may cause the stiffness of the blended binder to increase. Due to this increased stiffness, it is sometimes necessary for a "grade shift" in the virgin binder in order to result in the specifications for the desired performance grade. The use of higher percentages of RAP in construction would provide initial cost savings. However, a life cycle cost analysis was needed in order to determine whether use of higher percentages of RAP provided an economical advantage for the life cycle, not just initially. In order to predict life cycle costs, the fatigue life and rut resistance of mixtures containing various amounts (15%, 30% and 40%) of RAP were compared to a 100% virgin material mixture. The fatigue life and rut resistance of the mixtures were calculated from laboratory testing using Frequency Sweep Testing using Superpave Simple Shear Tester (SST) and Repeated Simple Shear Tests using SST. The SHRP A-003A surrogate models and the Asphalt Institute models were both used in order to predict pavement performance using the results from the Frequency Sweep Testing and the Repeated Simple Shear Test. Based on these results, the life cycle economic analysis was completed and the optimum percentage of RAP was determined for use in the construction of new pavements for NCDOT. The

development of warm mix asphalt (WMA) technology over the recent past has sparked interest in many researchers, engineers and government officials. The use of WMA has incentives including fuel savings, lower emissions, longer hauling distances and longer construction seasons since the use of WMA allows for lower production temperatures. Research has also shown that the reduced production temperatures may reduce the amount of oxidative hardening which may help reduce thermal cracking and block cracking. Due to this benefit, along with the anticipated benefit of better compactability using WMA, it is thought that WMA can be used in mixes containing higher percentages of RAP since less oxidative hardening of the asphalt binder may occur for the already more stiff RAP binder. Mixtures with higher percentages of RAP often have issues with thermal cracking and block cracking due to the stiff binder from the RAP blending with the virgin binder. In order to determine how the use of WMA additives effect the binder rheology of blends containing higher percentages of RAP, Dynamic Shear Rheometer (DSR) and Bending Beam Rheometer (BBR) testing were performed on virgin, blended and RAP binders containing Sasobit®, a WMA additive. These results can be used to determine the allowable amount of RAP that can be used with WMA.

An Investigation of Various Percentages of Reclaimed Asphalt Pavement on the Performance of Asphalt Pavements

by
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DEDICATION

Dedicated with love

To

My Family

BIOGRAPHY

Beth was born September 23, 1983 in Columbus, Ohio. She received her Bachelor's degree in Civil Engineering and Master's of Civil Engineering from North Carolina State University, Raleigh, in 2006 and 2008.

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Introduction

1.1 Introduction and Problem Statement

The recycling of asphalt pavements has become a very routine procedure throughout the country. With the increasing cost of asphalt binder and the growing concern over the availability of quality aggregates, the use of higher percentages of reclaimed asphalt pavements (RAP) has become of much interest across the country. Research has shown that the RAP recovered from construction sites still contains usable materials, both in the recycled aggregates and recycled binder. However, since the RAP binder has been aged during its service life, the use of RAP in new pavement construction may cause the stiffness of the blended binder to increase. Due to this increased stiffness, it is sometimes necessary for a “grade shift” in the virgin binder in order to result in the specifications for the desired performance grade. These specification limits make it cost prohibitive for contractors to use higher RAP contents in their mixes. This practice has led to vast quantities of RAP going unused and stockpiled. Research is needed to show that RAP materials can be used successfully in higher percentages.

With the road building boom of the early 2000s, stockpiles of RAP continue to grow. RAP is a product that the NCDOT initially owns, but then relinquishes to the contractor once the pavement is removed from a project. However, due to requirements governing adjustments in PG binder grade based on total percentage of RAP used in a mix, most contractors choose to limit the RAP content of their mixes to 15%. Therefore, the NCDOT is unable to realize the full cost savings that such a recycled product should provide. Research is needed to determine if the NCDOT could specify higher percentages of RAP in mixes and show if that RAP would give the NCDOT an equal or improved life cycle return on its money.
When considering the use of RAP in Superpave mixtures, several design and performance uncertainties arise, some of which include:

- With respect to Superpave binder tests and specifications, how much stiffer is the binder in RAP compared to that of virgin asphalt binders?

- Is there a maximum threshold percentage on the addition of RAP to a mixture with respect to design and performance? How much is too much? How much is practical?
- Is the use of RAP in asphalt mixtures economically attractive?

The development of warm mix asphalt (WMA) technology over the recent past has sparked interest in many researchers, engineers and government officials. The use of WMA has incentives including fuel savings, lower emissions, longer hauling distances and longer construction seasons since the use of WMA allows for lower production temperatures. Also, another key benefit to lower production temperatures is lowering the oxidative hardening of the asphalt binder that may occur at the higher production temperatures which may reduce thermal cracking, block cracking, and preventing the mix to be tender when placed [10].

Due to this benefit, along with the anticipated benefit of better compactability using WMA, it is thought that WMA can be used in mixes containing higher percentages of RAP since less oxidative hardening of the asphalt binder may occur for the already more stiff RAP binder. Mixtures with higher percentages of RAP often have issues with thermal cracking and block cracking due to the stiff binder from the RAP blending with the virgin binder. Because of this, the percentage of RAP is often limited or requires a grade shift of virgin binder to account for the stiff binder contributed by the RAP.

1.2 Research Objectives and Tasks

This research project addressed the above questions. In order to investigate the effects of RAP in the design and performance of new asphalt concrete mixtures and the effects o using WMA in mixtures containing RAP, the specific research objectives were:

- Evaluate the performance of mix designs using higher RAP percentages
- Determine which layers of the pavement structure could contain higher percentage of RAP without any significant reduction in performance life

- Perform a life cycle cost analysis showing the cost savings that could be realized if higher percentages of RAP are allowed.
- Determine how the addition of Sasobit® affects the binder rheology of mixtures containing RAP.

1.3 Research Methodology and Tasks

1.3.1 Task 1 Sample Procurement and Characterization

This research task included the selection and procurement of the two RAP samples. The properties of the two RAP samples were determined for use in the design of mixtures containing RAP later on.

1.3.1.1 Task 1.1 RAP Stockpile Site Selection and Sample Procurement

Two RAP stockpile sites were selected for use in this research subtask. The two sources of RAP were obtained from the CC Mangum Westgate Asphalt Plant and the Bylthe Pineville Asphalt plant. The RAP stockpiles selected were based on results from Dynamic Shear Rheometer (DSR) testing on recovered binder from the respective RAP sources, gradation and asphalt content. It was desired that the two sources of RAP have differing stiffness, gradation and asphalt content in hopes to be able to apply the results of this research as widely as possible.

1.3.1.2 Task 1.2 RAP Binder Content by Ignition

As part of the RAP stockpile selection, the binder content of the RAP sources was desired. This research subtask used AASHTO TP 53-95 “Test Method for Determining the Asphalt Content of Hot Mix Asphalt (HMA) by Ignition Method” in order to determine the binder content of each RAP sample which was later used in Task 4 during the design of mixtures containing RAP. This method also yielded aggregate from the RAP that was used to determine the aggregate gradation.

1.3.1.3 Task 1.3 RAP Aggregate Gradation

In addition to the RAP binder content, the gradations for each RAP source needed to be determined for use in mixture designs of Task 4. A sieve analysis using aggregates remaining after the ignition test was performed according to AASHTO T27-88 “Sieve Analysis of Fine and Coarse Aggregates” and AASHTO T11-90 “Material Finer Than 75µm (No. 200) Sieve in Mineral Aggregates by Washing”.

1.3.1.4 Task 1.4 RAP Aggregate Specific Gravity

In this research subtask, the RAP aggregate specific gravity was determined. This was needed in the design of mixtures containing RAP in order to calculate the specimen volumetric values (percent air voids, percent voids in mineral aggregate and percent voids filled with asphalt). AASHTO T84-88 “Specific Gravity and Absorption of Fine Aggregate” and AASHTO T85-88 “Specific Gravity and Absorption of Coarse Aggregate” were used to determine the respective specific gravities.

1.3.1.5 Task 1.5 RAP Binder Rheology

In this research subtask, the binder was reclaimed from the RAP samples using AASHTO T 319 “Test Method for the Quantitative Extraction and Recovery of Asphalt Binder from Hot Mix Asphalt”. The RAP binder was dissolved and washed from the aggregate using a toluene, a strong solvent. The binder was then reclaimed by heating the mixture and distilling the solvent.

AASHTO TP5-93 “Test Method for Determining the Rheological Properties of Asphalt Binder Using a Dynamic Shear Rheometer”, AASHTO T 313-09 “Standard Test Method for Determining the Flexural Creep Stiffness of Asphalt Binder Using the Bending Beam Rheometer” and AASHTO R-29 “Standard Practice for Grading or Verifying the Performance Grade of an Asphalt Binder” were used to determine the rheological properties and Superpave performance grade of the reclaimed RAP binders. This allowed the binders to be characterized completely at high-, intermediate-, and low-temperature values.

1.3.2 Task 2 Procurement and Characterization of Virgin Materials

This research task selected and procured the virgin materials needed to complete the mixture design in research Task 4. Characterization of the virgin materials was also completed in order to determine the required properties for the mixture design. It was desired that the virgin materials selected were comprised of materials that are an actual representation of materials used in mixture design, production and construction in North Carolina.

1.3.2.1 Task 2.1 Virgin Material Selection and Procurement

In order to develop applicable results for the NCDOT, the virgin materials selected for use were an actual representation of materials used in asphalt concrete pavements in North Carolina. Since manufactured aggregates are less variable than natural aggregates in both specific gravity and particle size distribution, manufactured aggregates were used for this research. The types of manufactured aggregate most commonly used in North Carolina are granites and limestone. Availability of aggregate in close proximity to North Carolina State University was another element that had a deciding factor in the selection of virgin aggregate type as it is more convenient and less costly. For this reason, granite aggregate from the Knightdale Quarry was selected and procured.

Again, in order to produce the most applicable results for NCDOT, the virgin binder selected was an actual representation of binders used for asphalt concrete pavements in North Carolina. The two asphalt binder grades most commonly used in North Carolina are PG 64-22 and PG70-22.

Since the binder recovered from the RAP has an increased stiffness from aging, a softer virgin binder grade may be necessary in order for the blended RAP-virgin binder to have the desired grade for the project requirements. For this reason, this research included virgin binder grades of PG 52-28, PG 58-22 and PG 64-22.

1.3.2.2 Task 2.2 Virgin Aggregate Specific Gravity

The purpose of this subtask was to determine the specific gravity of the virgin aggregate. AASHTO T84-88 “Specific Gravity and Absorption of Fine Aggregate” and AASHTO T85-88 “Specific Gravity and Absorption of Coarse Aggregate” were used in order to determine this. This is needed for Task 4 during the design of mixtures in order to calculate the specimen volumetric values (percent air voids, percent voids in mineral aggregate and percent voids filled with asphalt).

1.3.2.3 Task 2.3 Virgin Asphalt Binder Grade Verification

In this research subtask, AASHTO TP5-93 “Test Method for Determining the Rheological Properties of Asphalt Binder Using a Dynamic Shear Rheometer” and AASHTO T 313-09 “ Standard Test Method for Determining the Flexural Creep Stiffness of Asphalt Binder Using the Bending Beam Rheometer” were used to verify the performance grade of the virgin binders selected. These values were used in the development of the asphalt binder blending curves discussed in Task 3 below.

1.3.3 Task 3 Development of Asphalt Binder Blending Curves

Since the binder from RAP materials has been aged during the life of the pavement, the stiffness of the blended virgin-RAP binder increases. The resulting increase in the blended binder may require a “grade shift” of the virgin binder selected in order to result in the required stiffness of the desired binder grade. The relationship of the resulting blended binder stiffness and the percentage of RAP contained in the mixture for each virgin binder grade needed to be determined. Blending curves showing this relationship were developed in order to aid in the selection of the virgin binder grade or percentage of RAP needed to produce the final binder grade required.

1.3.3.1 Task 3.1 Rheological Testing of Binder Blends

In this research subtask, the rheological properties of the asphalt binder blends containing various percentages of RAP binder blended with virgin binder was determined using AASHTO TP5-93 “Test Method for Determining the Rheological Properties of Asphalt

Binder Using a Dynamic Shear Rheometer” and AASHTO T 313-09 “Standard Test Method for Determining the Flexural Creep Stiffness of Asphalt Binder Using the Bending Beam Rheometer”.

1.3.3.2 Task 3.2 Development of Binder Blending Charts

The information gathered in the previous subtask was used in this subtask in order to develop binder blending charts for determining the amount of RAP allowable in mixture designs for the desired binder grade.

1.3.4 Task 4 Superpave Mixture Design

The mixtures produced in the task were used in research Tasks 5 and 6 for mixture performance and analysis.

1.3.4.1 Task 4.1 Design of Mixtures Containing 100% Virgin Material

In this subtask, the designs of mixtures containing 100% virgin materials were developed. The mixture designs were governed by AASHTO R 35-04 “Superpave Volumetric Design for Hot Mix Asphalt (HMA)”.

1.3.4.2 Task 4.2 Design of Mixtures Containing Various Percentages of RAP

In this subtask, specimens containing various percentages of RAP were fabricated for use in analysis during Tasks 5 and 6. Since the mixtures containing RAP were compared to the mixture containing 100% virgin materials, the material proportions used in the RAP mixtures should replicate the material proportions used in the virgin mixture as closely as possible. To accomplish this, a gapped gradation of the virgin aggregate was used in order to account for the gradation of the RAP aggregate in order to produce a combined gradation similar to that used in the 100% virgin material mixture. The amount of virgin asphalt binder used for the virgin material mixtures was modified in order to account for the binder contributed by the RAP material in order to yield a similar optimum asphalt content.

1.3.5 Task 5 Mixture Characterization

The mixtures developed in Task 4 were characterized in research Task 5 using Superpave simple shear tests. These characterizations were used for comparisons between the various mixtures which were then used as part of the performance predictions for the mixtures. The simple shear tests are described below.

1.3.5.1 Task 5.1 Frequency Sweep Testing Using Superpave Simple Shear Tester (SST)

In this subtask, the Frequency Sweep Test at Constant Height (FSTCH) was performed according to Procedure E of AASHTO TP7-94 “Standard Test Method for Determining the Permanent Deformation and Fatigue Cracking Characteristics of Hot Mix Asphalts (HMA) Using the Simple Shear Test (SST) Device” in order to provide the rheological properties of the various mixtures. The FSTCH applies a sinusoidal shear strain of 0.01% at frequencies of 10, 5, 1, 0.5, 0.2, 0.1, 0.05, 0.02 and 0.01 Hz. In accordance with AASHTO TP7, the FSTCH were performed at 20^{o}C.

Resulting from the FSTCH, the complex modulus (G*) is known. The complex modulus measures the mixtures stiffness for the range of frequencies. These values were used to compare the similarities between mixtures containing 100% virgin materials and mixtures containing various percentages of RAP (15%, 30% and 40%). As a part of the performance analysis, the complex modulus was used in the Strategic Highway research Program’s (SHRP) A-003A surrogate performance prediction model for fatigue life in Task 6.1.

1.3.5.2 Task 5.2 Repeated Simple Shear Tests Using Superpave Simple Shear Tester (SST) Device

The Repeated Simple Shear Test at Constant Height (RSSTCH) is used to measure the accumulations of permanent strain in the test specimen for the test period. The shear load is applied in a haversine pulse for a duration of 0.1 second followed by a 0.6 second unload period. This results in a total loading cycle of 0.7 second. The RSSTCH is conducted for 5000 cycles or 5 percent of the permanent shear strain for the specimen is reached. The RSSTCH measures the accumulated permanent shear strain for each specimen. The accumulated permanent shear strain values obtained from mixtures containing 100% virgin materials were compared with values obtained from mixtures containing various amounts of RAP material since the accumulated permanent shear strain correlates to rut resistance of the mixtures.

1.3.6 Task 6 Mixture Performance Analysis

In this research task, predictions models were utilized in order to estimate the performance of the mixtures for comparison between mixtures containing 100% virgin materials to mixtures containing various amounts of RAP. Analysis was also conducted in order to determine which layers of pavement could contain higher percentages of RAP without a significant reduction in performance life. This analysis provided the information needed to conduct a life cycle cost analysis for all mixtures. From the cost analysis, the cost savings resulting from use of higher percentages of RAP was determined.

1.3.6.1 Task 6.1 Pavement Performance Prediction

This subtask predicted the performance of pavements against fatigue cracking and rutting using the results from the FSTCH and RSSTCH. The surrogate models from the SHRP A-003A as well as distress models developed by the Asphalt Institute (AI) were used to perform fatigue and rutting analysis. The models used for analysis are described below.

1.3.6.1.1 Task 6.1.1 Fatigue Model Analysis

The fatigue cracking model from SHRP A-003A considers horizontal tensile strain at the bottom of the pavement layer during loading, the initial flexural loss stiffness of the mixture (S_o") and the voids filled with asphalt (VFA). The shear stiffness measured during the FSTCH at 10Hz and 20^{o}C was used to determine the initial flexural loss stiffness using the following relationships:

$$S_o = 8.56*(G_o)^{0.913}$$
$$S_o^{"} = 81.125*(G_o^{"})^{0.725}$$

where,
S_o = initial flexural stiffness at 50th loading cycle (psi)
G_o = shear stiffness at 10Hz (psi)
S_o'' = initial flexural loss stiffness at 50th loading cycle (psi)
G_o'' = shear loss stiffness at 10Hz (psi)

This model requires the principle tensile strain at the bottom of the asphalt concrete layer. This was estimated using EVERSTRESS pavement analysis and design software. For this software, a pavement section must be assumed. The strain values were assessed at three locations: directly beneath the tire, at the edge of the tire and at the center of the dual tire configuration in order to consider the full loading configuration. The fatigue life of the pavement was estimated by the SHRP A-003A model as follows:

$$N_{supply} = 2.738*10^5 e^{0.077VFA} \varepsilon_0^{-3.624} S_o^{''-2.72}$$

where,
N_{supply} = estimated fatigue life of the pavement section in 18 kip axles (ESALs)
VFA = voids filled with asphalt for the mixture
ε_o = critical strain at the bottom of the asphalt layer

The Asphalt Institute model for determining fatigue life was also considered. Like the surrogate SHRP A-003A fatigue model, the tensile strain at the bottom of the asphalt concrete layer is needed. The AI model for estimating fatigue life follows:

$$N_f = 0.00796 \varepsilon_t^{-3.291} E_1^{-0.854}$$

where,
N_f = number of load applications to fatigue failure (20% cracked area)
ε_t = tensile strain at the bottom of the asphalt layer
E_1 = elastic modulus of asphalt layer (psi)

If the two models gave similar fatigue life predictions, the economic analysis would have used the average predicted axle loading value. However, since the models differed significantly, the more conservative, or lowest cycles to failure was used for the economic analysis.

1.3.6.1.2 Task 6.1.2 Rutting Model Analysis

According to SHRP A-003A, the rut depth is estimated as a function of the maximum permanent shear strain from the RSSTCH test. This relationship is as follows:

*Rut Depth (in) = 11 * Maximum permanent shear strain*

This relationship should hold true for all tire pressures but is expected to decrease with a decrease from the original pavement thickness of 15 inches [7]. The following equation converts the number of RSSTCH test loading cycles to 18-kip equivalent single axle loads (ESALs):

log (cycles) = -4.36 + 1.24 log (ESALs)

where,

cycles = number of cycles obtained from the RSSTCH test,

ESALs = equivalent 18-kip single axle loads

Again, the Asphalt Institute model for rutting was also used to estimate the rutting resistance for the pavement systems produced by the various mixtures. However, unlike the SHRP model, the AI model not only considers the mixture properties but also the pavement geometry and pavement system as a whole. The AI model considers the vertical compressive strain at the top of the subgrade layer as part of the model to determine the number of loading repetitions (N_d) required to cause a rut depth of 0.5 inch. The model is as follows:

$$N_d = 1.365 * 10^{-9} \varepsilon_c^{-4.477}$$

where,

ε_c = compression strain at top of the subgrade

Similar to the fatigue cracking analysis, EVERSTRESS pavement analysis software was used to estimate the vertical compressive strain at the top of the subgrade layer.

1.3.6.2 Task 6.2 Pavement Layer Analysis

In this research subtask, an analysis to determine the layers of pavement that can contain a higher percentage of RAP without any significant reduction in performance was performed. Mixtures with varying nominal aggregate size were used in order to simulate different layers.

1.3.6.3 Task 6.3 Economic Analysis

In this research subtask, an economic analysis was performed as a basis for comparison between mixtures containing various amounts of RAP to mixtures containing 100% virgin materials. This economic analysis of the life cycle cost of pavement sections aided in the decision making concerning the use of RAP in pavements.

An economic analysis for the life cycle cost of the pavements was conducted in order to take into account more than the initial difference in cost between pavements containing RAP material versus pavements containing 100% virgin materials. Although using RAP material for pavement construction will decrease the initial cost of construction, pavements containing RAP may require more maintenance or have a shorter service life than pavements containing 100% virgin materials reducing the initial construction savings or even resulting in more cost than pavements containing 100% virgin materials. For this reason, the life cycle analysis was utilized.

In order to conduct a life cycle cost analysis, it was recommended that either the present worth method or annual cost method be implemented. Both of these methods took into account initial costs of the pavement construction and all future year costs as well as salvage values. The present worth method converts all costs or returns to the present value for analysis. The annual cost method converts all costs and returns to a uniform annual cost for analysis. Both of these methods should result in similar conclusions and the pavement with the lowest life cycle cost should be selected. The following relationships were used for the present worth method and the annual cost method, respectively.

The present worth of a future sum can be found by:

$$PW = \frac{F}{(1+i)^n}$$

where,
PW = present worth of a sum of money that takes place *N* years from the base year.
F = future sum of an improvement at the end of year *N*, and
i = discount rate.

The present worth for several equal costs can be found by:

$$PW = \frac{A[(1+i)^N - 1]}{[i(1+i)^N]}$$

where,
PW = present worth of an annual uniform expenditure,
A = the uniform annual cost for N years,
N = the number of years in which the annual cost is experienced, and
i = discount rate.

The present worth of a gradient annual cost, or an annual cost that is expected to increase at a constant rate over time, can be calculated by:

$$PW = A_o + \left[G * \left(\frac{1}{i} \right) * \left\{ \frac{(1+i)-1}{i(1+i)^N} \right\} - \left\{ \frac{N}{(1+i)^N} \right\} \right]$$

where,
PW = present worth of a gradient annual cost,
A_o = value of the first expenditure at the end of the first year,
G = amount of the uniform increase per year,
N = number of years the gradient expenditure is encountered, and
i = discount rate.

The annual cost of a present worth can be calculated by:

$$A = PW * \left[\frac{i(1+i)}{(1+i)^N - 1} \right]$$

where,
A = annual uniform cost,
PW = present worth of a capital investment,
N = number of years in the analysis period, and,
i = discount rate.

The annual cost of a future investment can be calculated by:

$$A = F\left[\frac{1}{(1+i)^N - 1}\right]$$

where,
A = annual uniform cost,
F = future value of a discrete expenditure,
N = number of years from the baseline year the expenditures will take place, and,
i = discount rate.

If an annual cost is expected in increase at a constant rate over a period, the uniform annual cost can by calculated by:

$$A = A_o + G*\left(\frac{1}{i} - \frac{N}{(1+i)^N - 1}\right)$$

where,
A = uniform annual cost,
Ao = value of the expenditure at the end of the first year,
G = annual increase in the expenditure,
N = number of years in the analysis period, and,
i = discount rate.

1.3.7 Task 7 Warm Mix Asphalt Binder Rheology

The use of WMA may reduce oxidative hardening of the binder due to the reduced production temperatures which may reduce the amount of thermal cracking and block cracking. This may allow for higher percentages of RAP to be used since the binder from RAP materials has been aged during the life of the pavement, the stiffness of the blended virgin-RAP binder increases. The resulting increase in the blended binder may require a "grade shift" of the virgin binder selected in order to result in the required stiffness of the desired binder grade. The relationship of the resulting blended binder stiffness and the percentage of RAP contained in the mixture for each virgin binder grade needed to be determined. Blending curves showing this relationship were developed in order to aid in the selection of the virgin binder grade or percentage of RAP needed to produce the final binder grade required.

1.3.7.1 Task 7.1 Rheological Testing of Binder Blends

In this research subtask, the rheological properties of the asphalt binder blends containing various percentages of RAP binder blended with virgin binder containing Sasobit® at an amount of 1.5% by weight of the binder was determined using AASHTO TP5-93 "Test Method for Determining the Rheological Properties of Asphalt Binder Using a Dynamic Shear Rheometer" and AASHTO T 313-09 "Standard Test Method for Determining the Flexural Creep Stiffness of Asphalt Binder Using the Bending Beam Rheometer".

1.3.7.2 Task 7.2 Development of Binder Blending Charts

The information gathered in the previous subtask was used in this subtask in order to develop binder blending charts for determining the amount of RAP allowable in mixture designs containing Sasobit® for the desired binder grade.

1.4 Organization of Report

The goal of this report is to answer the research objectives. This report is organized into eight chapters. Chapter 2 gives a brief overview of the topic through a literature review. Chapter 3 discusses the material characterizations used in the research. Chapter 4 discusses the blending charts developed for aiding in the selection of RAP percentage to use. Chapters 5 and 6 discuss the mixture characterization and performance. Chapter 7 discusses the blending charts developed using Sasobit® and how the use of WMA affects mixtures containing higher percentages of RAP. The report is brought to a close with the summary of results and conclusions in Chapter 8.

Chapter 2
Literature Review

This chapter will give an overview of the past and current approaches towards using Reclaimed Asphalt Pavement (RAP) in new pavements and Warm Mix Asphalt (WMA) technology.

As RAP is so widely available and can provide cost savings, there has been a significant amount of research in the past on the effect of using RAP in pavement design and pavement performance. Many different approaches have been developed to determine the effect of RAP on the PG grade of the blended binder. Some of these approaches include the development of blending charts from rheological testing on the binder blends using the Dynamic Shear Rheometer (DSR) and Bending Beam Rheometer (BBR) according to AASHTO TP5-93 and AASHTO TP1-93, respectively, as well as conducting Superpave testing on the blended binder.

The studies conducted by Kandhal and Foo as well as Soleymani, Bahia and Bergan developed blending charts based on Superpave criteria in order to determine the effects of RAP on Superpave binder grades.

Kandhal and Foo conducted research to develop blending charts based on Superpave criteria based on the amount of virgin binder needed to be blended with the RAP in order to produce the desired PG binder grade [3]. Although the PG binder grade is dependent on high, intermediate and low temperature criteria, this study only focused on the high and intermediate temperatures.

The high temperature value of the blended mix was determined using two blending charts, one measuring the temperatures that satisfied the criteria of $G^*/\sin\delta$ equal to 1.0 kPa with varying percentage of RAP used in the blend and the other measuring the temperature that satisfied the criteria of $G^*/\sin\delta$ equal to 2.2 kPa with varying percentage of RAP used in the blend on unaged and Rolling Thin Film Oven (RTFO) aged residue, respectively [3]. The more conservative or lower of these two temperatures was determined to be the high temperature value of the blended mix. The intermediate temperature value of the blended mix was determined using a blending chart that measured the temperatures that satisfied the criteria of G*sin δ equal to 5.0 MPa on RTFO and Pressure Aging Vessel (PAV) aged residue [3].

The study used a virgin binder with a Superpave grade of PG 58-22 and varying percentages of RAP with the goal of determining the amount of RAP that was needed in order to produce a final blended mixture with a Superpave grade of PG 64-22. Table 2.1 below shows the results from the blending charts developed as a result of the research.

Table 2.1. Temperature Values of Superpave Criteria based on Varying Percentages of RAP

Recycled Mix	Temperature Sweep Blending Charts	Temperature Value (^oC)	High Temperature Value (^oC)	Intermediate Temperature Value (^oC)
20% RAP	G*/sinδ = 1 kPa	64.1	64.1	19.2
	G*/sinδ = 2.2 kPa	64.8		
	G*sinδ = 5 MPa	19.2		
30% RAP	G*/sinδ = 1 kPa	66.8	66.8	19.9
	G*/sinδ = 2.2 kPa	67.3		
	G*sinδ = 5 MPa	19.9		
40% RAP	G*/sinδ = 1 kPa	70.3	70.3	21.8
	G*/sinδ = 2.2 kPa	70.4		
	G*sinδ = 5 MPa	21.8		

Source: (3)

Kandhal and Foo's analysis of the data claimed that since there was a large margin between the observed intermediate temperatures and the required intermediate temperature of 25^oC,

“that much more RAP (more than 40% RAP) can be added to the recycled mix and still meet the intermediate temperature performance requirement. This indicates that the intermediate temperature requirement as specified by Superpave is too liberal” [3].
The study conducted by Soleymani, Bahia and Bergan also produced blending charts based on Superpave criteria in order to determine the amount of RAP that could be included while still meeting Superpave binder grade specifications. However, this study looked at all three temperature values needed to determine the Superpave binder grade.

The DSR)test was used to calculate the change in shear modulus (G*) and phase angle (δ) for the varying blended mixes in order to analyze the high and intermediate temperature criteria. The BBR test was used to calculate the change in stiffness (S) and creep rate (m-value) for the varying blended mixes in order to analyze the low temperature criteria.

Analysis showed linear relationships for the proportion of RAP in the blended mix and all criteria: G*, δ, S and m-value [8]. The validity of this claim was confirmed by statistical analysis. The blending chart is created by plotting the temperature that the binder satisfies the PG criteria. By conducting Superpave test on the virgin binder, blended binder and the binder recovered from the RAP to be used in the blend, four points are produced. Since a linear relationship is valid, the relationship between the temperature that the binder satisfies the PG criteria and percentage of RAP in the blend can be determined from the four points. Figure 2.1 below shows an example of the blending chart produced by a sample in this study for all three temperature values.

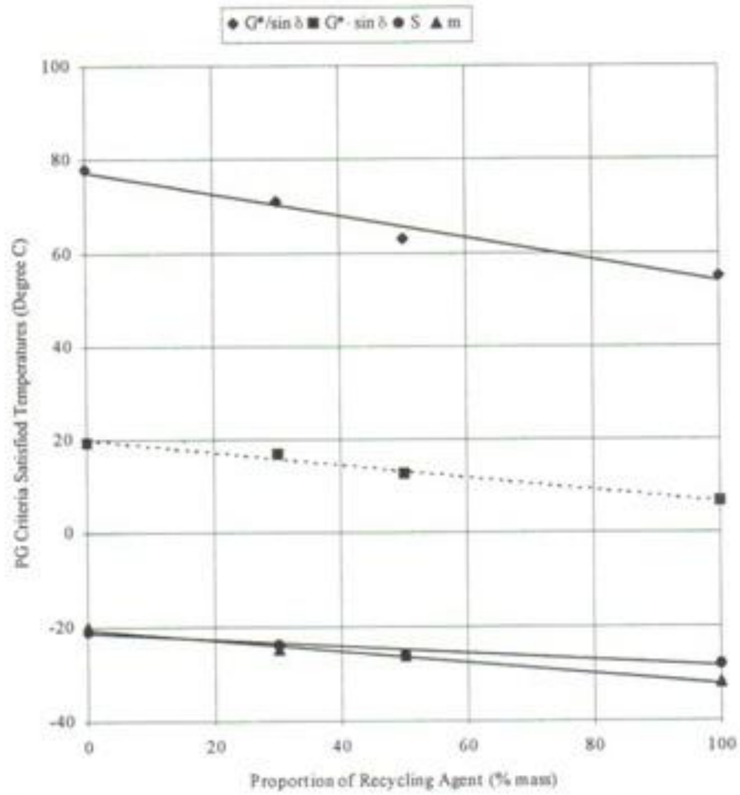


Figure 2.1. Blending Chart for 300-400 Asphalt Binder

Source: (8)

Kennedy, Tam and Solaimanian conducted a research study looking into the use of Superpave testing in order to determine the effect of RAP in the blended mix. Criteria for all temperature values were considered.

Samples were prepared with compositions of varying percentages of RAP binder mixed with virgin binder. The blended binders were subjected both to short term aging through RTFO to simulate aging during construction and long term aging though PAV to simulate field aging.

In order to determine the PG grade of the blended mix, the DSR and BBR Superpave tests were used for the high and intermediate temperature values and the low temperature value, respectively, after being properly aged for each method. The DSR results for high temperature values indicated that the stiffness, measured by $G^*/\sin\delta$, increased with increasing levels of RAP in the blend [4]. Results also indicate that at higher percentages of RAP, the stiffness increase becomes larger with increasing RAP percentage, whereas at smaller percentages of RAP, the increase of the percentage of RAP has a minimal effect on the stiffness [4]. Again, at the intermediate and low temperature values, higher percentages of RAP had the greatest effect on the stiffness of the blend [4]. However, the logarithmic creep rate experiences the opposite relationship, with lower percentages of RAP having a greater influence change than higher percentages of RAP [4]. Figure 2.2 shows the effect of the percentage of RAP in a blend at high temperatures on the stiffness. Similar figures were developed for all blends of different binder types and different temperature values. Table 2.2 below contains the resulting PG grade for the blended mixes in this study at varying percentages of RAP. Kennedy et al. state that “Superpave tests are recommended to be performed on the blend at four different blend percentages to determine the behavior of the blend. From this, the range of allowable RAP content is determined” [4].

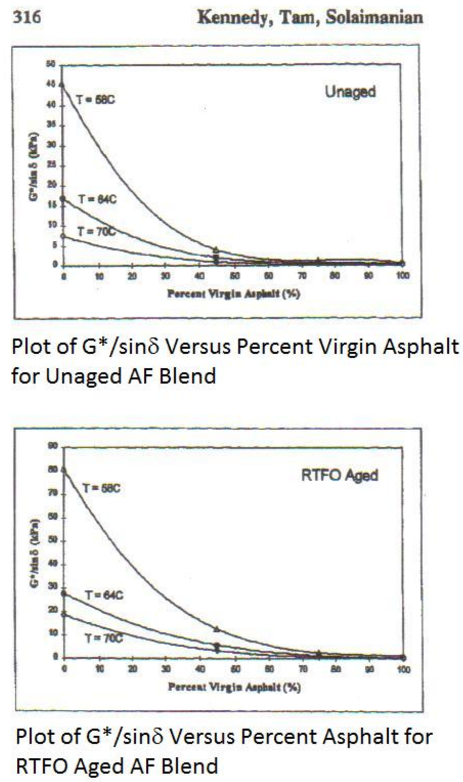


Figure 2.2. G*/sinδ Versus Percent Virgin Asphalt for Unaged AF and RTFO Aged AF

Source: (4)

Table 2.2. PG Grade and Blend Combinations

Percent Virgin Asphalt (%)	Virgin: AAM-1 RAP: AAF-1	Virgin: AAA-2 RAP: AAF-1	Virgin: AAD-1 RAP: AAG-1
0	PG 76-10	PG 76-10	PG 76-16
25	PG 70-10	-	-
45	PG 70-16	PG 64-22	PG 70-16
65	PG 70-16	-	-
75	PG 70-16	PG 58-34	PG 64-22
85	PG 64-16	-	-
100	PG 64-16	PG 46-34	PG 58-28

Source: (4)

Analysis concludes that the binder performance grade is not affected by the addition of up to 15% RAP, whereas the binder performance grade is increased one high temperature grade by the addition of 25% RAP [4]. This same addition only affects one blend low temperature grade, with an increase of one grade.

Kennedy et al. concluded that conducting Superpave testing on blended mixes is a legitimate procedure for determining the percentage of RAP that can be used in order to produce a blend that meets the specified binder criteria [4].

The research conducted by Stephens, Mahoney and Dippold was twofold. First they studied the effect of heating the RAP before mixing on the amount of blending between the virgin binder and RAP binder. Second, they studied the effective PG binder grade of a blended mix using the indirect tension test.

In order to determine the effect of heating the RAP before mixing on the amount of blending between the virgin binder and RAP binder, samples were fabricated with RAP that had been heated prior to mixing for varying amounts of time. The specimens were then tested using both unconfined compression and indirect tension tests in order to determine the change in strength of the specimens which would correlate the amount of blending that occurred between the virgin binder and the RAP binder. Analysis showed that the strength did increase with the addition of RAP that had not been heated prior to mixing suggesting that blending between the virgin binder and RAP binder had occurred [9]. Further increases in strength with heating shows that “more complete binder blending occurs in HMA mix containing RAP if the RAP during the mixing reaches a temperature that softens the RAP binder allowing intimate blending” [9].

Stephens et al. claim that the unconfined compression and indirect tension tests could both “produce a method for determining the effective PG grade of the binder in a HMA mix that contains RAP” [9] due to the results of the tests conducted on the specimens to determine the amount of preheating needed. For this research, however, the indirect tension test was used.

Virgin binder with grades of PG 58-34 and PG 64-28 were both used. Specimens were fabricated using all virgin binder as well as a blend with 15% RAP binder and virgin binder of both grades. The average tensile loads for the two specimens with all virgin binder were then plotted against the PG grade. A linear relationship between these two points was assumed. Then the average tensile load for the two specimens with RAP and virgin binder blend were plotted. The PG grade for the blended specimens can be calculated by moving horizontally from the point to intersect the line connecting the all virgin binder indirect tensile average strengths and dropping down to the x-axis in order to read the PG grade [9]. Figure 2.3 below shows the graph for the indirect tensile tests conducted at 28^{o}C. Testing was also done at other temperatures to simulate low temperature criteria as well as temperatures closer to Superpave service temperatures. Specimens with other percentages of RAP were also tested.

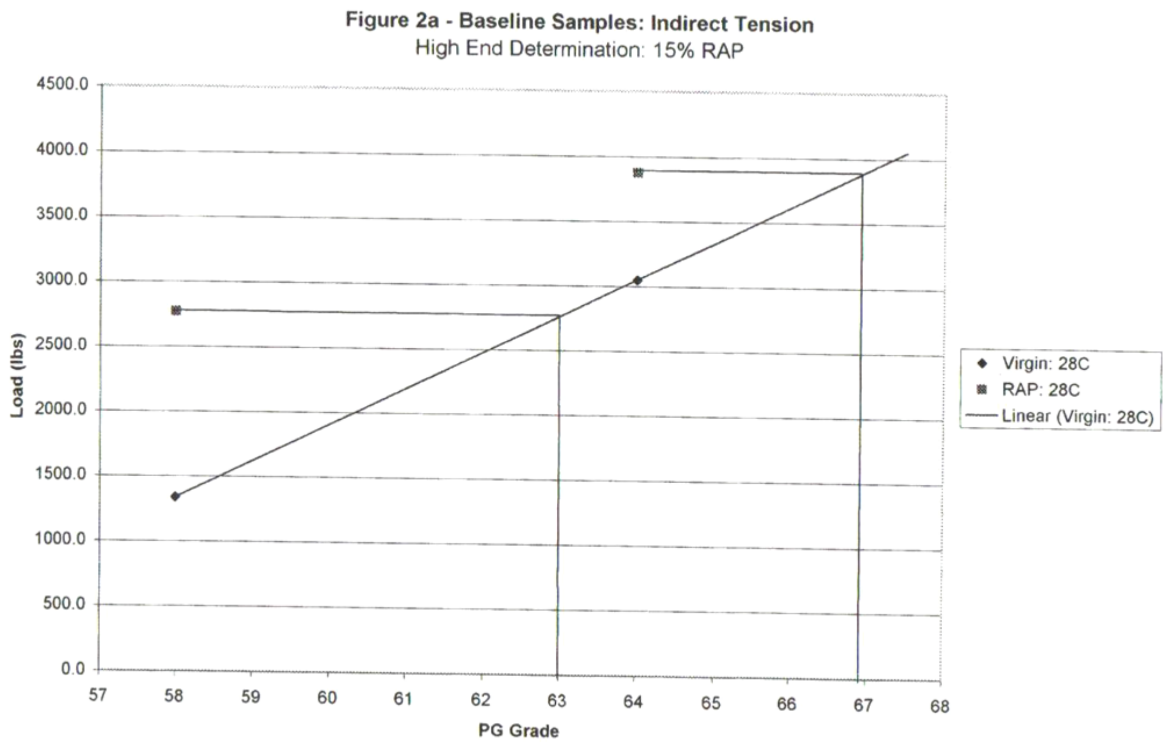


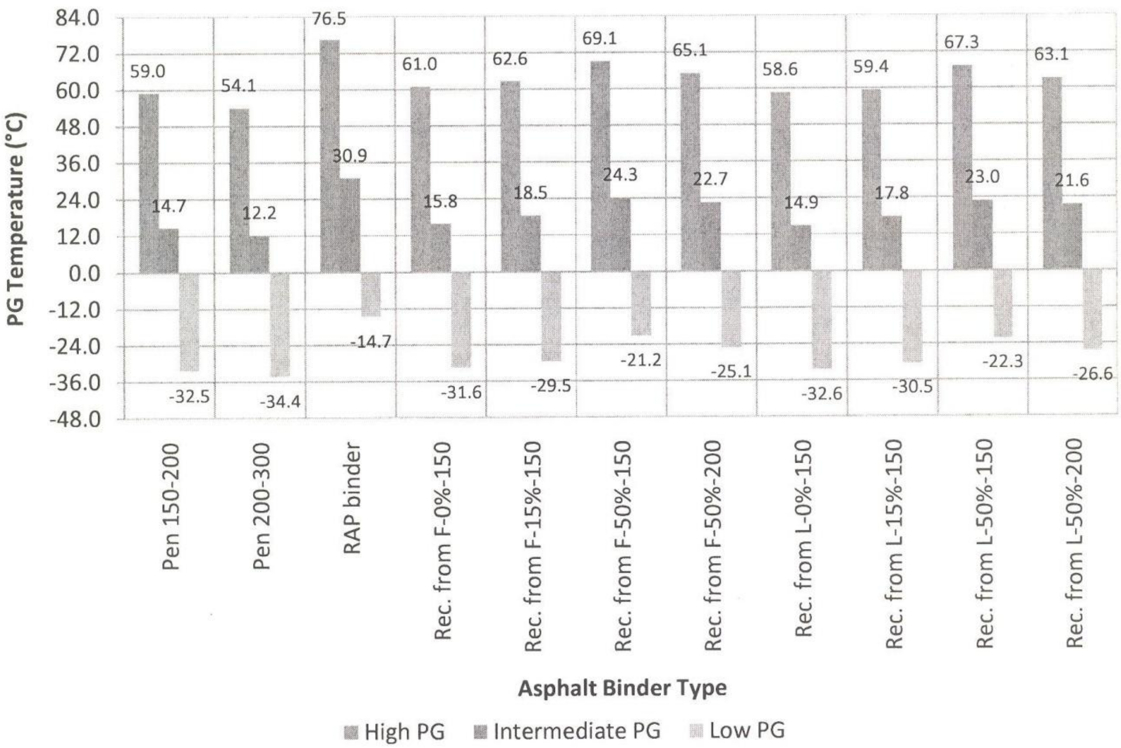
Figure 2.3. Indirect Tension vs. PG Grade at 28^{o}C

Source: (9)

The analysis of the results shows that an increase in RAP increases both the high and low temperature PG values. Stephens et al. state: "This change is anticipated because of the additional RAP binder tends to increase the hardness of the combined binders. This indicates that the test is sensitive enough to detect changes in the effective PG grade" [9].

A recent study performed by Luis Loria, Elie Y. Hajj, Peter E. Sebaaly, Matt Barton, Said Kaas and Tara Like investigated the "Performance Evaluation of Asphalt Mixtures With High RAP Content". The research considered mixtures containing 0, 15 and 50% RAP to determine the resistance to moisture susceptibility and thermal cracking as well as to determine the correlation between the blending chart process to predict the performance grade (PG) of the blended binders [12]. The study used Pen150-200 and Pen 200-300 binders as the virgin binders, which correspond to PG 58-28 and PG 52-34, with the target binder being Pen 150-200 [12]. In order to compare field-produced mixtures to laboratory-produced mixtures, loose mixtures from the top of the paving lift were sampled and samples of the cold feed aggregates, asphalt binders and RAP materials were sampled at the production plant to reproduce the mixtures in the laboratory [12].

Rheological properties of the asphalt blends were determined based on the Superpave Performance Grading (PG) binder system to determine the critical temperatures. Figure 2.4 below shows the results of the critical temperatures.



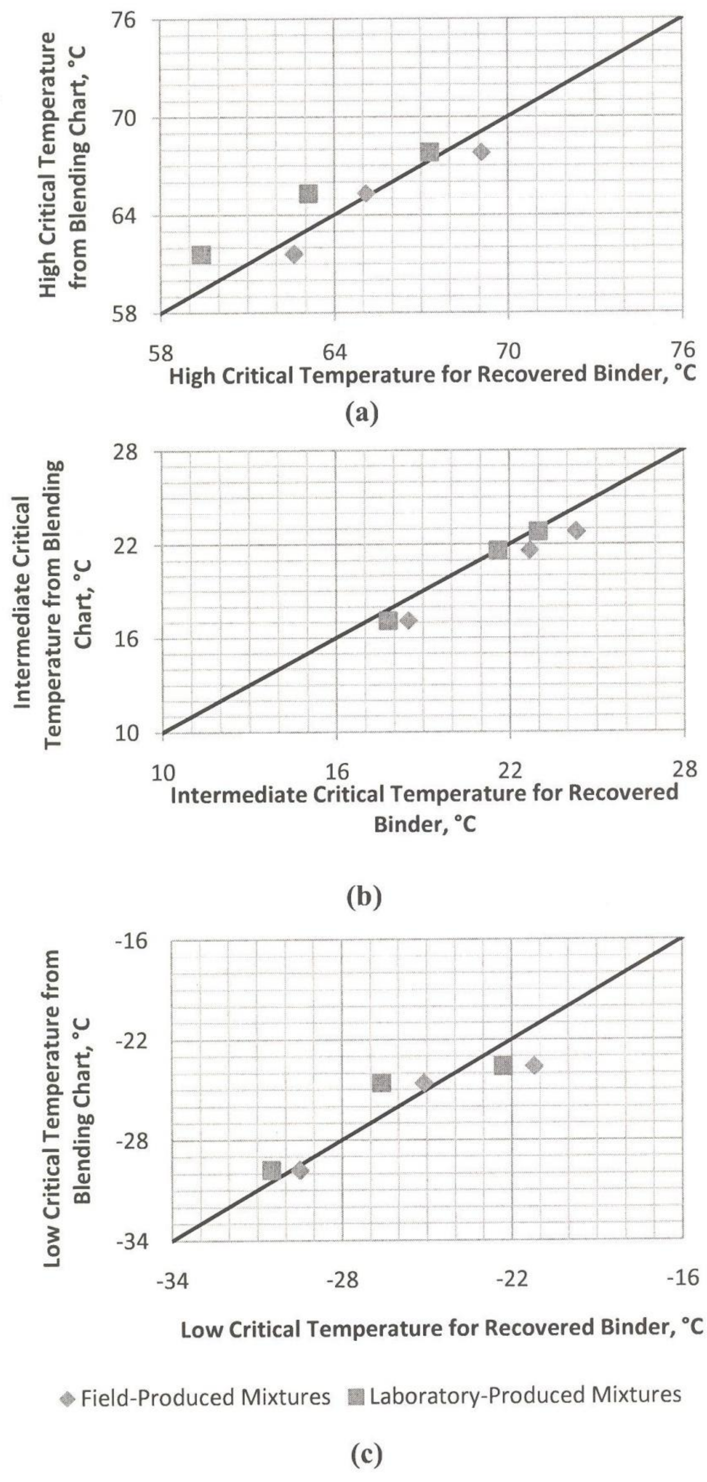
Source: [12]

Figure 2.4 Superpave PG Temperatures of Various Asphalt Binders

The results indicate only a difference of 2^{o}C and 5^{o}C between the two virgin binders for the low and high critical temperatures, respectively [12]. The increase of RAP in mixtures containing the PG 58-28 binder resulted in a higher and warmer high and low critical temperatures, respectively [12]. The field-produced mixtures resulted in more stiff recovered binders than the laboratory-produced mixtures which indicated that the aging process of the laboratory-produced mixtures did not simulate the aging of the field-produced mixtures [12]. Only the mixtures containing 0 and 15 percent RAP met the critical temperatures for the target PG 58-28 binder while the mixtures containing 50% RAP (and either virgin binder) only met the target high PG 58^{o}C but not the target low of -28^{o}C [12].

Since blending charts are often used to predict the amount of RAP that can be included in a mixture to meet the Superpave rheological specifications, the effectiveness to estimate the

PG of blended binders using blending charts was assessed. Critical temperatures were estimated using blending charts that were produced according to the recommendations of NCHRP project 09-12. A comparison between the estimated critical temperatures from the blending charts and the measured critical temperatures from the recovered asphalt binder are shown in Figure 2.5 below. The figure shows a good correlation between the two methods and that the critical temperature could be overestimated or underestimated by $2^{o}C$, assuming the recovered binder grade is correct [12].



Source: [12]

Figure 2.5 Comparison Between Estimated and Measured (a) High Critical Temperature (b) Intermediate Critical Temperature (c) Low Critical Temperature

Moisture sensitivity was evaluated using the indirect tensile strengths (TS) of unconditioned and conditioned specimens and the indirect tensile strength ratio (TSR) after multiple freeze-thaw (F-T) cycles. Dynamic modulus testing was performed to determine mechanical properties and thermal cracking resistance was predicted using the thermal stress restrained specimen test (TSRST) after multiple F-T cycles. Either one or three F-T cycles were used to condition the specimens.

The AASHTO T283 moisture sensitivity analysis after multiple F-T cycles showed that the use of 50% RAP did not cause additional reduction in resistance of the HMA mixtures to moisture damage [12]. It also showed that the laboratory-produced mixtures generally had a higher or similar TS than the field-produced mixtures [12]. However, the $|E^*|$ test did show additional reduction in the resistance to moisture damage in HMA mixtures that used 50% RAP after 3 F-T cycles but these mixtures still exhibited a relatively high $|E^*|$ compared to the virgin mixtures [12].

The thermal cracking analysis using the TSRST showed no additional reduction of the fracture stress after 3 F-T cycles due to the use of RAP [12]. The TSRST fracture temperature was reduced with the use of 50% RAP with the virgin binder; however, a similar fracture temperature to the virgin mixture was observed when a softer virgin binder was used with 50% RAP [12]. The TSRST fracture temperatures were within 1^{o}C of the critical low temperature for mixtures containing 0% and 15% RAP and 5 to 8^{o}C colder than the critical low temperature for mixtures containing 50% RAP [12].

The development of WMA technology over the recent past has sparked interest in many researchers, engineers and government officials. The use of WMA allows for lower production temperatures of asphalt mixtures. The use of these lower temperatures can translate to fuel cost savings for the contractors and lower emissions which can also reduce cost since 30-50 percent of the overhead costs can be attributed to emission control for asphalt plants [10]. Other incentives for using WMA include the possibility of asphalt plants to be placed in non-attainment areas, allowing longer hauling distances and longer construction seasons with the reduced temperatures and emissions [10]. Due to the lower operating temperatures, less oxidative hardening of that asphalt may occur which may reduce thermal cracking, block cracking, and preventing the mix to be tender when placed [10].

Graham Hurley and Brian Prowell from the National Center for Asphalt Technology (NCAT) performed a study on "Evaluation of Sasobit® for Use in Warm Mix Asphalt". The research objectives were "to determine the applicability of Sasobit® in warm mix asphalt applications including typical paving operations and environmental conditions commonly found in the United States, including the performance of mixes in quick turn-over situations and high temperature conditions" [10]. The study used two asphalt binder grades (PG 64-22 and PG 58-28) to be mixed with the Sasobit® to produce modified binders [10]. By adding either Sasobit® and Sasoflex® to the PG 58-28 binder, PG 64-22 and PG 70-22 binders were produced, respectively [10]. Sasoflex® was also added to PG 64-22 binder to produce PG 76-22 binder [10]. These binders were compared to control binders PG 64-22 and PG 76-22 containing no additives. After verifying the mix designs at 300^{o}F (149^{o}C), all combinations were also compacted at three lower temperatures (265, 230, and 190^{o}F (129, 110, 88^{o}C)) [10]. Once compacted, volumetric properties were measured on all samples. These properties indicated "increasing air voids with decreasing temperatures for some of the combinations" [10] and that "the addition of Sasobit® resulted in lower air voids than the corresponding control mixtures in all 18 aggregate, binder, and temperature combinations" [10].

The research considered Resilient Modulus, APA Rutting, Strength Gain, and Moisture Sensitivity [10]. Binder testing was also performed to determine the aging affect of Sasobit® and Sasoflex®. Comparing the original DSR results to the RTFO DSR results indicated that "the PG 64-22 with Sasobit® and the PG 70-22 with Sasoflex® both exhibited reduced aging when compared to the base binder" [10]. The results of the RTFO DSR tests, shown in Table 2.3 below, showed "the PG 58-28 base binder was 174 percent of the original DSR value, compared to 121 percent for the PG 64-22 with Sasobit® and 69 percent for the PG 70-22 with Sasoflex®. This indicated the reduced aging of the binder with the addition of Sasobit®" [10].

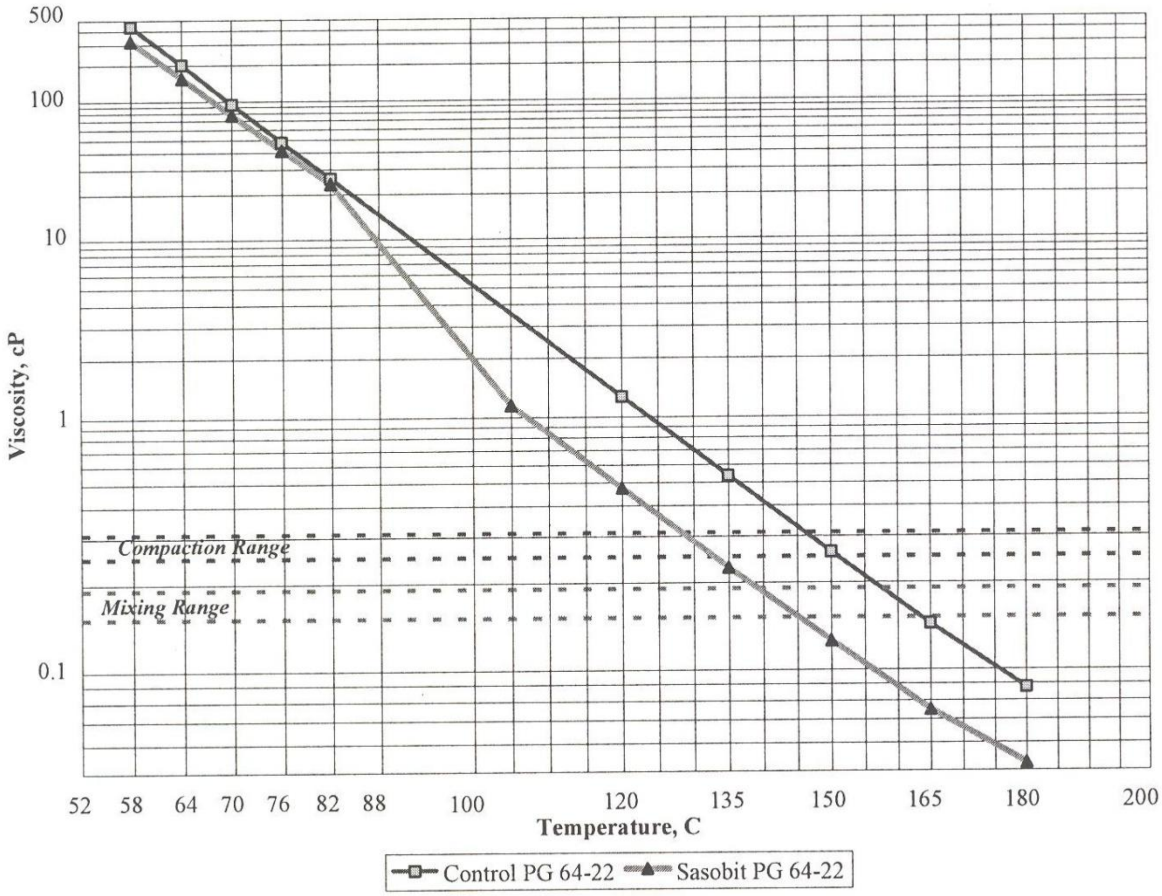
Table 2.3 Binder Test Results

Test	PG 58-28 (Base)	PG 64-22 (Control and Base)	PG 64-22 (Sasobit®)	PG 70-22 (Sasoflex)	PG 76-22	PG 76-22 (Sasoflex)
Modifier	None	None	2.5% Sasobit®	4% Sasoflex	None	4% Sasoflex
Test Temp., °C	58	64	64	70	76	76
Original DSR, G*/sin δ, kPa	1.015	1.815	1.790	2.689	1.290	1.461
RTFO DSR, G*/sin δ, kPa	2.781	3.868	3.950	4.548	3.096	2.682
Test Temp., °C	19	25	25	28	31	31
PAV DSR. G*sinδ, kPa	4138	3554	2906	2448	1059	2635
Test Temp., °C	-18	-12	-12	-12	-12	-12
BBR Creep Stiffness (S), MPa	248	208	164	153	165	251
BBR m-value	0.316	0.317	0.306	0.328	0.315	0.292[1]

[1]Does not meet the minimum requirements of AASHTO M320 (m-value > 0.300)

Source: [10]

From the binder testing, a plot of viscosity versus temperature was produced to compare the PG 64-22 modified with Sasobit® to the PG 64-22 control [10]. From Figure 2.6 below, it can be seen "how Sasobit® can reduce viscosity in the mixing and compaction temperature range while producing approximately the same (or in some cases greater) viscosity at in-service pavement temperature" [10]. Figure 2.6 also shows that a reduction in compaction temperature of approximately 32^{o}F (18^{o}C) is possible for the Sasobit® modified PG 64-22 over the PG 64-22 control [10].



Source: [10]

Figure 2.6 Mixing and Compaction Temperature for PG 64-22 Binders

A comparison of the densification results of the samples showed that except for four cases, mixtures including Sasobit® had improved compaction over the control mixtures for all binder, aggregate, and temperature combinations [10]. For the four cases that compaction was not improved, it is suggested that this is a result of including SBS(Sasolfex®) which may have caused an increase in air voids due to the stiffened binder [10]. Since there is no SBS in the mixtures containing PG 64-22, the compaction improvement was more pronounced [10]. An Analysis of Variance (ANOVA) was performed to determine which factors (aggregate type, binder grade, presence of Sasobit®, and compaction temperature) had a statistically significant impact on air voids. The ANOVA showed that for PG 64-22, "aggregate type, presence of Sasobit®, and compaction temperature were all significant, as well as all of the interactions except for the two-way interaction between aggregate type and Sasobit®" [10]. Based on a Tukey's test after the ANOVA, a reduction in air void content by an average of 0.87 percent with a 95 percent confidence interval of 0.49 to 1.25 percent was seen with the inclusion of Sasobit® [10]. The ANOVA showed that for PG 70-22, "all factors and interactions except for the presence of Sasobit® and the two-way interaction between compaction temperature and aggregate type were significant" [10]. Based on a Tukey's test after the ANOVA comparing the PG 70-22 with Sasobit® to the PG 64-22 control, a reduction in air void content by an average of 0.11 percent with a 95 percent confidence interval of -0.51 to 0.28 percent which indicates more compactability [10]. The ANOVA for PG 76-22 showed that compaction temperature and aggregate type were significant [10]. Based on a Tukey's test after the ANOVA of the PG 76-22 with Sasoflex® a reduction of air void content by an average of 0.07 percent with a 95 percent confidence interval of -0.26 to 0.41 percent [10].

Based on the Resilient Modulus comparisons, it was found that the addition of Sasobit® was not a significant factor and that it neither increased nor decreased the stiffness at any compaction temperature [10]. From the APA rutting analysis, it was determined that the rutting potential of mixtures containing Sasobit® decreased over the control mixtures [10]. However, as the mixing and compaction temperatures were reduced, the rutting potential increased, probably as a result of the decreased binder aging but the mixtures containing Sasobit® were less sensitive to this decrease [10].

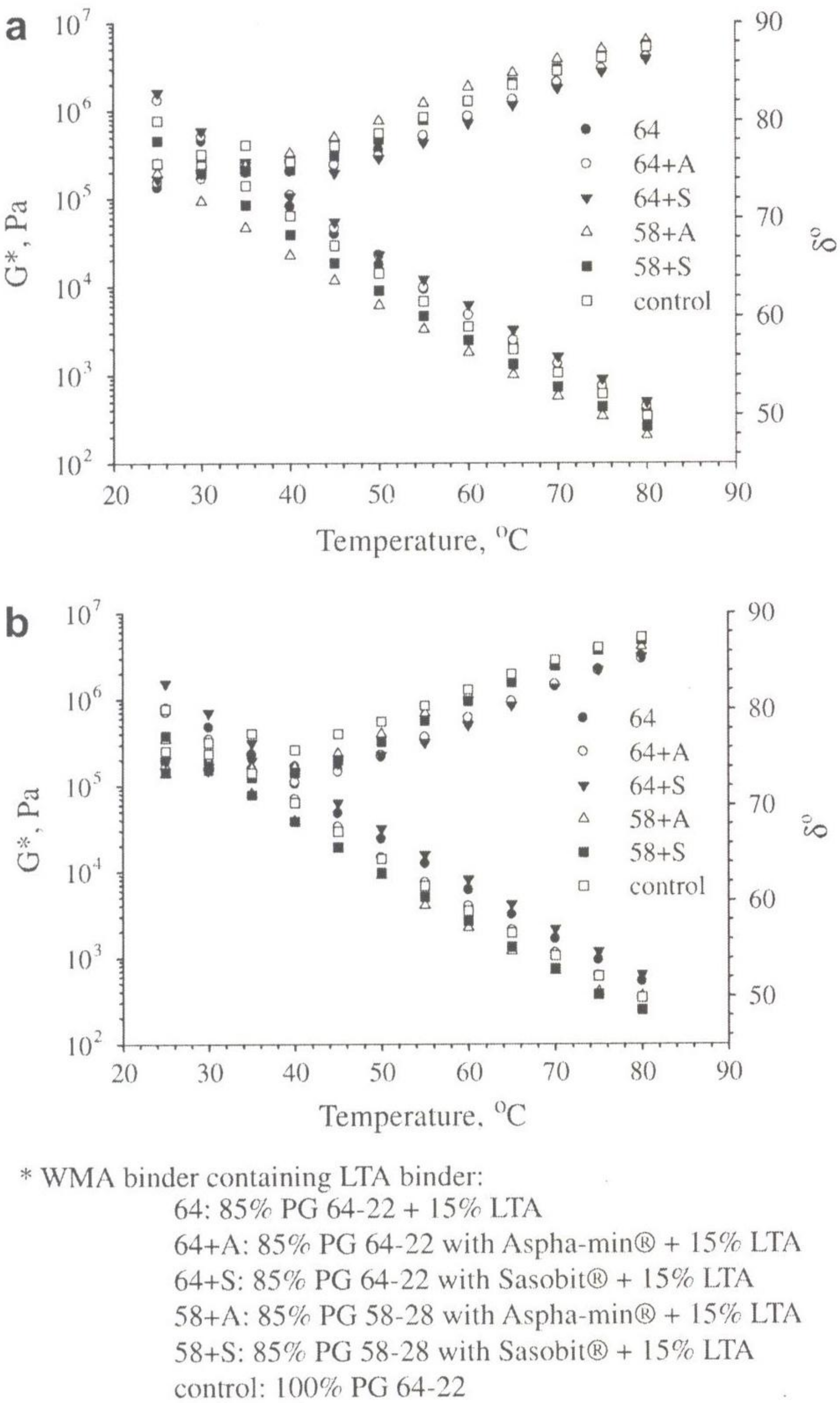
An investigation into the strength gain of the mixtures to evaluate the potential of rutting immediately after construction was performed. Results indicated that mixtures containing Sasobit® had lower indirect tensile strengths in some cases [10]. However, both the APA and Hamburg Wheel test indicated mixtures containing Sasobit® had good rutting resistance [10].

As a result of decreased mixing temperatures used with WMA, moisture susceptibility is often a concern since moisture in the aggregates may not completely evaporate. Moisture susceptibility was assessed using tensile strength ratio and Hamburg tests. The results indicated both reduced tensile strength ratio and visual stripping for both the control and mixtures containing Sasobit® produced at 250^{o}F (121^{o}C) [10]. The use of an anti-stripping agent (AKZO Nobel Magnabond) showed improved tensile strength ratios and Hamburg tests [10].

The researchers recommended that the minimum mixing and compaction temperatures should be 265^{o}F (129^{o}C) and 230^{o}F (110^{o}C), respectively [10]. They also recommended that if the mixing temperature were to drop below 265^{o}F (129^{o}C), that a grade shift one high temperature grade higher should be used to reduce the increased rutting potential and decreased production temperatures [10].

Hakseo Kim, Soon-Jae Lee and Serji N. Amirkhanian performed a study titled "Rheology of Warm Mix Asphalt Binders with Aged Binders". The objectives of the study were to "investigate the properties of WMA binders containing long-term aged (LTA) binders through a rheological tool" [11]. Both Aspha-min® and Sasobit® were the WMA additives considered in the study. LTA binders were produced using two sources of PG 64-22 binders to simulate the addition of RAP and mixtures containing 15% LTA binders and 85% virgin binders (PG 64-22 and PG 58-28) were used for comparison [11]. Flow behavior, creep loading and response, frequency dependence test and a temperature dependence test were performed to determine the rheological analyses [11].

The analysis of the viscous flow showed that at 60^{o}C, Newtonian flow was followed by the recycled WMA binders [11]. The analysis also showed that when Sasobit® was combined with the lower PG grade, shear thinning flow was observed suggesting that it could be polymerized [11]. Rut resistance at critical pavement temperature (60^{o}C) was observed with the addition of Sasobit® to the recycled binder since the viscosity increased [11]. Better rut resistance was also seen by the results of the creep recovery test and the repeated creep recovery test in binders containing the recycled WMA additives than the recycled binders alone with lower creep compliance values [11]. The recycled binders containing the WMA additives showed improved temperature susceptibility in the temperature dependence test since the percent change of the phase angle was less over the temperature increase as can be seen in Figure 2.7 below [11]. Lastly, the frequency sweep test showed better elastic properties for recycled binders containing Sasobit® with lower phase angles and high complex modulus [11].



Source: [11]

Figure 2.7 Temperature Dependence Curves: (a) Binder Source A and (b) Binder Source B

It is a widely accepted fact that the use of RAP in the construction of new asphalt pavements can be beneficial, as it provides both cost savings and a reduction of environmental effects. However, the development of Superpave did not consider the use of RAP when determining the criteria for mix and pavement design. Therefore, research has been conducted in order to determine a procedure to measure the effects of the addition of RAP to Superpave mixtures. This chapter provided an overview of different research studies that examined this effect. This chapter also gave a brief introduction on how the use of WMA technology affects the binder rheology and mixture properties. However, most of these studies focused on the addition of lower percentages of RAP and also did not research the effect of performance of using RAP in construction. Therefore, this research will focus on using higher percentages of RAP and the effects on pavement performance.

The following chapter will describe the characteristics of the materials used. It will also describe the mix design procedure and results used for this research.

Chapter 3
Material Characteristics and Mix Design

This chapter will discuss the characteristics of the materials used as well as the mix design procedure for the selected mixtures.

3.1 Virgin Materials

A single source of aggregate was used for this research. Granite aggregate from the Knightdale Quarry was procured since it reflected an aggregate commonly used in North Carolina mix designs and due to its close proximity to North Carolina State University.

Once the material was procured, the aggregates properties were measured according to AASHTO T84-88 "Specific Gravity and Absorption of Fine Aggregate" and AASHTO T85-88 "Specific Gravity and Absorption of Coarse Aggregate". Table 3.1 below contains these properties.

Table 3.1 Aggregate Specific Gravity

	Bulk S.G.	**Apparent S.G.**
Coarse	2.61	2.652
Fine	2.614	2.656

Three virgin binder grades were used in this research, PG52-28, PG 58-22 and PG 64-22. Each of the virgin binders were artificially aged in the Rolling Thin Film Oven (RTFO) in order to simulate the aging due to the mixture process and construction. The residue from the RTFO was then aged further in the Pressure Aging Vessel (PAV) in order to simulate long term aging.

Dynamic Shear Rheometer (DSR) testing was completed on the virgin binders according to AASHTO TP5-93 "Test Method for Determining the Rheological Properties of Asphalt Binder Using a Dynamic Shear Rheometer". The DSR testing produced rheological properties for the binders including complex modulus (G*) and the phase angle (delta, δ). Each binder was tested at several temperatures in order to form various temperature gradients to be used for the blending charts discussed in the next chapter.

Bending Beam Rheometer (BBR) testing was also completed on the virgin binders according to AASHTO T 313-09 “Standard Method of Test for Determining the Flexural Creep Stiffness of Asphalt Binder Using the Bending Beam Rheometer (BBR)”. The BBR testing produced rheological properties for the binders including creep stiffness (S) and slope (m).

Table 3.2, Table 3.3, Table 3.4 and Table 3.5 below contain the rheological data obtained from the DSR and BBR tests used to verify the virgin binder grades. According to AASHTO R-29 “Standard Practice for Grading or Verifying the Performance Grade of an Asphalt Binder” , the Performance Grade (PG) of the binder was verified. Determine the high temperature grade by finding the highest temperature that satisfies both $G^*/\sin\delta \geq 1.0$ kPa for original binder and $G^*/\sin\delta \geq 2.2$ kPa for RTFO aged binder. Determine the intermediate temperature grade by finding the temperature which satisfies $G^*\sin\delta \leq 5000$ kPa. Determine the low temperature by finding the warmest low temperature that satisfies both $S \leq 300$ MPa and m-value ≥ 0.300. Tables 3.2-3.5 show that the virgin binders meet or exceed these specifications at the corresponding temperatures for the specified PG.

Table 3.2 Binder Rheological Properties-DSR Original Binder

Virgin Binder Grade	**Average G*/sinδ (kPa) (Standard Deviation) At Test Temperature**				
	52°C	**58 °C**	**64 °C**	**70 °C**	**76 °C**
PG 52-28	1.58 (0.02)	0.76 (0.10)	0.41 (0.03)	0.21 (0.01)	0.12 (0.01)
PG 58-22		1.62 (0.12)	0.78 (0.05)	0.38 (0.04)	0.21 (0.02)
PG 64-22			1.71 (0.14)	0.85 (0.07)	0.83 (0.02)

Table 3.3 Binder Rheological Properties-DSR RTFO Binder

Virgin Binder Grade	Average G*/sinδ (kPa) (Standard Deviation) At Test Temperature				
	52°C	58 °C	64 °C	70 °C	76 °C
PG 52-28	3.54 (0.18)	1.57 (0.09)	0.75 (0.03)	0.38 (0.02)	0.20 (0.01)
PG 58-22		5.05 (0.27)	2.43 (0.07)	1.23 (0.04)	0.64 (0.05)
PG 64-22			5.25 (0.14)	2.51 (0.04)	1.23 (0.03)

Table 3.4 Binder Rheological Properties-DSR PAV Binder

Virgin Binder Grade	Average G*(sinδ) (kPa) (Standard Deviation) At Test Temperature					
	16 °C	19 °C	22 °C	25 °C	28 °C	31 °C
PG 52-28	3284 (504)	2110 (329)	1336 (212)	827 (134)	516 (88)	322 (58)
PG 58-22	5472 (128)	3639 (76)	2393 (40)	1551 (15)	1019 (3)	675 (3)
PG 64-22	12115 (486)	8755 (356)	5884 (242)	3954 (173)	2659 (126)	1776 (95)

Table 3.5 Virgin Binder Rheological Properties-BBR PAV Binder

Virgin Binder Grade	Creep Stiffness (Mpa)	Slope (m)
PG 52-28	194	0.375
PG 58-22	80.7	0.405
PG 64-22	170.5	0.349

3.2 RAP Sources

Two RAP sources were sought out to be used in this research. It was desired to choose two sources that had various stiffness, gradation and asphalt content in hopes to be able to apply the results of this research as widely as possible. In order to achieve this, eight different sources of RAP were selected from across the state. RAP samples from each of the eight sources were procured. The binder from the RAP was extracted by NCDOT personnel for rheological testing according to AASHTO T 319 "Quantitative Extraction and Recovery of

Asphalt Binder from Hot Mix Asphalt”. The recycled binder was dissolved and washed from the aggregate using Toulene, a strong solvent. The binder was then be reclaimed by heating the mixture and distilling the solvent. Ignition testing was also performed according to AASHTO TP 53-95 “Test Method for Determining the Asphalt Content of Hot Mix Asphalt (HMA) by Ignition Method” on each of the samples in order to perform sieve analysis and to determine the asphalt content.

Table 3.6 contains the source of each RAP. Table 3.7 below contains the gradation for each of the RAP sources. Table 3.8 below contains the average asphalt content for each of the RAP sources.

Table 3.6 RAP Source Key

RAP	Source
RAP #1	Barnhill, Fayetteville RAP #1
RAP #2	Barnhill, Fayetteville RAP #2
RAP #3	Maymeade Marion
RAP #4	Blythe Pineville
RAP #5	ST Wooten Wilmington
RAP #6	CC Mangum Knightdale
RAP #7	CC Mangum Westgate
RAP #8	REA West Raleigh

Table 3.7 Average RAP Aggregate Gradations

Sieve Size (mm)	RAP #1	RAP #2	RAP #3	RAP #4	RAP #5	RAP #6	RAP #7	RAP #8
37.5	100	100	100	100	100	100	100	100
25.0	100	100	100	100	100	100	100	100
19.0	100	100	100	100	100	100	100	100
12.5	99	99	98	98	98	100	98	99
9.5	97	96	91	93	95	97	95	96
4.75	81	85	70	74	84	83	79	77
2.36	65	73	48	59	70	67	63	60
1.18	54	62	34	50	60	52	50	48
0.600	40	47	25	40	49	38	37	35
0.300	25	27	18	27	35	24	26	24
0.150	15	14	13	17	18	14	16	15
0.075	8.5	8.6	9.4	10.2	11.4	8.8	10.3	9.4

Table 3.8 Average RAP Asphalt Content

RAP Source	Asphalt Content (%)
RAP #1	5.6
RAP #2	5.1
RAP #3	4.1
RAP #4	4.8
RAP #5	5.5
RAP #6	4.7
RAP #7	5.2
RAP #8	5.2

The binders extracted from the RAP were artificially aged in the RTFO in order to simulate the aging due to the mixture process and construction. The residue from the RTFO was then aged further in the PAV in order to simulate long term aging.

DSR testing was completed on the binder extracted from each RAP source according to AASHTO TP5-93 “Test Method for Determining the Rheological Properties of Asphalt Binder Using a Dynamic Shear Rheometer”. The DSR testing produced rheological properties for the binders including complex modulus (G*) and the phase angle (delta, δ). Tables 3.9-3.11 contain the rheological data for the original, RTFO and PAV aged binders, respectively. As can be seen by the data in Tables 3.9-3.10 the G*/sinδ values from the recovered RAP binder are much higher than the G*/sinδ values of the virgin binders in Tables 3.2-3.3. This is a result of the increases stiffness of the RAP binders due to the aging that occurred during its service life. Table 3.12 shows that the RAP binders pass the specification of PAV aged binders at warmer temperatures than the virgin binders. Again this is a result of the increased stiffness of the RAP binder.

Table 3.9 Average G*/sinδ for Original RAP Binders

Temperature (^{o}C)	Average G*/sinδ for Original RAP Binders (kPa)							
	Barnhill 1	Barnhill 2	CCM-Knightdale	CCM-Westgate	Maymeade Marion	Pineville	REA	ST Wooten
64		45.7		37.0		29.8	22.1	32.9
70		20.4		17.8		13.4	10.3	14.8
76	5.4	9.2	6.4	8.6	3.5	6.1	4.9	6.8
82	2.6	4.2	3.3	4.1	1.7	2.9	2.4	3.1
88	1.3	2.0	1.7	2.1	0.8	1.4	1.2	1.5

Table 3.10 Average G*/sinδ for RTFO Aged RAP Binders

Temperature (^{o}C)	Average G*/sinδ for Original RAP Binders (kPa)							
	Barnhill 1	Barnhill 2	CCM-Knightdale	CCM-Westgate	Maymeade Marion	Pineville	REA	ST Wooten
64				112.8				
70				52.9				
76	46.7	13.0	24.1	24.9	15.8	20.7	25.8	42.3
82	22.5	6.1	11.9	11.6	7.0	9.6	12.3	19.1
88	10.8	3.0	5.8	5.6	3.2	4.5	6.0	8.6

Table 3.11 Average G*sinδ for PAV Aged RAP Binders

Temperature (^{o}C)	Average G*sinδ for Original RAP Binders (kPa)							
	Barnhill 1	Barnhill 2	CCM-Knightdale	CCM-Westgate	Maymeade Marion	Pineville	REA	ST Wooten
28							7134.3	
31	12518.3	7460.7	8758.7	6213.6	10651.4		5472.6	13491.9
34	9758.0	5415.4	6565.4	5505.6	7906.7	7039.6	4547.4	10266.6
37	7360.1	3845.2	4834.9	4453	5669.1	5133.7		7620.1
40	5429.0		3767.4		5193.6	3749.7		7879.8
43	4419.5				3643.8			5626.5

In order for the results of the research to be applicable to as much of the state as possible, it is desirable to choose two RAP sources that differ in characteristics. The two RAP sources selected were Blythe Pineville and CC Mangum Westgate. The Blythe Pineville RAP consists of a coarse gradation and a low asphalt content. The DSR testing shows that the binder is less stiff than the others. The CC Mangum Westgate RAP consists of a coarse gradation and a higher asphalt content. The DSR testing shows that the binder is stiffer than most others. The two RAP sources also represent various regions of the state, with Blythe Pineville coming from the southwestern region and CC Mangum Westgate coming from the central region. The gradations resulting from blending the RAP sources at various percentages with the virgin gradation meets specifications for both 9.5 mm mixtures as well as 19.0 mm mixtures which are the two mixtures that were used in this project.

Tables 3.12-3.14 show the full comparison of DSR testing for the two RAP sources. Due to the increase in stiffness of the reclaimed RAP binder, the specifications for DSR testing on both unaged binder and RTFO aged binder are met for all temperatures. However, for the DSR testing on the PAV aged binder, the reclaimed RAP binder does not pass the specification at any temperature. Blending the RAP binder with virgin binders is needed in order for the specification to be met.

Table 3.12 RAP Binder Rheological Properties-Original Binder

RAP Source	Average G*/sinδ (kPa) (Standard Deviation) At Test Temperature				
	52°C	58 °C	64 °C	70 °C	76 °C
Westgate	154.6 (5.2)	70.3 (2.1)	33.5 (3.3)	15.8 (1.8)	7.5 (1.0)
Pineville	228.8 (2.8)	97.6 (1.4)	36.2 (6.8)	16.0 (2.9)	7.2 (1.2)

Table 3.13 RAP Binder Rheological Properties-RTFO Binder

RAP Source	Average G*/sinδ (kPa) (Standard Deviation) At Test Temperature				
	52°C	58 °C	64 °C	70 °C	76 °C
Westgate	630.1 (40.7)	283.8 (16.9)	112.8 (N/A)	52.9 (N/A)	24.9 (0.03)
Pineville	563.2 (34.9)	251.2 (15.0)	110.8 (6.0)	49.8 (2.4)	21.4 (1.1)

Table 3.14 RAP Binder Rheological Properties-PAV Binder

RAP Source	Average G*(sinδ) (kPa) (Standard Deviation) At Test Temperature					
	16 °C	19 °C	22 °C	25 °C	28 °C	31 °C
Westgate	30708.6 (1089.0)	25441.2 (888.1)	20494.4 (679.2)	15982.0 (609.0)	12192.1 (467.2)	9084.7 (345.7)
Pineville	26916.1 (3758.8)	22378.6 (3283.3)	18242.3 (2889.0)	14358.6 (2355.3)	11092.3 (1838.0)	8366.3 (1369.3)

3.3 Mix Design Procedure

Since PG 64-22 is a prominent asphalt binder grade used in North Carolina, mixtures using PG 64-22 were desired for this project. One surface course and one binder course were desired in order to analyze the different effects of higher percentages of RAP in the different courses. S-9.5B and I-19.0C were the two NCDOT mixture types selected for use in this project.

Virgin mix designs, those mixes containing 0% RAP, were conducted for both the 9.5 mm and 19.0 mm mixtures. Initially, three trial aggregate structures were chosen that passed the control points for the respective nominal maximum size aggregate mixtures. Table 3.15 contains the three trial aggregate structures for the 9.5 mm mixtures. The three trial aggregate structures were mixed at a constant binder content. Based on the volumetric calculations for the trial aggregate structures, a design aggregate structure was selected based on the specified NCDOT volumetric properties. Table 3.16 contains the volumetric properties for each of the trial aggregate structures. As can be seen in the table, only the first trial aggregate structure satisfies all the specifications. Therefore, this will become the design aggregate structure. Table 3.17 below contains the design aggregate structure for the 9.5 mm mixture. Figure 3.1 below shows the 9.5 mm design aggregate gradation.

Table 3.15 9.5 mm Trial Aggregate Structures

	% Passing		
Sieve Size, mm	Trial Blend #1	Trial Blend #2	Trial Blend #3
12.5	100	100	100
9.5	97	93	95
4.75	86	58	70
2.36	65	41	40
1.18	50	27	29
0.6	30	18	22
0.3	22	13	17
0.15	10	8	8
0.075	6	4	5

Table 3.16 Trial Aggregate Structure Volumetric Properties

	Trial Blend #1	Trial Blend #2	Trial Blend #3	NCDOT Spec
Trial Asphalt Content % of Total Mixture	5.3	5.3	5.3	--
% G_{mm} at N_{des}	94.9	96.9	96.8	--
% Air Voids at N_{des}	5.06	3.06	3.19	--
Corrected Air Voids at N_{des}	4.0	4.0	4.0	**4.0**
Estimated Asphalt Content (P_b) for 4% Air Voids	5.6	4.8	4.9	--
Estimated VMA at P_b	15.5	**13.8**	**14.0**	**Min. 15.0 %**
Estimated VFA at P_b	74.2	71.1	71.3	**65-80**
% G_{mm} at N_{ini}	87.9	86.3	86.9	**Max. 90.5**
Estimated Effective Asphalt Content	5.15	4.35	4.40	--
Dust Proportion	1.165	0.920	1.136	**0.6-1.4**

Table 3.17 9.5 mm Design Aggregate Structure

	% Passing	
Sieve Size, mm	**Mix Gradation**	**Control Points**
12.5	100	100
9.5	97	90-100
4.75	86	> 90
2.36	65	32-67
1.18	50	
0.6	30	
0.3	22	
0.15	10	
0.075	6	2-10

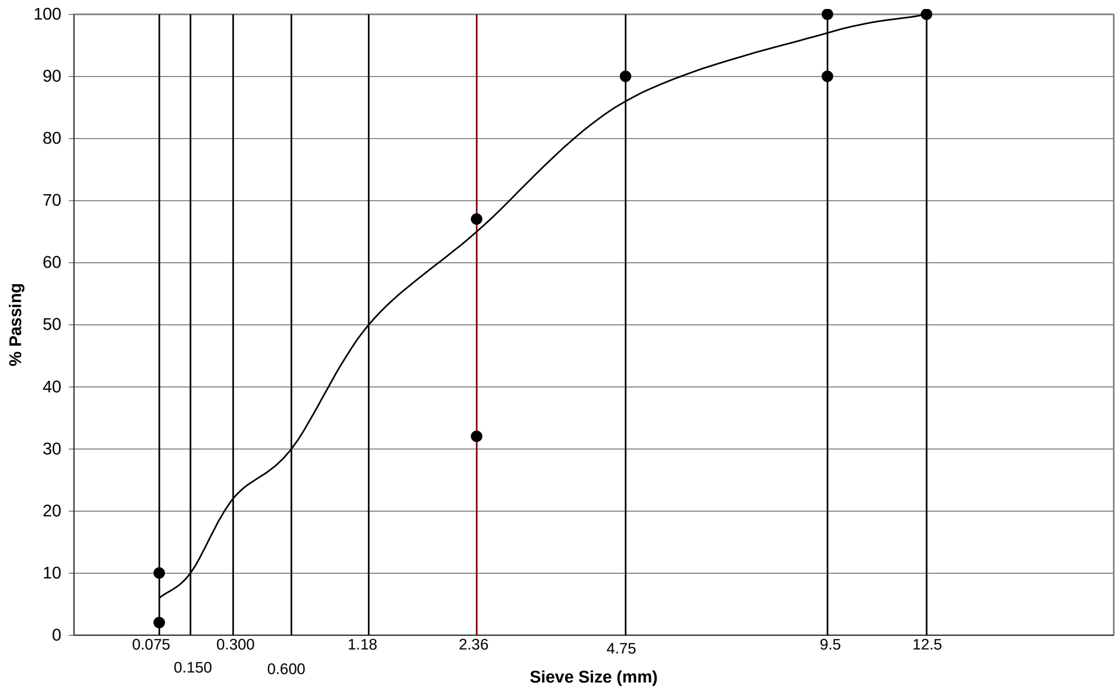


Figure 3.1 Gradation

Table 3.18 contains the three trial aggregate structures for the 19.0 mm mixtures. The three trial aggregate structures were mixed at a constant binder content. Based on the volumetric calculations for the trial aggregate structures, a design aggregate structure was selected based on the specified NCDOT volumetric properties. Table 3.19 contains the volumetric properties for each of the trial aggregate structures. As can be seen in the table, only the third trial aggregate structure satisfies all the specifications. Therefore, this will become the design aggregate structure. Table 3.20 below contains the design aggregate structure for the 19.0 mm mixture. Figure 3.2 below shows the 19.0 mm design aggregate gradation.

Table 3.18 19.0 mm Trial Aggregate Structures

Sieve Size, mm	% Passing		
	Trial Blend #1	Trial Blend #2	Trial Blend #3
25.0	100	100	100
19.0	95	94	93
12.5	76	73	75
9.5	61	60	65
4.75	44	37	40
2.36	32	25	27
1.18	21	14	16
0.6	15	11	10
0.3	12	8	7
0.15	10	5	5
0.075	5	4	4

Table 3.19 Trial Aggregate Structure Volumetric Properties

	Trial Blend #1	Trial Blend #2	Trial Blend #3	NCDOT Spec
Trial Asphalt Content % of Total Mixture	4.4	4.4	4.4	--
% G_{mm} at N_{des}	94.9	95.1	92.6	--
% Air Voids at N_{des}	5.1	4.96	7.36	--
Corrected Air Voids at N_{des}	4	4	4	**4.0**
Estimated Asphalt Content (P_b) for 4% Air Voids	5.1	5.0	6.1	--
Estimated VMA at P_b	14.0	14.6	15.5	**Min. 13.0 %**
Estimated VFA at P_b	**63.7**	66.1	74.1	**65-75**
% G_{mm} at N_{ini}	84.7	84.7	82.9	**Max. 90.0**
Estimated Effective Asphalt Content	3.82	4.32	5.6	--
Dust Proportion	**1.832**	**1.619**	0.710	**0.6-1.4**

Table 3.20 19.0 mm Design Aggregate Structure

Sieve Size, mm	% Passing	
	Mix Gradation	Control Points
25.0	100	100
19.0	93	90-100
12.5	75	> 90
9.5	65	
4.75	40	
2.36	27	23-49
1.18	16	
0.6	10	
0.3	6	
0.15	5	
0.075	4	3-8

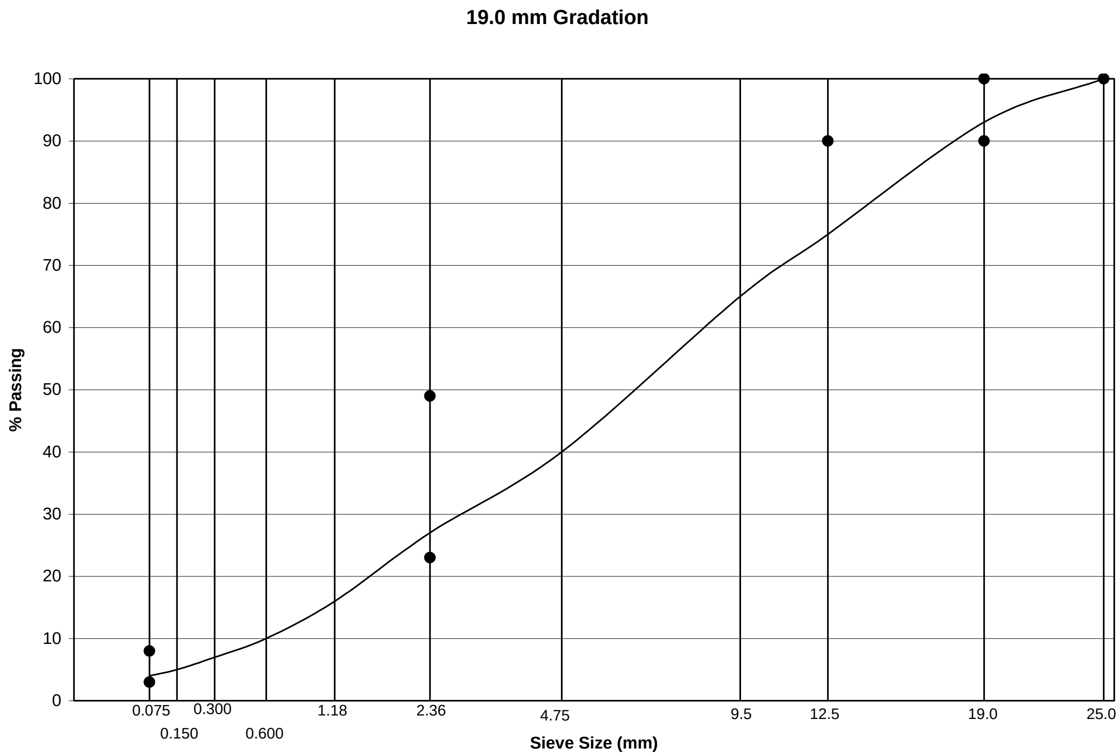


Figure 3.2 Gradation

Once the design aggregate structure was selected, mixtures with different asphalt contents (± 0.5, +1% initial asphalt content) were tested in order to determine the optimum asphalt content based on 4% air voids at N_{des}. The optimum asphalt contents for the 9.5 mm mixtures with PG 64-22 binder, PG 58-22 binder and PG 52-28 binder were 5.56%, 5.37% and 5.765%, respectively. The optimum asphalt contents for the 19.0 mm mixtures with PG 64-22 binder, PG 58-22 binder and PG 52-28 binder were 5.24%, 5.37% and 5.04%, respectively. Once the optimum asphalt content was determined, volumetric properties were checked at the corresponding asphalt content to determine if the specifications were met. Table 3.21, Table 3.22 and Table 3.23 below compare the volumetric properties at the optimum asphalt content to the specifications for the 9.5 mm mixtures with PG 64-22 binder, PG 58-22 binder and PG 52-28, respectively. Table 3.24, Table 3.25 and Table 3.26 below compare the volumetric properties at the optimum asphalt content to the specifications for the 19.0 mm mixtures with PG 64-22 binder, PG 58-22 binder and PG 52-28, respectively.

Table 3.21 Volumetric Properties for 9.5 mm Mixture with PG 64-22 Binder

	Mixture	**Specification**
%Air	4%	4%
%VMA	15.53	> 15%
%VFA	73.8	65-80%
%Gmm @ Nini	87.9	≤ 90.5%

Table 3.22 Volumetric Properties for 9.5 mm Mixture with PG 58-22 Binder

	Mixture	**Specification**
%Air	4%	4%
%VMA	15.61	> 15%
%VFA	74.1	65-80%
%Gmm @ Nini	88.2	≤ 90.5%

Table 3.23 Volumetric Properties for 9.5 mm Mixture with PG 52-28 Binder

	Mixture	**Specification**
%Air	4%	4%
%VMA	15.48	> 15%
%VFA	74.1	65-80%
%Gmm @ Nini	88.1	≤ 90.5%

Table 3.24 Volumetric Properties for 19.0 mm Mixture with PG 64-22 Binder

	Mixture	**Specification**
%Air	4%	4%
%VMA	14.3	> 13%
%VFA	72.2	65-75%
%Gmm @ Nini	85.5	≤ 90%

Table 3.25 Volumetric Properties for 19.0 mm Mixture with PG 58-22 Binder

	Mixture	**Specification**
%Air	4%	4%
%VMA	14.52	> 13%
%VFA	72.9	65-75%
%Gmm @ Nini	87.8	≤ 90%

Table 3.26 Volumetric Properties for 19.0 mm Mixture with PG 52-28 Binder

	Mixture	**Specification**
%Air	4%	4%
%VMA	14.26	> 13%
%VFA	72.27	65-75%
%Gmm @ Nini	86.3	≤ 90%

These mix designs were also used for the fabrication of specimens that contained RAP. Mixtures containing 15%, 30% and 40% RAP were considered for this project. In order for the results of the mixture characterization discussed in Chapter 5 of both the virgin and RAP specimens to be comparable, the RAP specimens were fabricated using the same mix design as the virgin specimens. In order to account for the aggregates contained in the RAP, the gradation used for the virgin mix designs was adjusted so that the combination of the aggregates contributed by the RAP and the virgin aggregates would follow the original virgin gradation as closely as possible. The amount of virgin asphalt binder was also adjusted to account for the binder contributed by the RAP.

This chapter has described the characteristics of the materials used in this research. It also gave an overview of the mix design for the virgin mixtures. The next chapter will discuss the blending charts developed from the rheological testing conducted for this chapter.

Chapter 4
Asphalt Binder Blending Charts

In this chapter, the binder rheology of the blended RAP binders and the formation of blending charts will be discussed. The blending charts will allow contractors to determine the amount of RAP that is acceptable to use in mixtures.

4.1 Dynamic Shear Rheometer Testing

Dynamic Shear Rheometer (DSR) testing was completed on the blended binders according to AASHTO TP5-93 "Test Method for Determining the Rheological Properties of Asphalt Binder Using a Dynamic Shear Rheometer". The DSR testing produced rheological properties for the binders including complex modulus (G*) and the phase angle (delta, δ). Each binder was tested at several temperatures in order to form various temperature gradients for the blending charts. The blended binders consisted of a mix of 70% virgin binder and 30% binder extracted from the RAP sources. Binders were aged in the Rolling Thin Film Oven (RTFO) to simulate short term aging caused during construction and then aged in the Pressure Aging Vessel (PAV) to simulate long term aging.

Table 4.1 below contain the average $G^*/\sin\delta$ values for the original blended binders. The standard deviation is denoted in the parenthesis. Figure 4.1 depicts the results of Table 4.1.

Table 4.1. G*/sinδ Values for Original Blended Binders

Virgin Binder Grade	RAP Source	Average G*/sinδ (kPa) (Standard Deviation) At Test Temperature				
		52°C	58 °C	64 °C	70 °C	76 °C
PG 52-28	Westgate	8.52 (0.82)	3.69 (0.30)	1.59 (0.14)	0.76 (0.07)	0.42 (0.02)
	Pineville	6.20 (0.27)	2.30 (0.45)	1.06 (0.18)	0.60 (0.03)	0.30 (0.02)
PG 58-22	Westgate		6.16 (0.50)	2.73 (0.16)	1.34 (0.04)	0.68 (0.02)
	Pineville		5.47 (0.27)	2.41 (0.21)	1.19 (0.09)	0.61 (0.04)
PG 64-22	Westgate			4.87 (0.32)	2.35 (0.15)	1.14 (0.07)
	Pineville			3.74 (0.04)	1.83 (0.04)	0.91 (0.01)

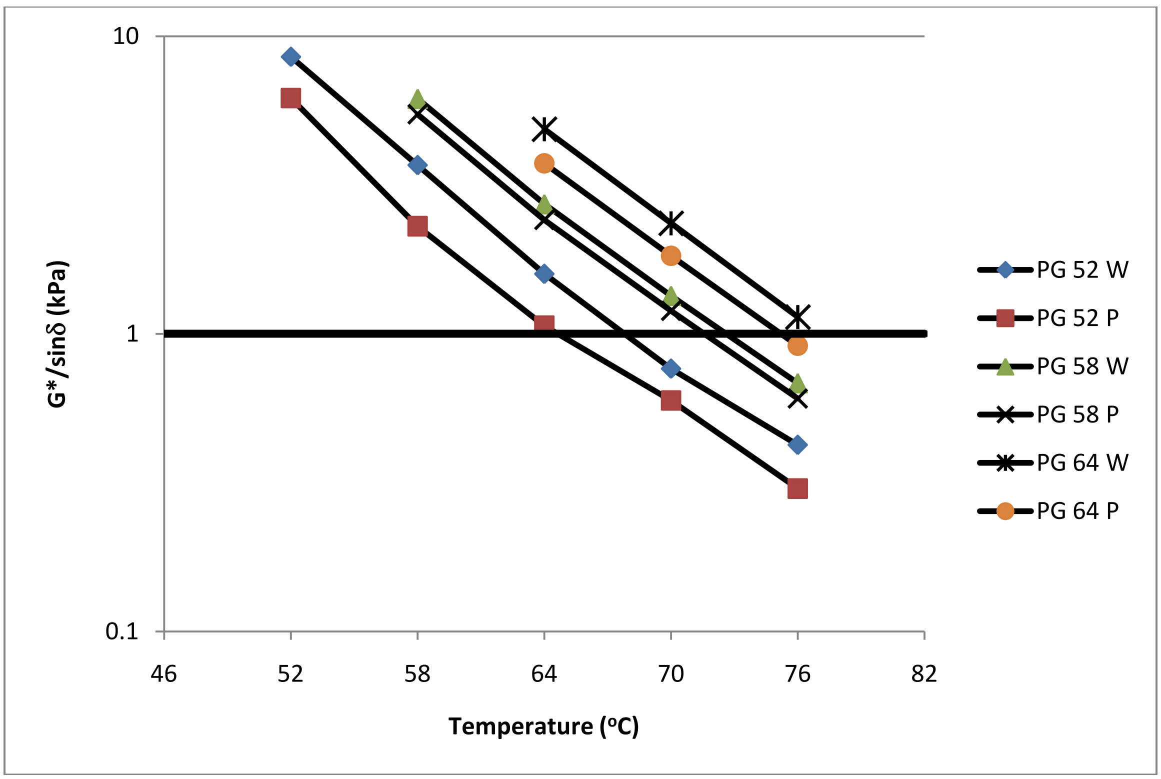


Figure 4.1 DSR Test Results for Blended Original Aged Binders Containing 30% RAP

The results of Figure 4.1 depict how the addition of 30% RAP increases the stiffness of the binder grade. Due to this increase, the high temperature grading for the binder has increased from the original virgin binder. To determine the high temperature grade, determine the highest temperature that G*/sinδ ≥ 1.0 kPa. PG 52 binders become PG 64, PG 58 binders become PG 70 and PG 64 binders become PG76. This shows that the addition of 30% RAP increases the original binder by two grades.

Table 4.2 below contain the average G*/sinδ values for the RTFO aged blended binders. The standard deviation is denoted in the parenthesis. Figure 4.2 depicts the results of Table 4.2.

Table 4.2 G*/sinδ Values for RTFO Aged Blended Binders

Virgin Binder Grade	RAP Source	Average G*/sinδ (kPa) (Standard Deviation) At Test Temperature				
		52°C	**58°C**	**64°C**	**70°C**	**76°C**
PG 52-28	**Westgate**	21.74 (1.90)	9.20 (0.66)	4.14 (0.23)	1.90 (0.13)	0.92 (0.07)
	Pineville	6.31 (0.46)	2.65 (0.13)	1.21 (0.07)	0.55 (0.05)	0.30 (0.03)
PG 58-22	**Westgate**		22.35 (1.88)	10.77 (0.62)	5.12 (0.26)	2.52 (0.09)
	Pineville		15.95 (0.60)	7.35 (0.29)	3.50 (0.12)	1.72 (0.06)
PG 64-22	**Westgate**			17.11 (1.44)	7.81 (0.82)	3.63 (0.47)
	Pineville			17.26 (0.95)	7.99 (0.59)	3.73 (0.36)

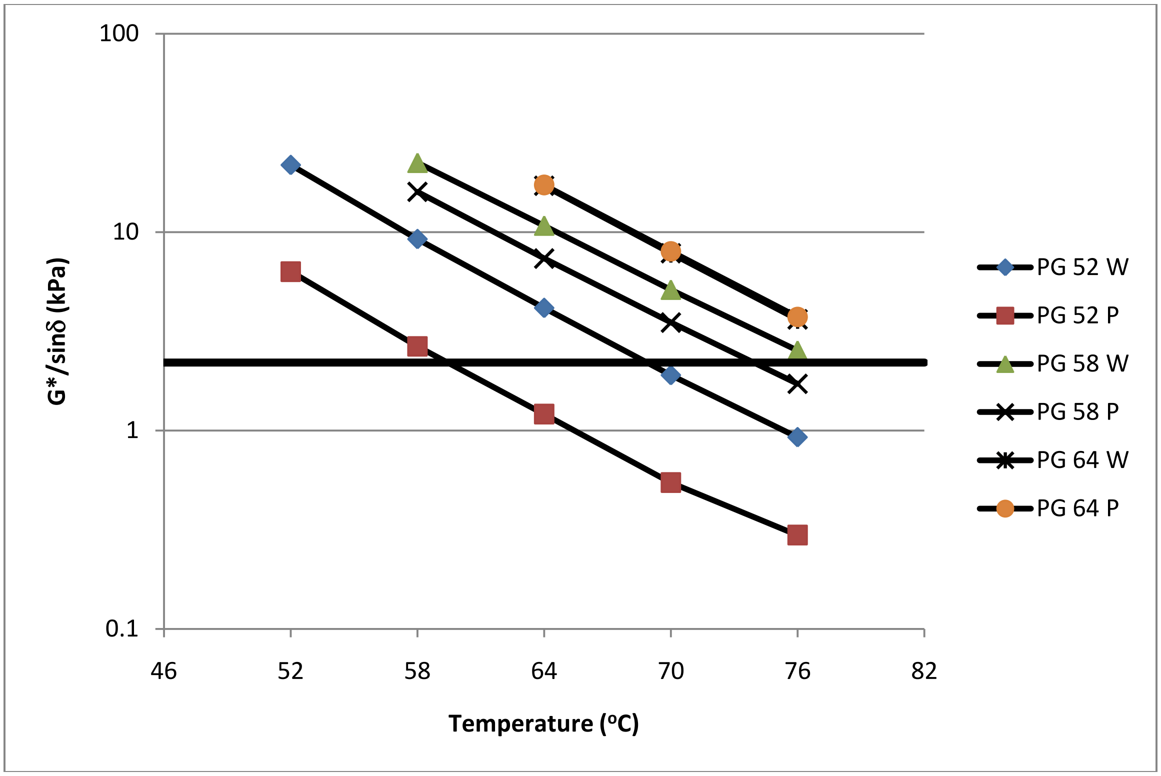


Figure 4.2 DSR Test Results for Blended RTFO Aged Binders Containing 30% RAP

The results of Figure 4.2 depict how the addition of 30% RAP increases the stiffness of the binder grade. Due to this increase, the high temperature grading for the binder has increased from the original virgin binder. To determine the high temperature grade, determine the highest temperature that G*/sinδ ≥ 2.2 kPa. The PG 52 Pineville blended binder becomes PG 58, the PG 52 Westgate blended binder becomes PG 64, the PG 58 Pineville blended binder becomes PG 70, the PG 58 Westgate blended binder becomes PG 76 and the PG 64 binders become PG76. This shows that the addition of 30% RAP increases the original binder by at least two grades, with the exception of the PG 52 Pineville binder blend.

For both the original and RTFO aged binders, as the temperature increases the value of G*/sinδ decrease while holding the binder constant. Similarly, the value of G*/sinδ increases as the virgin binder grade increases from PG 52-28 to PG64-22 while holding the temperature constant. This is expected because the PG 52-28 is a softer binder than both PG 58-22 and PG 64-22.

Table 4.3 below contains the average G*(sinδ) values for the PAV aged blended binders. The standard deviation is denoted in the parenthesis. Figure 4.3 depicts the results of Table 4.3.

Table 4.3 Average G*(sinδ) for PAV Aged Binders.

Virgin Binder Grade	RAP Source	Average G*(sinδ) (kPa) (Standard Deviation) At Test Temperature					
		16 °C	19 °C	22 °C	25 °C	28 °C	31 °C
PG 52-28	Westgate	9753 (1261)	7022 (917)	4923 (639)	3378 (440)	2309 (302)	1437 (830)
	Pineville	10196 (580)	7233 (384)	5039 (272)	3411 (185)	2304 (124)	1533 (84)
PG 58-22	Westgate	8223 (230)	5913 (N/A)	3998 (N/A)	2761 (1594)	1906 (1102)	1285 (38)
	Pineville	8962 (781)	6245 (528)	4309 (364)	2904 (245)	1964 (164)	1319 (110)
PG 64-22	Westgate	11438 (442)	8795 (345)	6345 (269)	4541 (195)	3259 (148)	2307 (114)
	Pineville	11062 (416)	8490 (322)	6209 (320)	4300 (95)	3073 (75)	2167 (69)

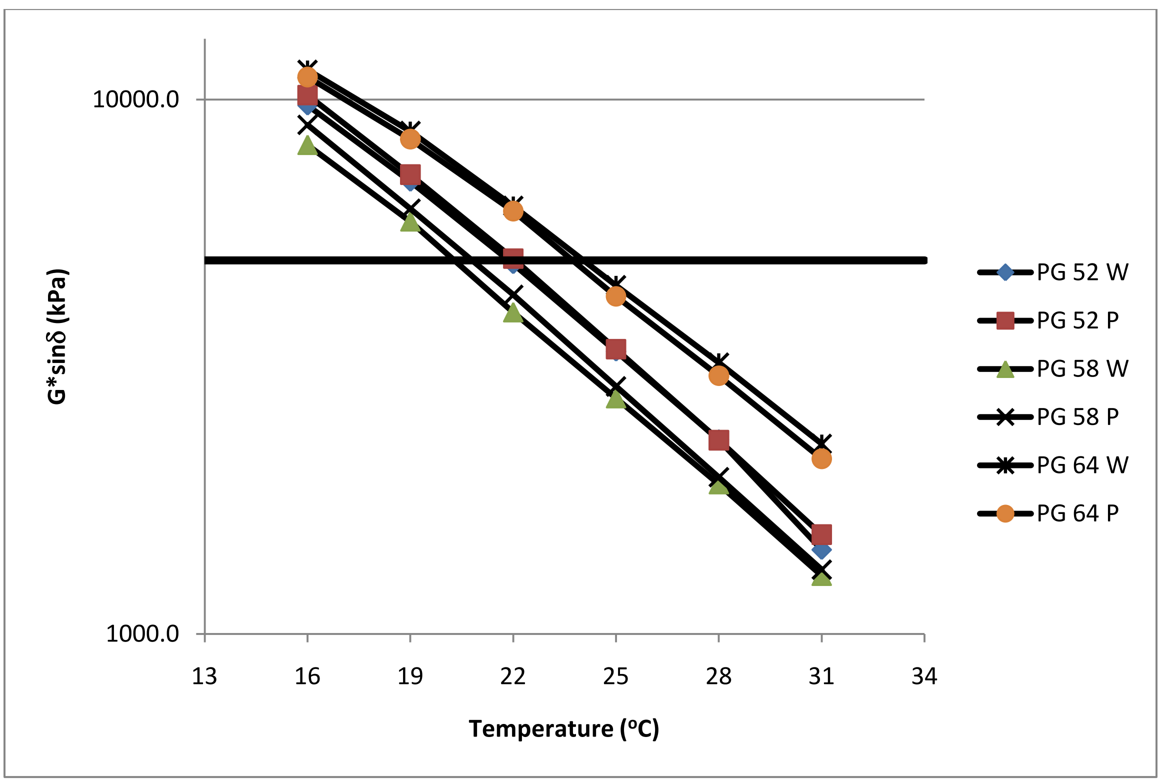


Figure 4.3 DSR Test Results for Blended PAV Aged Binders Containing 30% RAP

The results of Figure 4.3 depict how the addition of 30% RAP increases the stiffness of the binder grade. The performance grade of the binder can be determined by selecting the temperature that satisfies the $G^*\sin\delta \leq 5000$ kPa requirement. The PG 52 Westgate blend and PG 58 binders satisfy the requirement at 22^{o}C while the PG 52 Pineville blend and PG 64 binders satisfy the requirement at 25^{o}C. The PG 58 and PG 64 binders passing at these temperatures translate to a low binder grade of -22, the same as the virgin binder. However, the PG 52 Pineville blend and PG 52 Westgate blend pass at temperatures that translate to a lower binder grade of -10 and -16, respectively, for the original binder grade.

The above data, along with the rheological data from the virgin binders and the RAP binders discussed in the previous chapter were compiled together to form blending charts. Once the data was plotted, exponential trendlines were added for each temperature combination. The exponential equations were used to determine the amount of RAP that can be used at certain temperatures in order to meet the specifications for the given test. Figures 4.4-4.12 below contain the blending charts for each combination of virgin binder. The figures can be used to determine the percentage of RAP necessary to meet the requirement of $G^*/\sin\delta \geq 1.0$ kPa for original binders, $G^*/\sin\delta \geq 2.2$ kPa for RTFO aged binders and $G^*\sin\delta \leq 5000$ kPa for PAV aged binders.

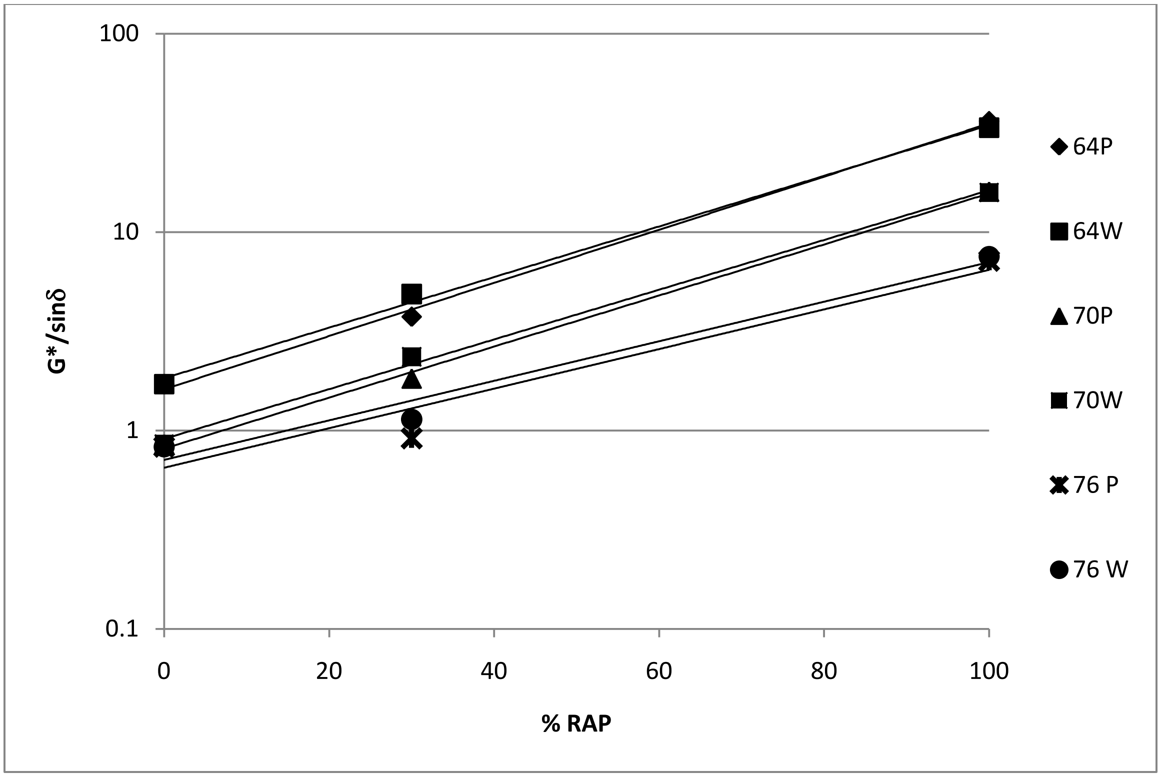


Figure 4.4 DSR Original PG 64-22 Blending Chart

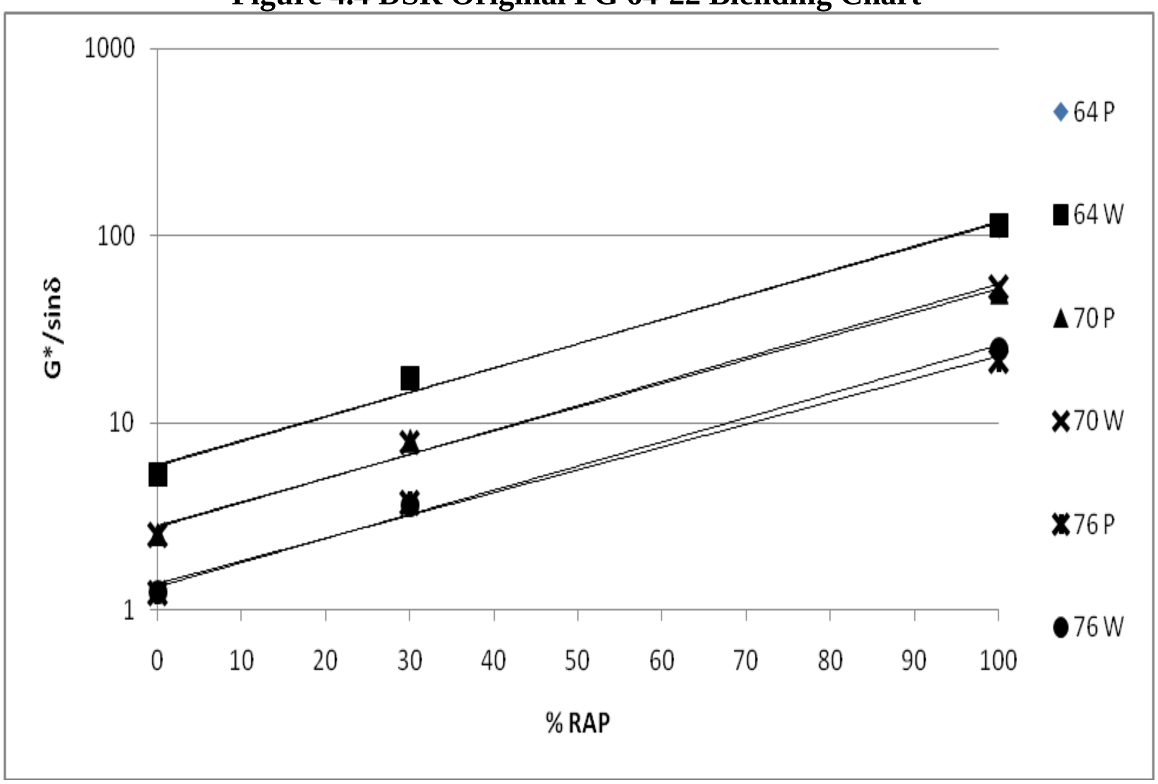


Figure 4.5 DSR RTFO PG 64-22 Blending Chart

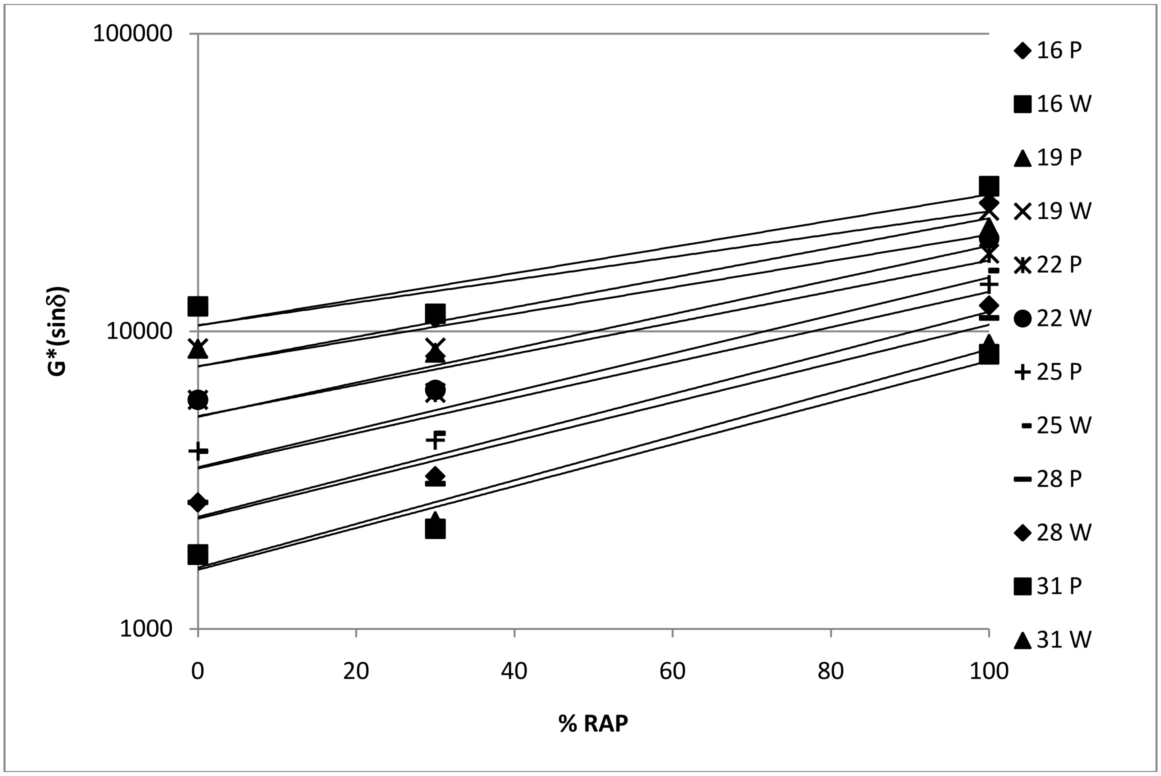


Figure 4.6 DSR PAV PG 64-22 Blending Chart

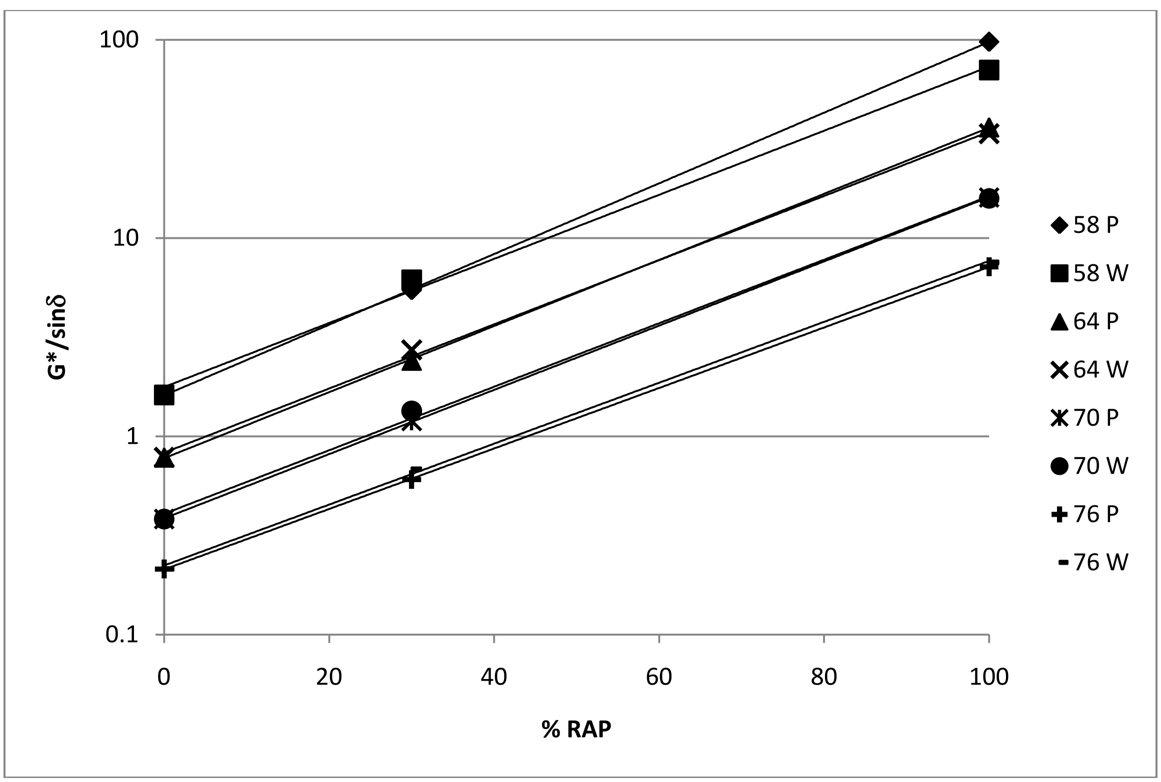


Figure 4.7 DSR Original PG 58-22 Blending Chart

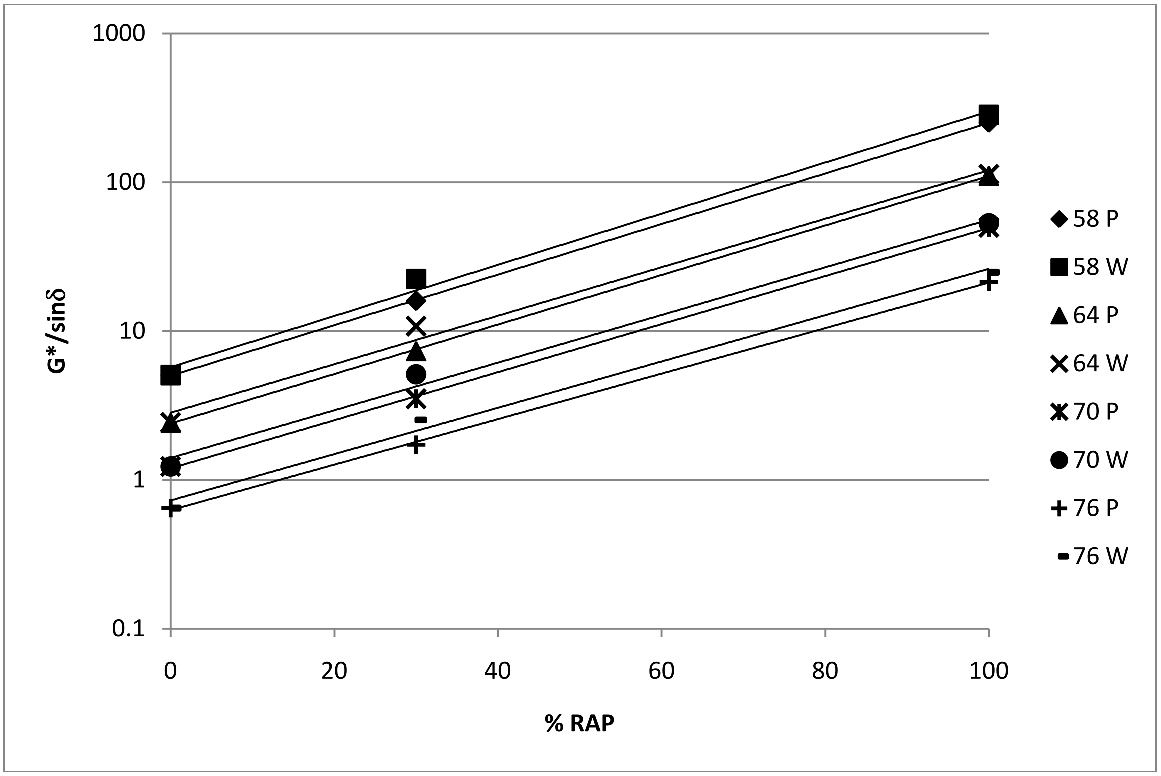


Figure 4.8 DSR RTFO PG 58-22 Blending Chart

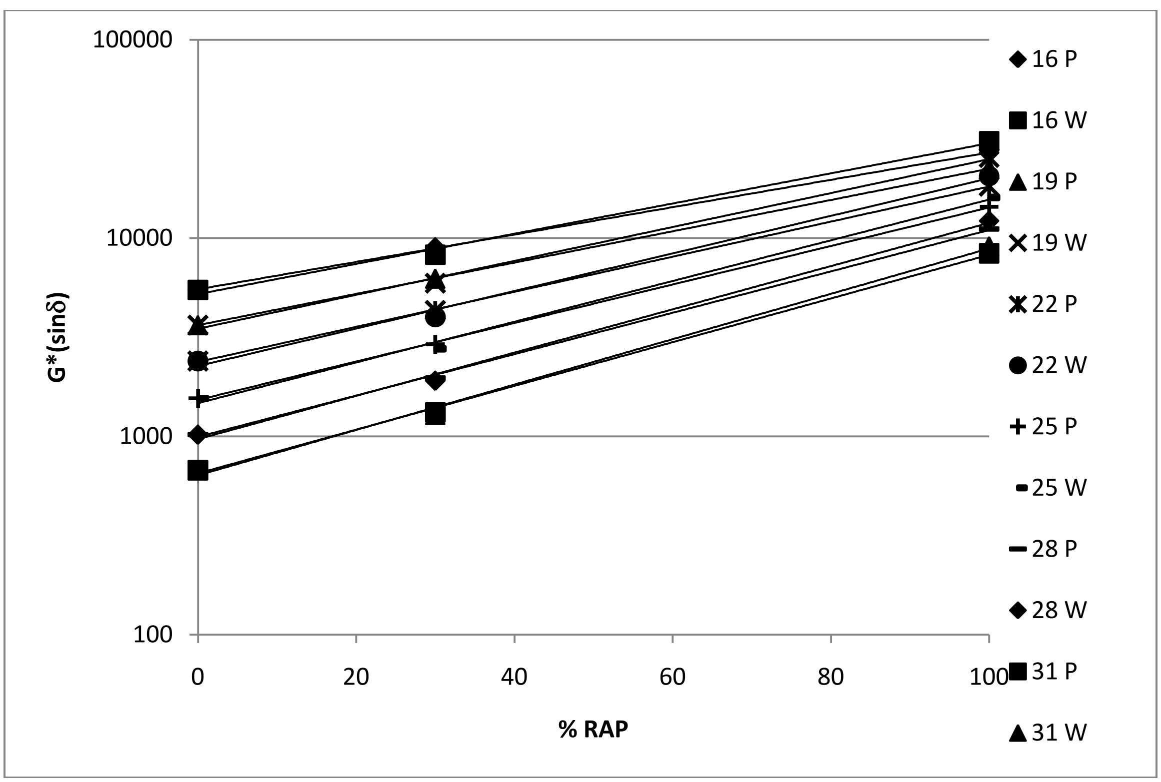


Figure 4.9 DSR PAV PG 58-22 Blending Chart

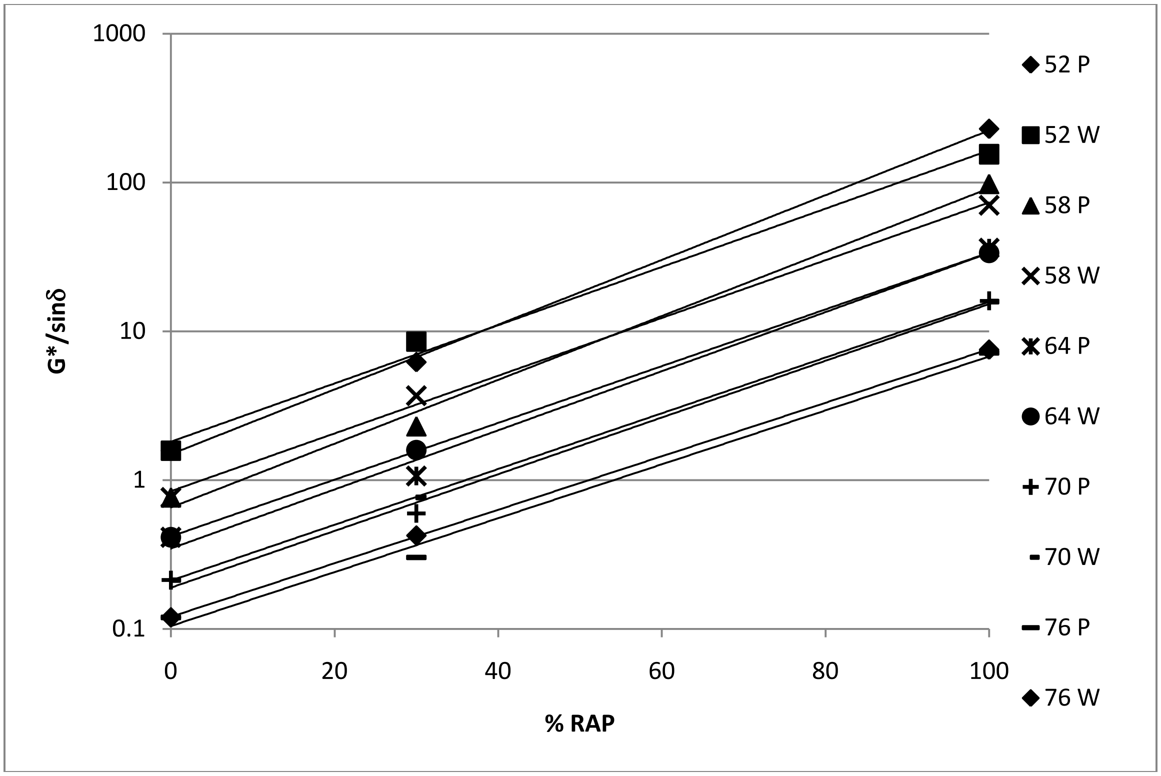


Figure 4.10 DSR Original PG 52-28 Blending Chart

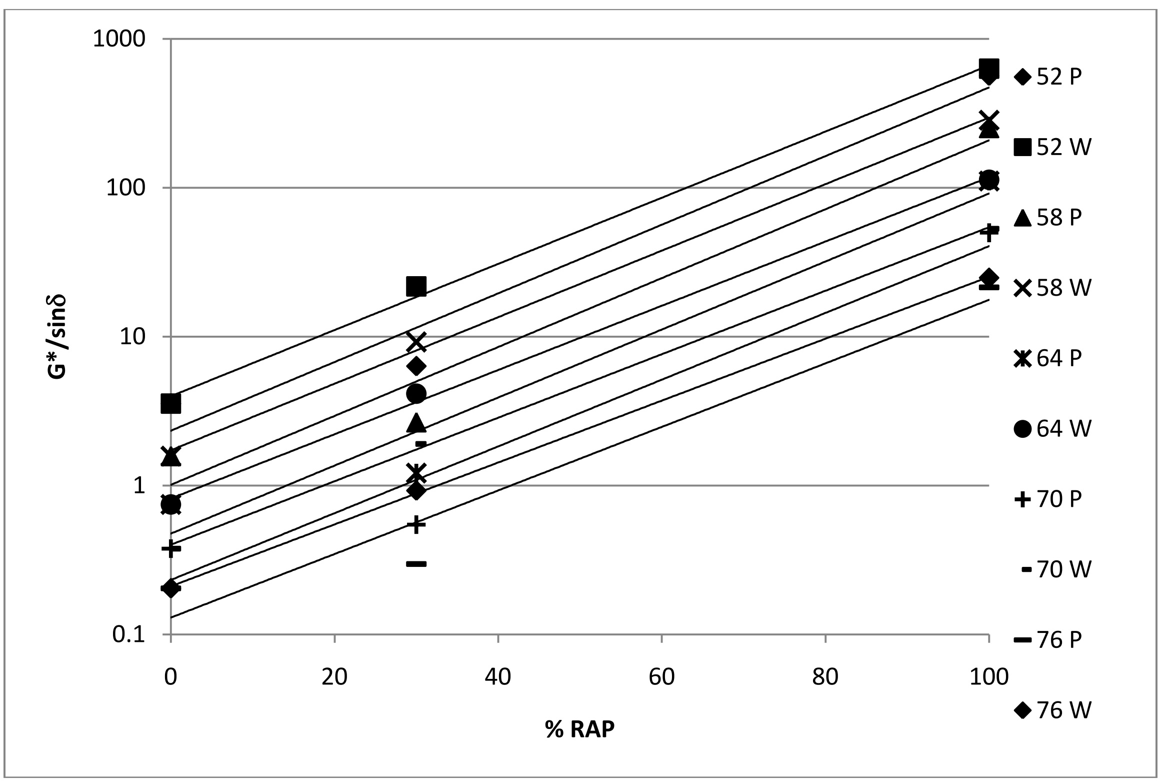


Figure 4.11 DSR RTFO PG 52-28 Blending Chart

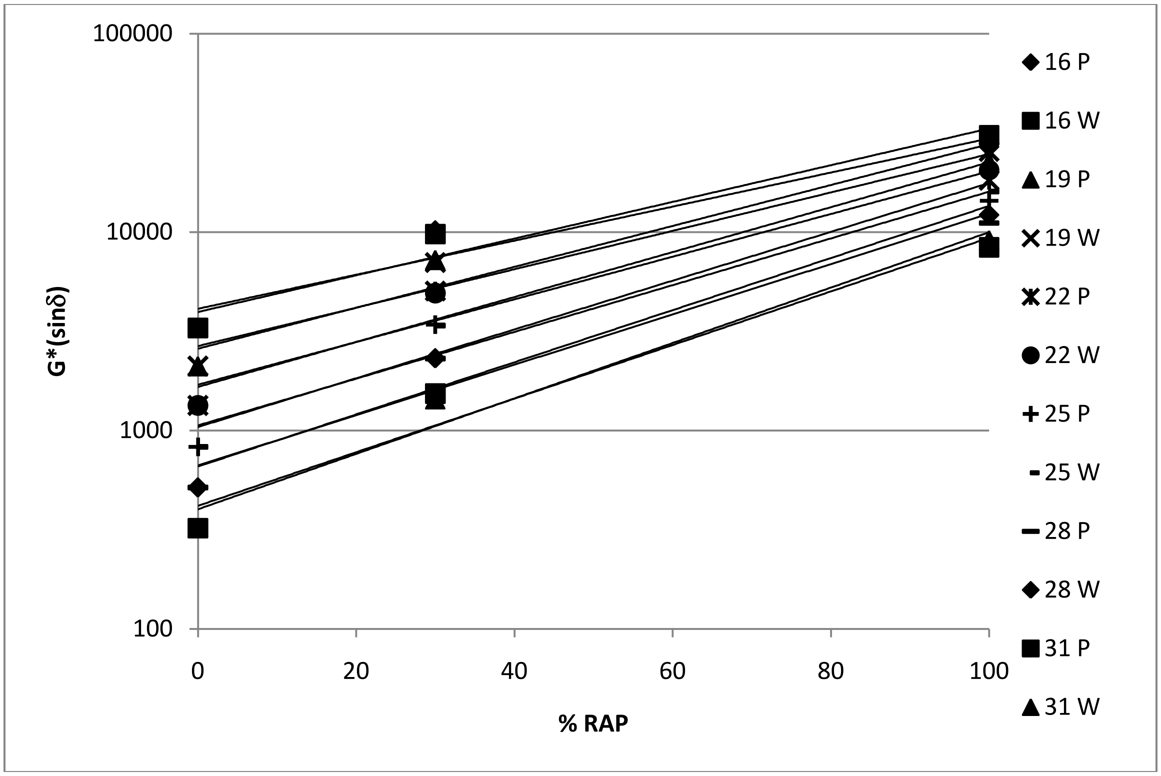


Figure 4.12 DSR PAV PG 52-28 Blending Chart

Table 4.4 and Table 4.5 below contain the minimum percentage of RAP needed to meet the specification of G*/sinδ= 1.0 and G*/sinδ= 2.2, respectively, based on the exponential equations from the blending charts at the different temperatures. For the most part, the binder from the Westgate RAP exhibits a higher G*/sinδ. Therefore, blends containing binder from the Westgate RAP generally need less RAP in order to meet the specification than mixtures containing the softer Pineville RAP. For example, if a mixture using PG 52-28 virgin binder is blended with Pineville RAP, in order to meet the specification for the high temperature grade of PG 64 and unaged binder, there needs to be a minimum of 23.20 % RAP in the blend to meet the specification of G*/sinδ= 1.0. Similarly, in order to meet the specification of G*/sinδ= 2.2 for RTFO aged binder, there needs to be a minimum of 29.14% RAP for a high temperature grade of PG 64. Therefore, the minimum for the high temperature grade for this blend would be 29.14% RAP.

Table 4.4 Minimum Percentage of RAP Binder to Satisfy G*/sinδ= 1.0 for Unaged Binder

Virgin Binder Grade	RAP Source	Temperature °C	$G^*/\sin\delta = Ae^{B(\%RAP)}$ A	$G^*/\sin\delta = Ae^{B(\%RAP)}$ B	Minimum % RAP
PG 52-28	Pineville	52	-	-	0
		58	0.6536	0.0494	8.6
		64	0.3463	0.0457	23.2
		70	0.1891	0.0439	37.9
		76	0.1044	0.0417	54.2
	Westgate	52	-	-	0
		58	0.8418	0.0447	3.9
		64	0.4178	0.0439	19.9
		70	0.2111	0.0431	36.1
		76	0.1205	0.0414	51.1
PG 58-22	Pineville	58	-	-	0
		64	0.7745	0.0348	7.3
		70	0.3854	0.0373	25.6
		76	0.2128	0.0351	44.1
	Westgate	58	-	-	0
		64	0.8261	0.0373	5.1
		70	0.4065	0.0369	24.4
		76	0.2229	0.0354	42.4
PG 64-22	Pineville	64	-	-	0
		70	0.9064	0.0298	3.3
		76	0.7099	0.023	14.9
	Westgate	64	-	-	0
		70	0.8094	0.0296	7.1
		76	0.6479	0.023	18.9

Table 4.5 Minimum Percentage of RAP Binder to Satisfy G*/sinδ= 2.2 for RTFO Binder

Virgin Binder Grade	RAP Source	Temperature °C	$G^*/\sin\delta = Ae^{B(\%RAP)}$ A	B	Minimum % RAP
PG 52-28	Pineville	52	-	-	0
		58	1.0098	0.0533	14.61
		64	0.475	0.0526	29.14
		70	0.232	0.0516	43.59
		76	0.1296	0.0491	57.67
	Westgate	52	-	-	0
		58	1.7238	0.0514	4.75
		64	0.8175	0.0497	19.92
		70	0.3998	0.0491	34.73
		76	0.2101	0.0479	49.03
PG 58-22	Pineville	58	-	-	0
		64	-	-	0
		70	1.1944	0.0372	16.42
		76	0.6251	0.0352	35.75
	Westgate	58	-	-	0
		64	-	-	0
		70	1.4024	0.0369	12.20
		76	0.7266	0.0358	30.95
PG 64-22	Pineville	64	-	-	0
		70	-	-	0
		76	1.3762	0.0279	16.81
	Westgate	64	-	-	0
		70	-	-	0
		76	1.3332	0.0296	16.92

Table 4.6 below contains the maximum percentage of RAP allowed in order to meet the specification G*sinδ= 5000 kPa, based on the exponential equations from the blending charts. For the most part, the binder from the Westgate RAP exhibits a higher G*sinδ. Therefore, blends containing the binder from the Westgate RAP generally are allowed less RAP in order to meet the specification than mixtures containing the softer Pineville RAP. For example, if a mixture using PG 52-28 virgin binder is blended with Pineville RAP, in order to meet the specification for the low temperature grade of PG 64-22 binder, there can be a maximum 57% RAP to meet the specification of G*sinδ= 5000 kPa. For PG 64 binders, the temperature of 25°C corresponds to a low grade of -22.

Table 4.6 Maximum Percentage of RAP Binder to Satisfy G*sinδ= 5000 kPa for PAV Binder

Virgin Binder Grade	RAP Source	Temperature °C	$G^*/\sin\delta = Ae^{B(\%RAP)}$ A	B	Maximum % RAP
PG 52-28	Pineville	16	4102.0	0.0198	10.0
		19	2661.0	0.0223	28.28
		22	1699.9	0.0248	43.50
		25	1059.8	0.0271	57.25
		28	665.5	0.0292	69.06
		31	416.88	0.0311	--
	Westgate	16	3952.2	0.0213	11.04
		19	2581.7	0.0237	27.89
		22	1656.7	0.0261	42.32
		25	1040.3	0.0283	55.47
		28	657.91	0.0302	67.16
		31	400.62	0.0322	78.39
PG 58-22	Pineville	16	-	-	0
		19	3631.4	0.0182	17.57
		22	2370.4	0.0204	36.59
		25	1523.4	0.0224	53.06
		28	992.37	0.024	67.38
		31	649.79	0.0254	80.34
	Westgate	16	-	-	0
		19	3484.7	0.0197	18.33
		22	2258.0	0.0218	36.47
		25	1468.5	0.0236	51.92
		28	967.07	0.0251	65.46
		31	635.31	0.0263	78.44
PG 64-22	Pineville	16	-	-	0
		19	-	-	0
		22	-	-	0
		25	3457.5	0.0137	26.93
		28	2344.8	0.015	50.48
		31	1578.8	0.0162	71.16
	Westgate	16	-	-	0
		19	-	-	0
		22	-	-	0
		25	3491.7	0.0147	24.43
		28	2376.5	0.0159	46.78
		31	1605.6	0.0169	67.22

4.2 Bending Beam Rheometer Testing

Bending Beam Rheometer (BBR) testing was completed on the blended binders according to AASHTO T 313-09 “Standard Method of Test for Determining the Flexural Creep Stiffness of Asphalt Binder Using the Bending Beam Rheometer (BBR)”. The BBR testing produced rheological properties for the binders including creep stiffness (S) and the m-value (slope). Each binder was tested at -12^{o}C. The blended binders consisted of a mix of 70% virgin binder and 30% binder extracted from the RAP sources.

Table 4.7 below contains the average creep stiffness and m-values for the virgin binders and binders recovered from the RAP sources. Table 4.8 below contains the average creep stiffness and m-values for the blended binders. The addition of 30% RAP to the PG 52-28 virgin binder resulted in an increase in creep stiffness of 95.9% and 90.3% for Westgate and Pineville blends, respectively. The addition of 30% RAP to the PG 58-22 virgin binder resulted in an increase in creep stiffness of 53.7% and 59.9% for Westgate and Pineville blends, respectively. The addition of 30% RAP to the PG 64-22 virgin binder actually resulted in a decrease in creep stiffness of 7.3% and 0.3% for Westgate and Pineville blends, respectively. This result is not expected. As the virgin binder grade in the blend increases from PG 52-28 to PG 64-22, the increase in creep stiffness becomes less. This is expected since as the virgin binder creep stiffness increases with increasing binder grade, the higher creep stiffness from the reclaimed RAP binder has less of an effect on the binder blend.

The addition of 30% RAP to the PG 52-28 virgin binder resulted in a decrease in m-value of 21.4% and 20.3% for Westgate and Pineville blends, respectively. The addition of 30% RAP to the PG 58-22 virgin binder resulted in a decrease in m-value of 11.5% and 10.0% for Westgate and Pineville blends, respectively. The addition of 30% RAP to the PG 64-22 virgin binder resulted in a decrease in m-value of 10.5% and 9.0% for Westgate and Pineville blends, respectively. This reduction in m-value is expected since the binder reclaimed from the RAP is stiffer thus likely to need more time to recover, which is what the m-value signifies.

Table 4.7 Creep Stiffness and m-values of Virgin and RAP Binders

Binder	Creep Stiffness (Mpa)	m-value
PG 52-28 Virgin	72.5	0.453
PG 58-22 Virgin	80.7	0.4045
PG 64-22 Virgin	170.5	0.3485
Westgate RAP	263	0.253
Pineville RAP	322	0.234

Table 4.8 Creep Stiffness and m-values of Blended Binders

	RAP Source	Creep Stiffness (Mpa)	m-value
PG 52-28	**Westgate**	142	0.356
	Pineville	138	0.361
PG 58-22	**Westgate**	124	0.358
	Pineville	129	0.364
PG64-22	**Westgate**	158	0.312
	Pineville	170	0.317

The values from Table 4.7 and Table 4.8 were combined in order to produce blending charts for the creep stiffness and m-values in order to determine the maximum allowable amount of RAP in a mixture to pass the BBR specifications to control for thermal cracking. Figures 4.13-4.18 show the blending charts for the creep stiffness and m-values at the various performance grades.

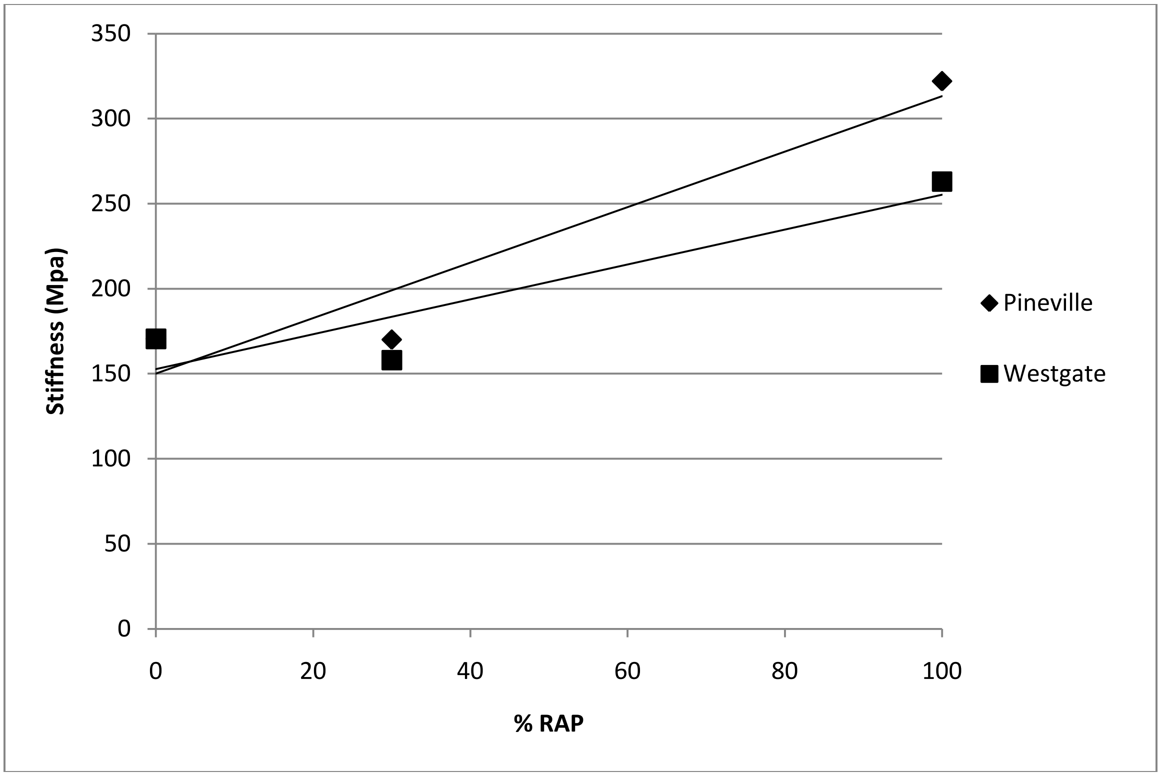


Figure 4.13 BBR PG 64-22 Creep Stiffness Blending Chart

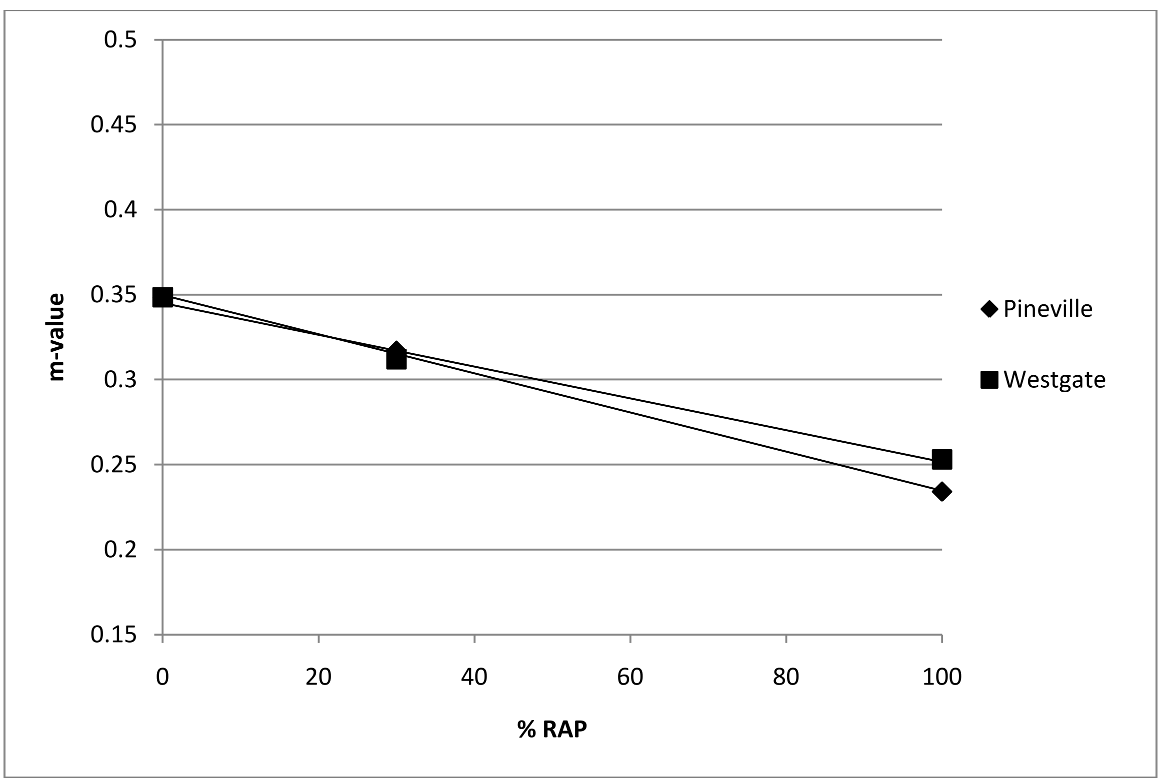


Figure 4.14 BBR PG 64-22 m-value Blending Chart

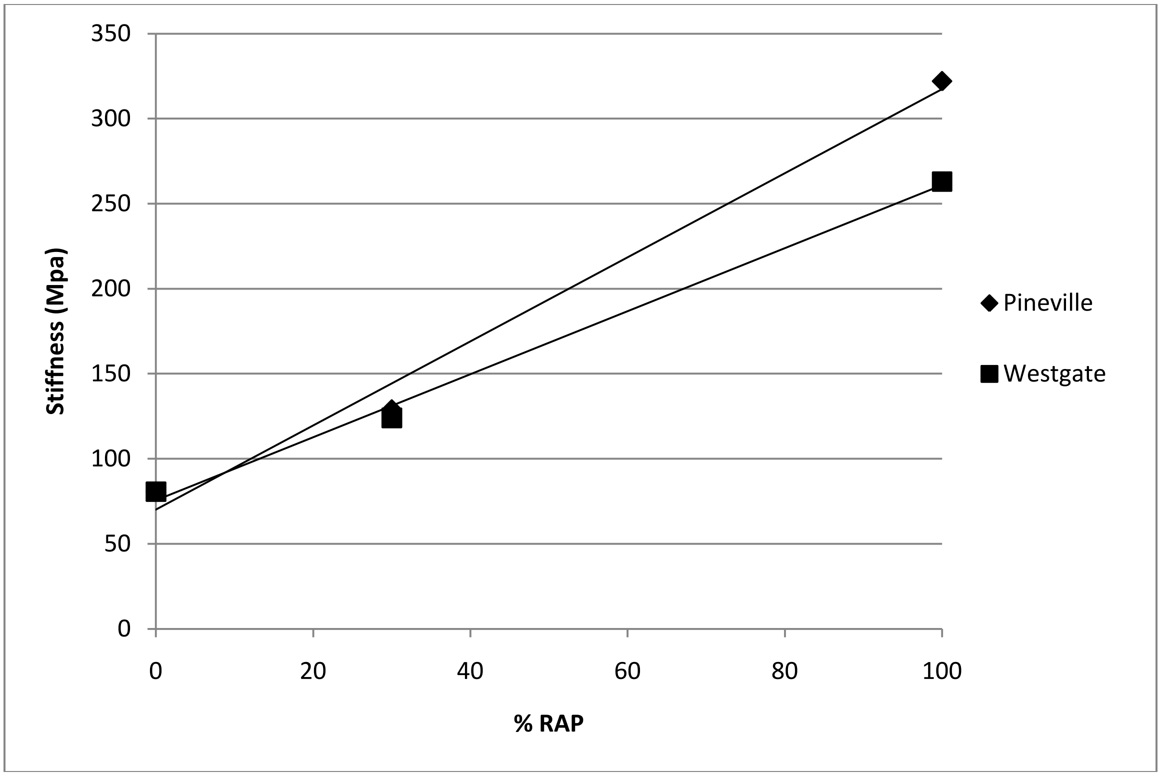


Figure 4.15 BBR PG 58-22 Creep Stiffness Blending Chart

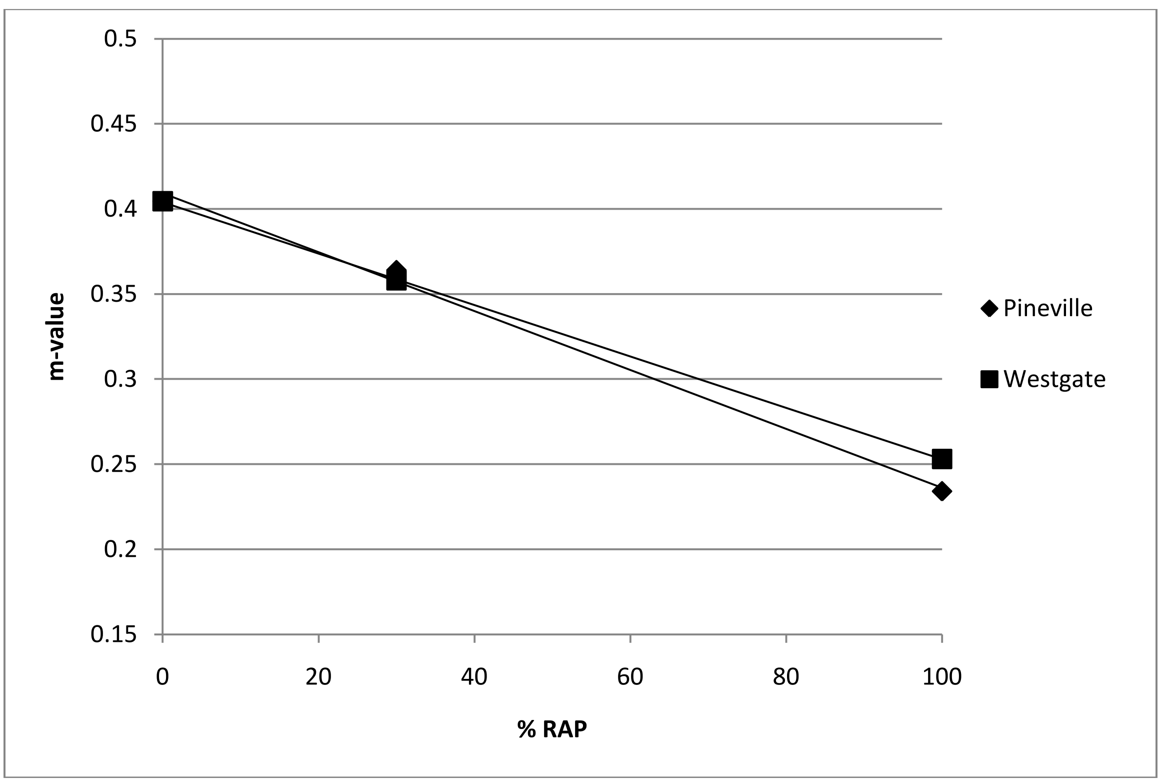


Figure 4.16 BBR PG 58-22 m-value Blending Chart

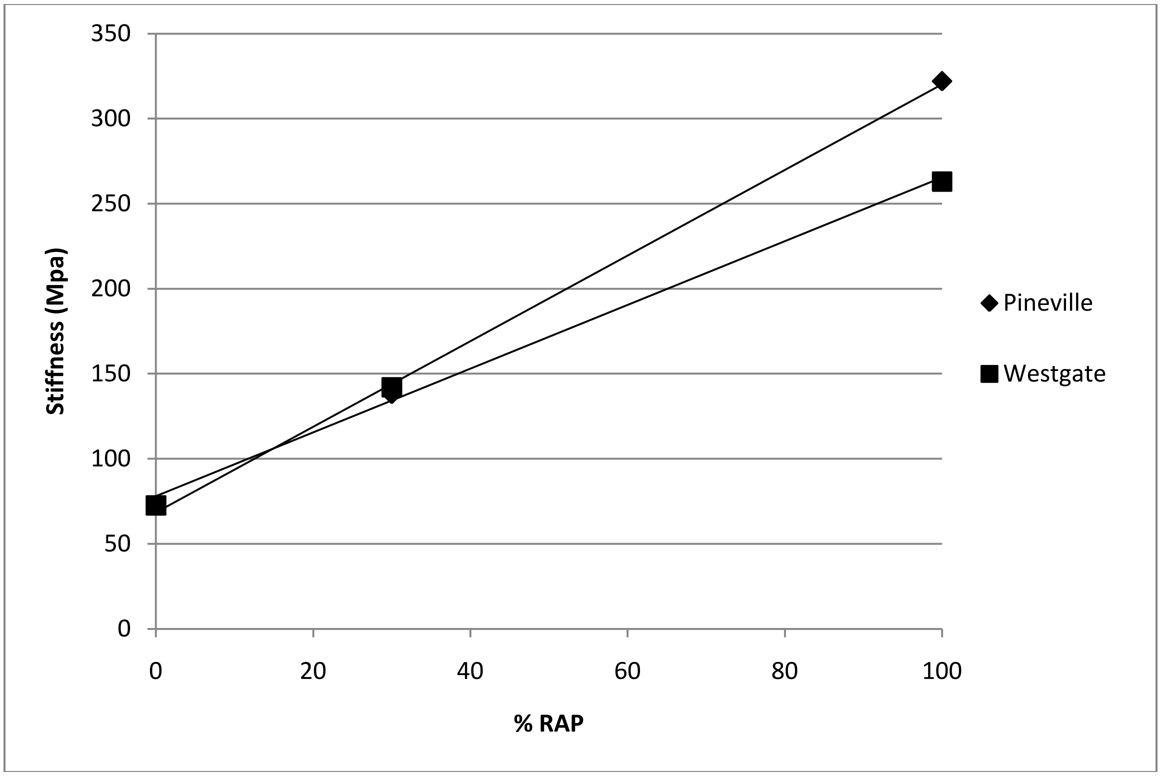


Figure 4.17 BBR PG 52-28 Creep Stiffness Blending Chart

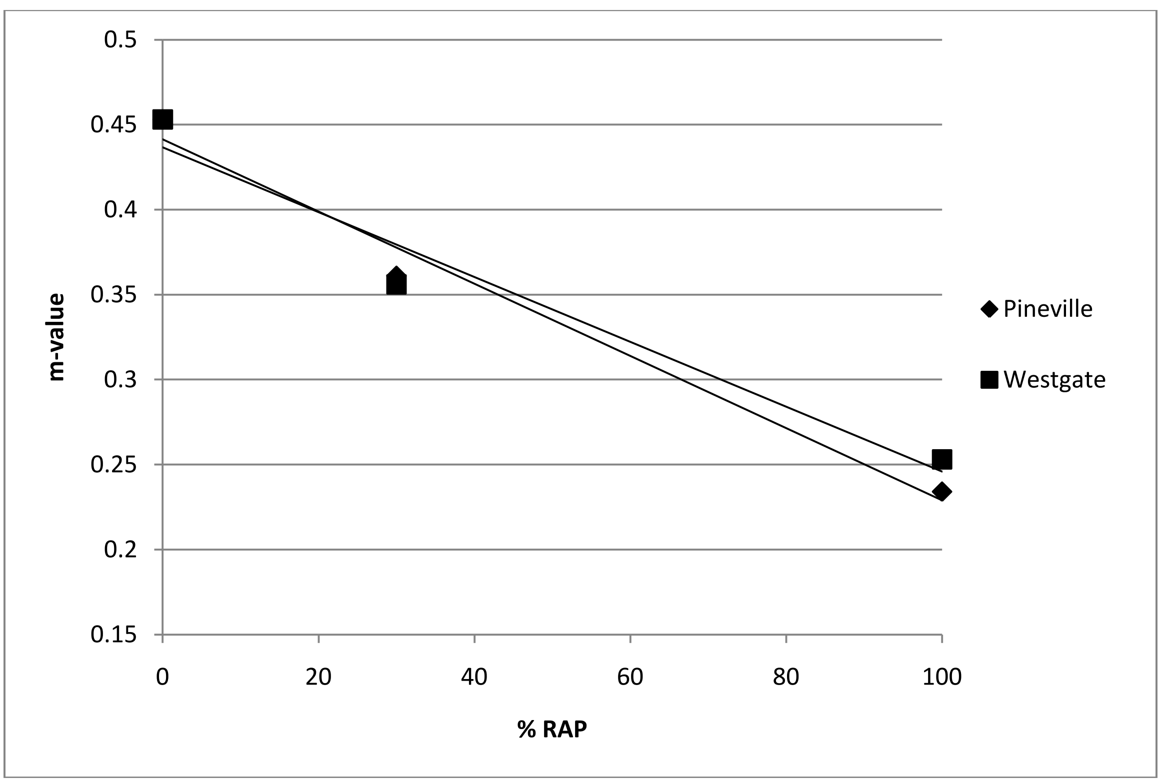


Figure 4.18 BBR PG 52-28 m-value Blending Chart

Table 4.9 and Table 4.10 below contains the maximum percentage of RAP allowed in order to meet the specification S=300 Mpa and m-value= 0.300, respectively, based on the linear equations from the blending charts. Table 4.9 shows that mixtures are able to satisfy the stiffness specification with 91%-100% RAP. However, the controlling variable for thermal cracking from the BBR test is the m-value. Mixtures with PG 64-22 binder are able to contain 41%-50% RAP. Mixtures with PG 58-22 binder are able to contain 64%-69% RAP. Mixtures with PG 52-28 binder are able to contain 67%-71% RAP.

Table 4.9 Maximum Percentage of RAP Binder to Satisfy S = 300 Mpa for PAV Binder

Virgin Binder Grade	RAP Source	S = m*x+b		Maximum % RAP
		m	b	
PG 52-28	Pineville	2.5187	68.358	91
	Westgate	1.8737	77.972	100
PG 58-22	Pineville	2.4740	70.027	92
	Westgate	1.8518	75.654	100
PG 64-22	Pineville	1.6313	150.14	91
	Westgate	1.0269	152.67	100

Table 4.10 Maximum Percentage of RAP Binder to Satisfy m-value= 0.300 for PAV Binder

Virgin Binder Grade	RAP Source	m-value = m*x+b		Maximum % RAP
		m	b	
PG 52-28	Pineville	-0.0021	0.4413	67
	Westgate	-0.0019	0.4366	71
PG 58-22	Pineville	-0.0017	0.4092	64
	Westgate	-0.0015	0.4040	69
PG 64-22	Pineville	-0.0012	0.3498	41
	Westgate	-0.0009	0.3450	50

Combining the results from Tables 4.4-4.6 and Tables 4.9-4.10, the minimum and maximum amount of RAP is determined in order to still pass all specifications for a PG 64-22 binder. Table 4.11 below contains these values. Using virgin PG 64-22 binder, the maximum amount of RAP is 24%-27%. Using PG 58-22 binder, the maximum amount of RAP is 52-53%. Using PG 52-28 binder, the maximum amount of RAP is 55-57%.

Table 4.11 Minimum and Maximum Percentage of RAP Binder to Satisfy all PG 64-22 Specifications

Virgin Binder Grade	RAP Source	Minimum Original DSR	Minimum RTFO DSR	Maximum PAV DSR	Maximum BBR S	Maximum BBR m-value
PG 52-28	Pineville	24	30	57	91	67
	Westgate	20	20	55	100	71
PG 58-22	Pineville	8	-	53	92	64
	Westgate	6	-	52	100	69
PG 64-22	Pineville	-	-	27	91	41
	Westgate	-	-	24	100	50

This chapter has discussed the rheology of the blended RAP binders and the formation of blending charts. The blending charts will allow contractors to determine the amount of RAP that is acceptable to use in mixtures. The values formulated in this chapter will be combined with the values formulated in Chapters 5 and 6 regarding the pavement performance in order to determine the optimum amount of RAP to use in mixtures.

Chapter 5
Mixture Characterization

The mixtures developed and fabricated in Chapter 3 will be characterized in this chapter using Superpave simple shear tests. These characterizations will be used for comparisons between the various mixtures. The results will be used in the next chapter as part of the performance predictions for the mixtures.

The Superpave Simple Shear Tester (SST) was used to conduct both Frequency Sweep Test at Constant Height (FSTCH) and Repeated Simple Shear Test at Constant Height (RSSTCH).

The FSTCH applies a sinusoidal shear strain of 0.01% at frequencies of 10, 5, 1, 0.5, 0.2, 0.1, 0.05, 0.02 and 0.01 Hz. In accordance with AASHTO TP7, the FSTCH were performed at 20^{o}C. Resulting from the FSTCH, the complex modulus (G*) and phase angle (δ) are known. The complex modulus measures the mixtures stiffness for the range of frequencies. These values were used to compare the similarities between mixtures containing 100% virgin materials and mixtures containing various percentages of RAP. As a part of the performance analysis, the complex modulus was used in the SHRP A-003A surrogate performance prediction model for fatigue life in Chapter 6.

The RSSTCH is used to measure the accumulations of permanent strain in the test specimen for the test period. The shear load is applied in a haversine pulse for a duration of 0.1 second followed by a 0.6 second unload period. This results in a total loading cycle of 0.7 second. The RSSTCH is conducted for 5000 cycles or 5 percent of the permanent shear strain for the specimen is reached. The RSSTCH measures the accumulated permanent shear strain for each specimen. The RSSTCH were performed at 59.3 ^{o}C as this is the average seven day high temperature with 98% reliability for Raleigh, North Carolina. The accumulated permanent shear strain correlates to rut resistance and the values obtained from mixtures containing 100% virgin materials were compared with values obtained from mixtures containing various amounts of RAP material.

The SST machine is depicted in Figure 5.1. Figure 5.2 below shows the specimen setup in the molds with the Linear Variable Differential Transformer (LVDT).

Figure 5.1 Superpave Simple Shear Tester (SST)

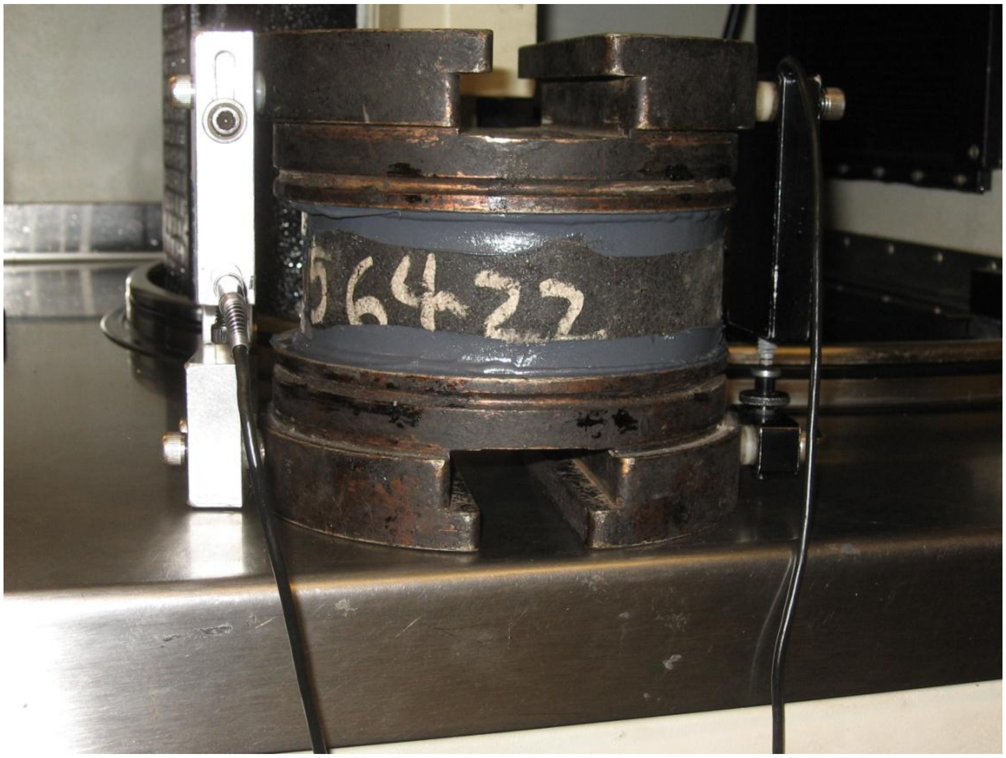


Figure 5.2 Simple Shear (FSTCH and RSTCH) Test Specimen

Using the SST, testing for FSTCH and RSSTCH was completed for the virgin 9.5mm and 19.0 mm specimens with PG 64-22 binder, PG 58-22 binder and PG 52-28 binder. Figures 5.3-5.6 below depict comparisons among mixtures containing the three various binder grades for both 9.5 mm mixtures and 19.0 mm mixtures for FSTCH and RSSTCH, respectively.

The results from the FSTCH indicate trends of increasing complex modulus with increasing frequency. Also, as the binder grade increases, from PG 52-28 to PG 64-22, the complex modulus increases. This would be expected as the complex modulus of PG 64-22 binder is larger than the complex modulus of PG 52-28 binder when temperature is constant.

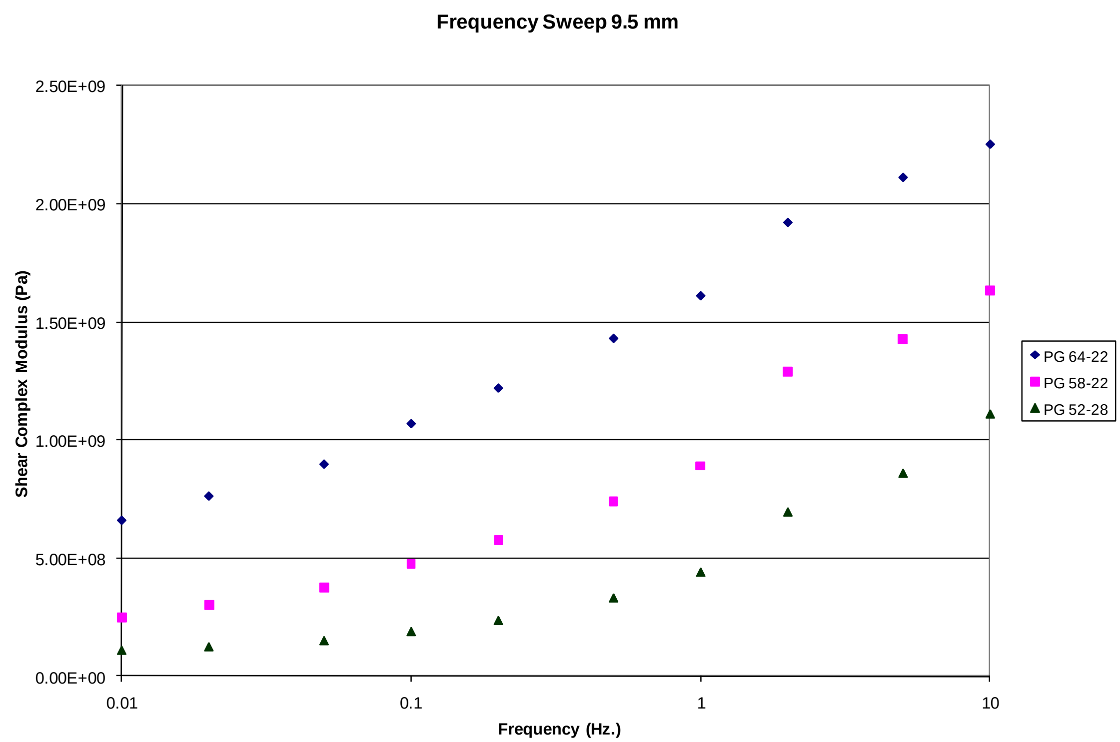


Figure 5.3 9.5 mm Virgin Frequency Sweep Comparison

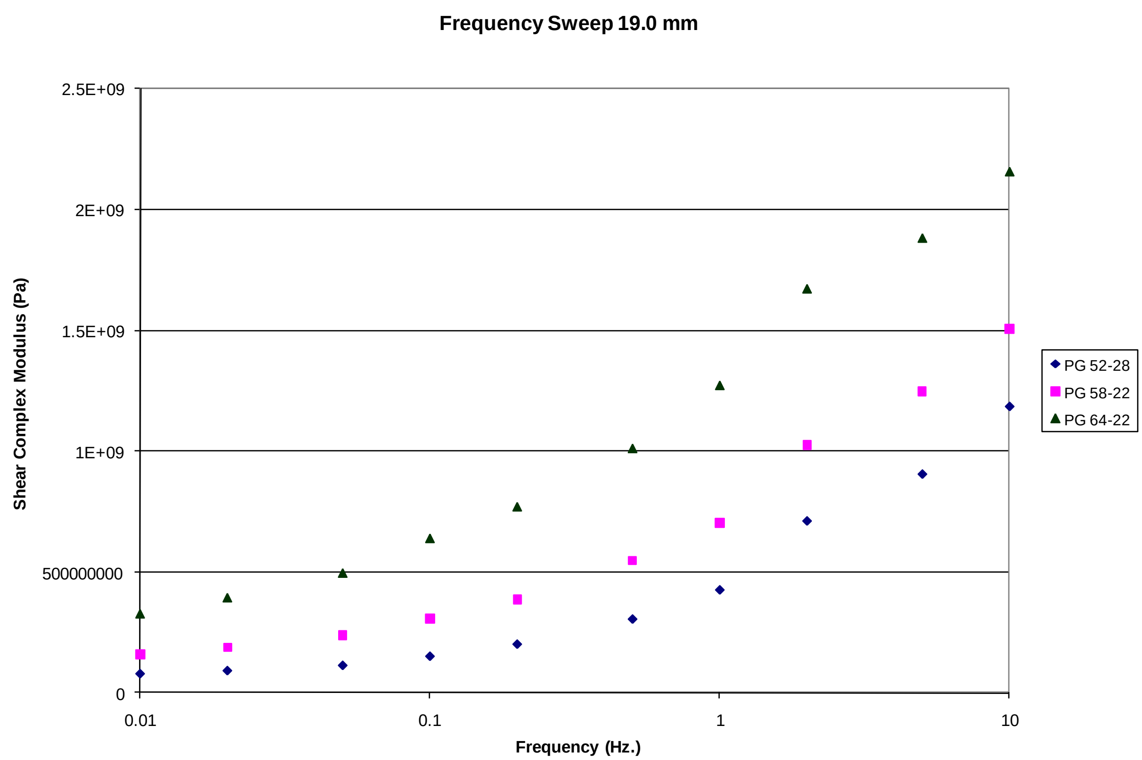


Figure 5.4 19.0 mm Virgin Frequency Sweep Comparison

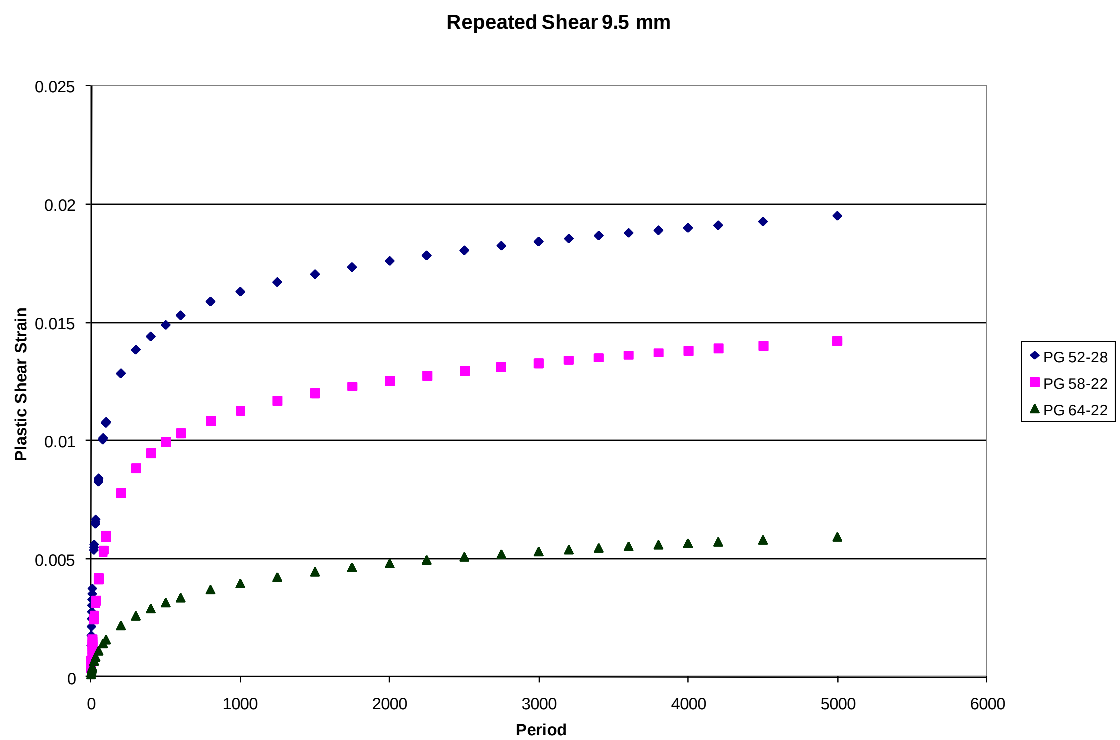


Figure 5.5 9.5 mm Virgin Repeated Shear Comparison

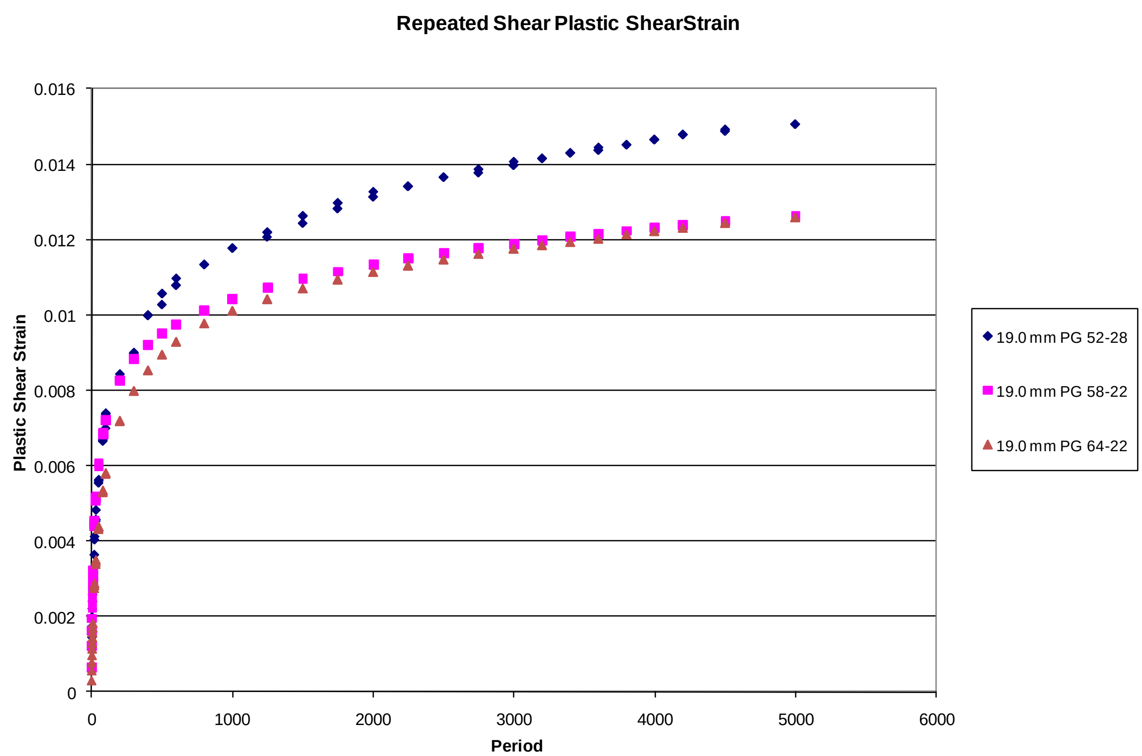


Figure 5.6 19.0 mm Virgin Repeated Shear Comparison

After 5000 cycles of repeated shear, the mixtures containing PG 64-22 binder exhibited the least amount of strain for both virgin 9.5mm mixtures and 19.0 mm mixtures. Mixtures with PG 58-22 binder exhibited less strain than the mixtures with PG 52-28 binder. This can be expected as mixtures with stiffer binders exhibited less strain.

5.1 Frequency Sweep Analysis

Using the SST, testing for FSTCH was completed for the 9.5mm specimens at the various RAP percentages (15%, 30%, and 40%) with PG 64-22 binder, PG 58-22 binder and PG 52-28 binder and both RAP sources (Westgate and Pineville). Figures 5.7-5.12 below depict comparisons among mixtures containing the three various binder grades, various percentages of RAP and both RAP sources for 9.5 mm mixtures for FSTCH.

The results from the FSTCH indicate trends of increasing complex modulus with increasing frequency. Also, as the binder grade increases, from PG 52-28 to PG 64-22, the complex modulus increases. This trend holds true at all percentages of RAP. This would be expected as the complex modulus of PG 64-22 binder is larger than the complex modulus of PG 52-28 binder when temperature is constant.

Table 5.1 Comparison of Complex Modulus for 9.5 mm Westgate Mixtures

		Complex Modulus (Pa)	
Binder Grade	RAP Percentage	0.01 Hz	10 Hz
PG 64-22	15%	4.56E+08	2.15E+09
	30%	5.26E+08	2.21E+09
	40%	7.45E+08	2.60E+09
PG 58-22	15%	2.30E+08	1.48E+09
	30%	2.97E+08	1.66E+09
	40%	3.39E+08	1.89E+09
PG 52-28	15%	1.20E+08	1.29E+09
	30%	1.30E+08	1.29E+09
	40%	1.55E+08	1.48E+09

Table 5.2 Comparison of Complex Modulus for 9.5 mm Pineville Mixtures

		Complex Modulus (Pa)	
Binder Grade	**RAP Percentage**	**0.01 Hz**	**10 Hz**
PG 64-22	15%	3.71E+08	2.07E+09
	30%	4.06E+08	2.13E+09
	40%	4.47E+09	2.17E+09
PG 58-22	15%	2.01E+08	1.45E+09
	30%	2.70E+08	1.56E+09
	40%	3.26E+08	1.56E+09
PG 52-28	15%	9.76E+07	1.14E+09
	30%	1.91E+08	1.41E+09
	40%	2.11E+08	1.53E+09

The complex modulus of mixtures with higher percentages of RAP increases while holding the binder grade constant. Again, this can be expected since the complex modulus of the RAP binder is greater due to its aging caused during its service life.

Tables 5.1 and 5.2 above contain the complex modulus at 0.01 Hertz and 10 Hertz for each binder grade and the three percentages of RAP for Westgate RAP and Pineville RAP, respectively. The stiffness at 10 Hertz will be used in later analysis when computing the fatigue life.

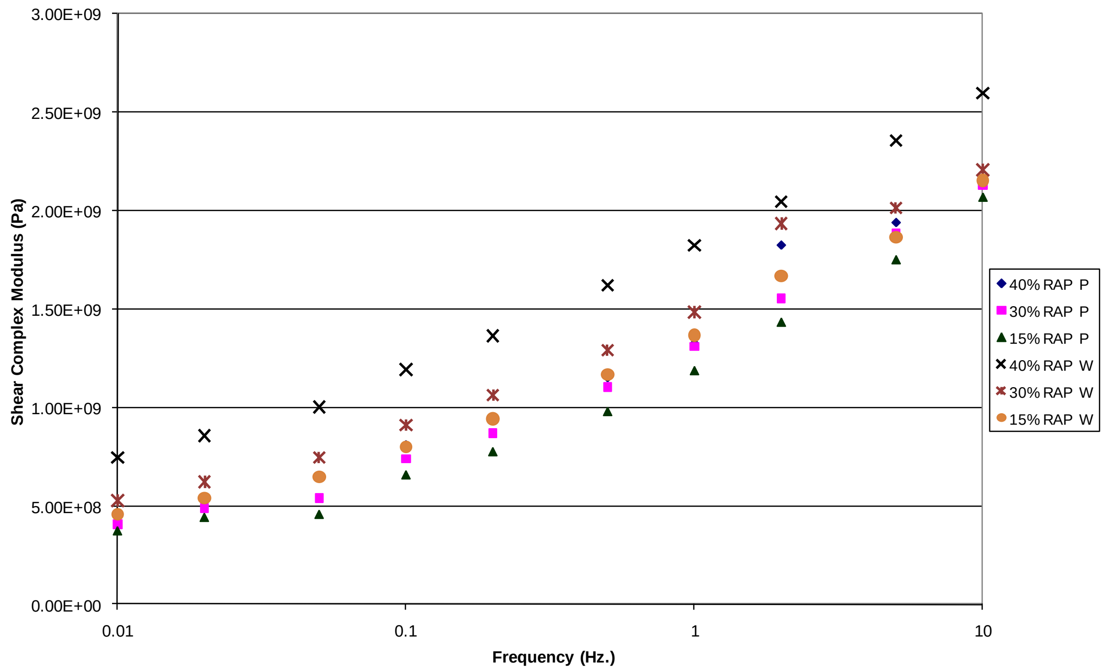


Figure 5.7 9.5 mm Frequency Sweep Comparison for PG 64-22

Figure 5.7 depicts the comparison for the various RAP percentages and both RAP sources using PG 64-22 binder. The complex modulus for mixtures containing 30% Westgate RAP is higher than mixtures containing 40% Pineville RAP. Although it would be expected that the mixture with a higher percentage of RAP would have a larger complex modulus, the difference is probably caused by the difference in the complex modulus of the RAP sources. Since the Westgate RAP had a higher complex modulus than the Pineville RAP, it can be expected that the blends containing Westgate RAP will have a higher complex modulus, even at lower percentages of RAP. The expected trend of increasing RAP increases complex modulus hold true for each percentage and both RAP sources. The complex modulus for mixtures containing PG 64-22 binder range from 2.15 X 10^9 Pa to 2.60 X 10^9 Pa at 10 Hz.

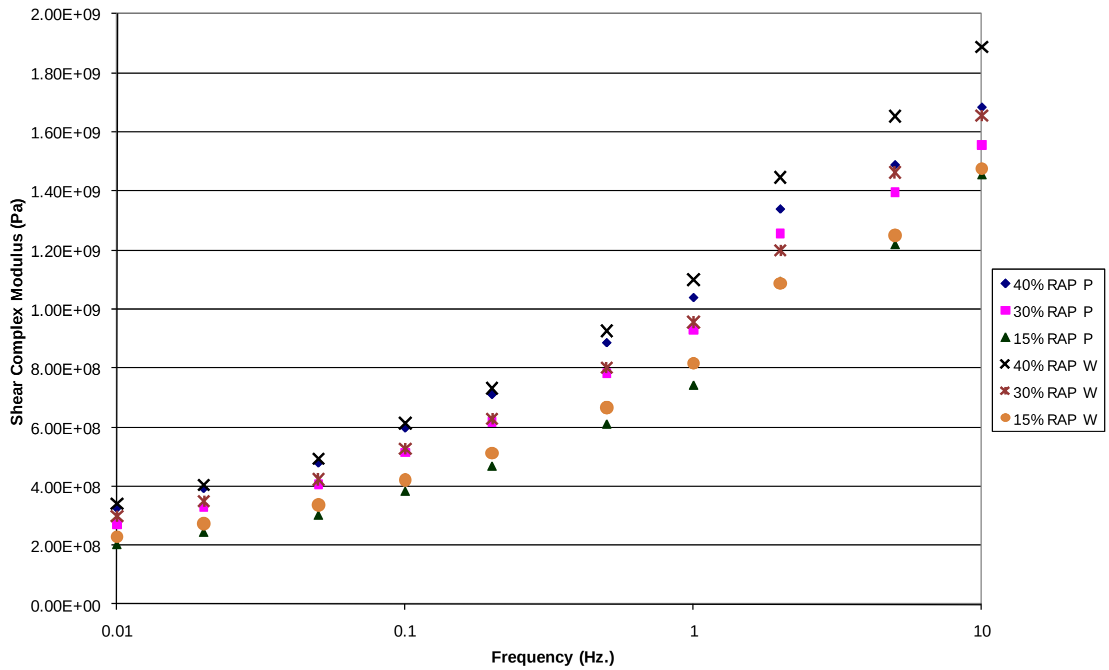


Figure 5.8 9.5 mm Frequency Sweep Comparison for PG 58-22

Figure 5.8 depicts the comparison for the various RAP percentages and both RAP sources using PG 58-22 binder. This data shows expected trends with mixtures containing 15% RAP having the lowest complex modulus and mixtures containing 40% RAP having the highest complex modulus. At each percentage, the mixtures containing Westgate RAP have a larger complex modulus than mixtures containing Pineville RAP. However, unlike the blends containing PG 64-22, these blends are grouped together with similar percentages, i.e., the mixture containing 30% Westgate RAP does not have a higher complex modulus than the mixture containing 40% Pineville RAP. The complex modulus for mixtures containing PG 58-22 binder range from 1.45 X 10^9 Pa to 1.89 X 10^9 Pa at 10 Hz. These values are less than the mixtures containing PG 64-22 binder.

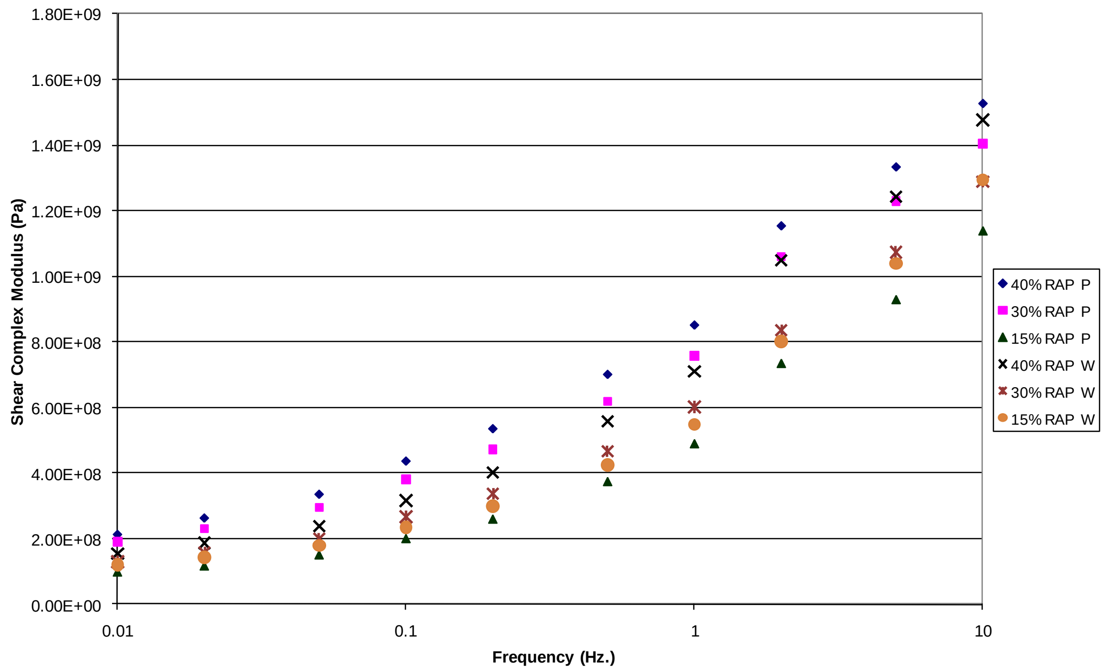


Figure 5.9 9.5 mm Frequency Sweep Comparison for PG 52-28

Figure 5.9 depicts the comparison for the various RAP percentages and both RAP sources using PG 52-28 binder. At the lower and middle frequencies (0.01 Hz-2 Hz) the mixture containing 40% Westgate RAP has a lower complex modulus than the mixture containing 30% Pineville RAP. However, at the higher frequencies (5 Hz, 10 Hz) the mixture containing 40% Westgate RAP has a higher complex modulus than the mixture with 30% Pineville RAP. Since the upcoming analysis uses the complex modulus at 10 Hz, this trend is adequate. The complex modulus for mixtures containing PG 52-28 binder range from 1.14 X 10^9 Pa to 1.53 X 10^9 Pa at 10 Hz. These values are less than the mixtures containing PG 64-22 binder and PG 58-22 binder.

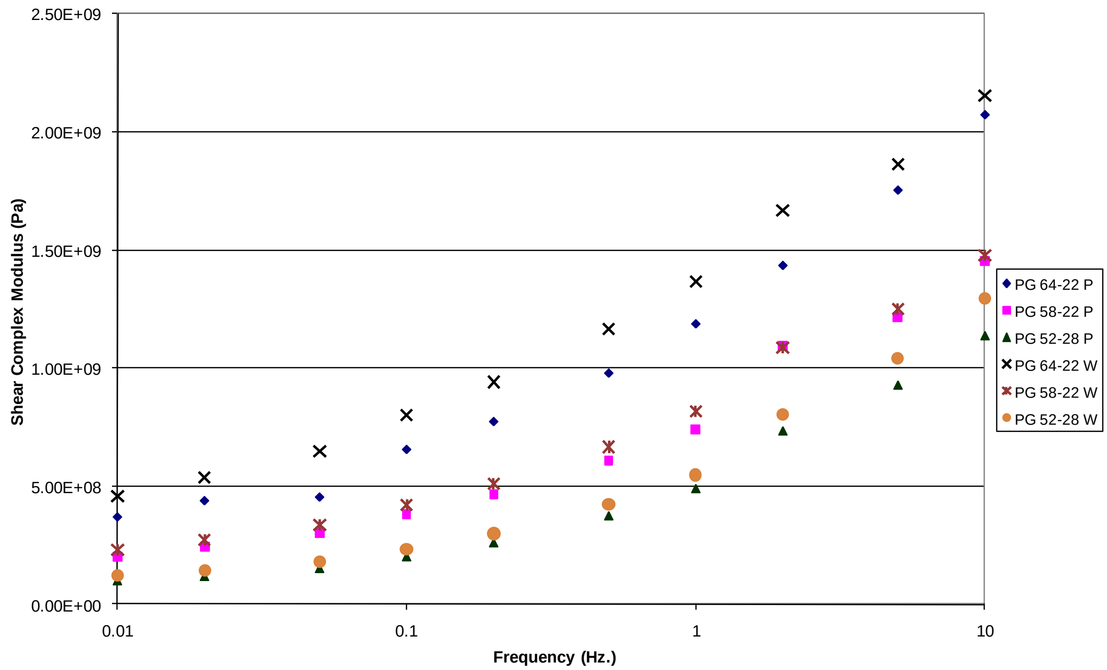


Figure 5.10 9.5 mm Frequency Sweep Comparison with 15% RAP

Figure 5.10 depicts the comparison for the various binder grades and RAP sources using 15% RAP. The mixtures containing PG 64-22 binder have the highest complex modulus followed by mixtures containing PG 58-22 binder and then mixtures containing PG 52-28 binder. This is expected as virgin PG 64-22 binder has a highest complex modulus followed by PG 58-22 binder and then PG 52-28 binder. The complex modulus for mixtures containing 15% RAP range from 1.14 X 10^9 Pa to 2.15 X 10^9 Pa at 10 Hz.

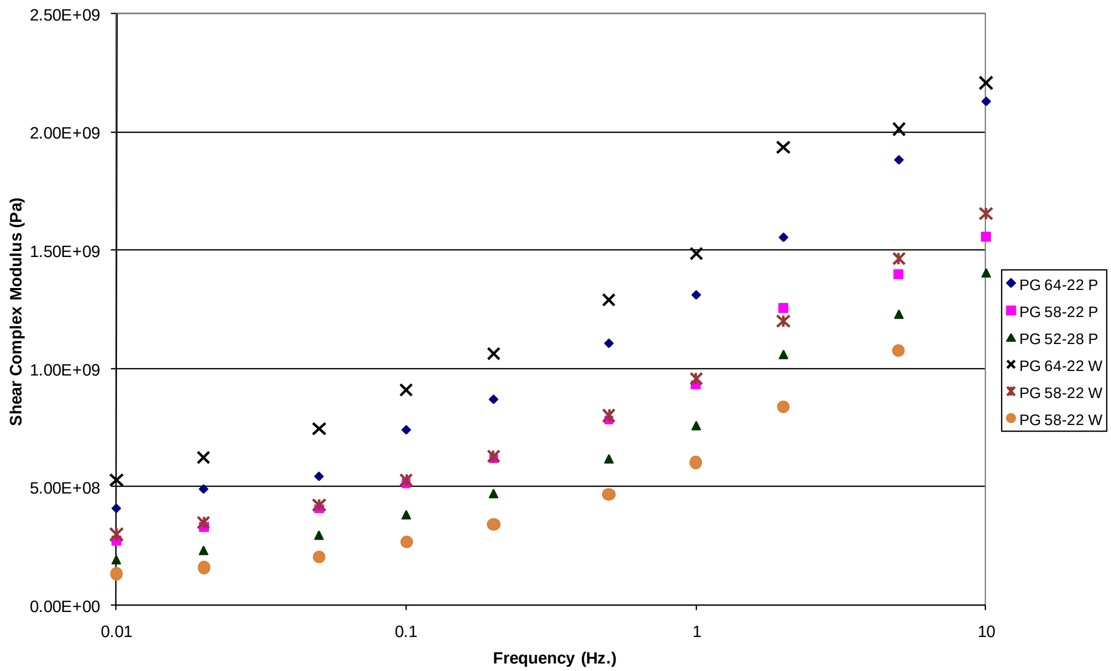


Figure 5.11 9.5 mm Frequency Sweep Comparison with 30% RAP

Figure 5.11 depicts the comparison for the various binder grades and RAP sources using 30% RAP. The mixtures containing PG 64-22 binder have the highest complex modulus followed by mixtures containing PG 58-22 binder and then mixtures containing PG 52-28 binder. This is expected as virgin PG 64-22 binder has a highest complex modulus followed by PG 58-22 binder and then PG 52-28 binder. The complex modulus for mixtures containing 30% RAP range from 1.29 X 10^9 Pa to 2.21 X 10^9 Pa at 10 Hz. These values are larger than the mixtures containing 15% RAP.

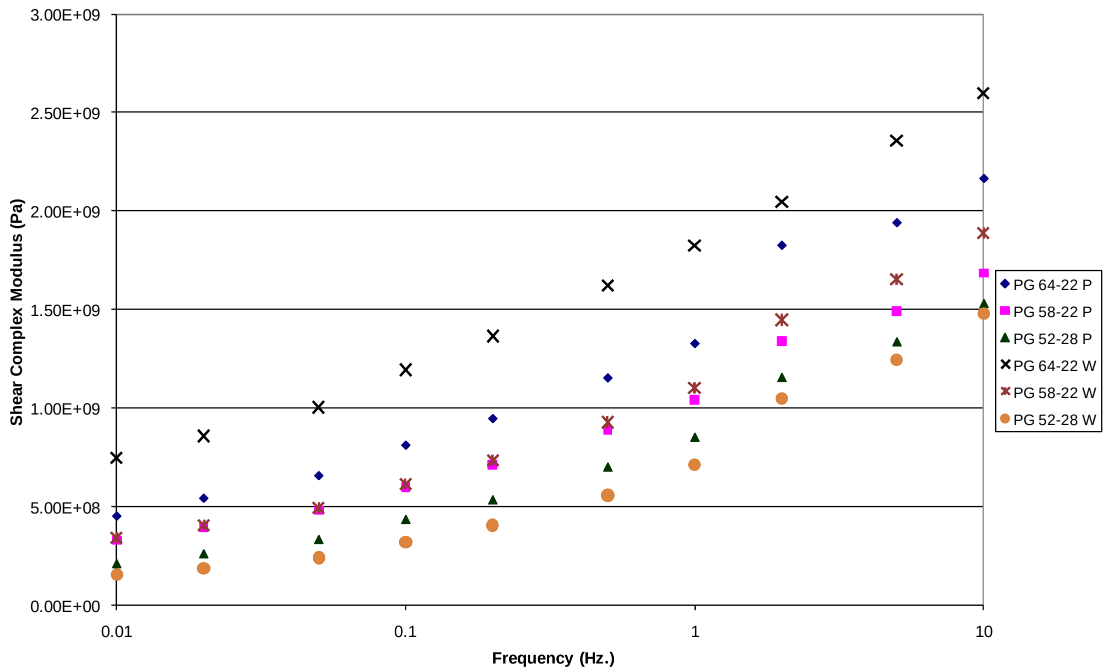


Figure 5.12 9.5 mm Frequency Sweep Comparison with 40% RAP

Figure 5.12 depicts the comparison for the various binder grades and RAP sources using 40% RAP. The mixtures containing PG 64-22 binder have the highest complex modulus followed by mixtures containing PG 58-22 binder and then mixtures containing PG 52-28 binder. This is expected as virgin PG 64-22 binder has a highest complex modulus followed by PG 58-22 binder and then PG 52-28 binder. The complex modulus for mixtures containing 40% RAP range from 1.48 X 10^9 Pa to 2.60 X 10^9 Pa at 10 Hz. These values are larger than the mixtures containing 15% and 30% RAP.

Using the SST, testing for FSTCH was completed for the 19.0 mm specimens at the various RAP percentages (15%, 30%, and 40%) with PG 64-22 binder, PG 58-22 binder and PG 52-28 binder and both RAP sources (Westgate and Pineville). Figures 5.13-5.18 below depict comparisons among mixtures containing the three various binder grades, various percentages of RAP and both RAP sources for 19.0 mm mixtures for FSTCH.

The results from the FSTCH indicate trends of increasing complex modulus with increasing frequency. Also, as the binder grade increases, from PG 52-28 to PG 64-22, the complex modulus increases. This trend holds true at all percentages of RAP. This would be expected as the complex modulus of PG 64-22 binder is larger than the complex modulus of PG 52-28 binder when temperature is constant.

Table 5.3 Comparison of Complex Modulus for 19.0 mm Westgate Mixtures

		Complex Modulus (Pa)	
Binder Grade	**RAP Percentage**	**0.01 Hz**	**10 Hz**
PG 64-22	15%	2.81E+08	2.24E+09
	30%	3.37E+08	2.87E+09
	40%	3.70E+08	4.17E+09
PG 58-22	15%	1.41E+08	1.64E+09
	30%	2.04E+08	1.80E+09
	40%	2.50E+08	2.42E+09
PG 52-28	15%	1.01E+08	1.35E+09
	30%	1.01E+08	1.47E+09
	40%	1.38E+08	1.81E+09

Table 5.4 Comparison of Complex Modulus for 19.0 mm Pineville Mixtures

		Complex Modulus (Pa)	
Binder Grade	**RAP Percentage**	**0.01 Hz**	**10 Hz**
PG 64-22	15%	2.71E+08	2.05E+09
	30%	3.01E+08	2.69E+09
	40%	3.72E+08	4.02E+09
PG 58-22	15%	1.24E+08	1.57E+09
	30%	1.87E+08	1.77E+09
	40%	2.49E+08	2.18E+09
PG 52-28	15%	9.21E+07	1.34E+09
	30%	1.18E+08	1.56E+09
	40%	1.58E+08	1.74E+09

The complex modulus of mixtures with higher percentages of RAP increases while holding the binder grade constant. Again, this can be expected since the complex modulus of the RAP binder is greater due to its aging caused during its service life.

Tables 5.3 and 5.4 above contain the complex modulus at 0.01 Hertz and 10 Hertz for each binder grade and the three percentages of RAP. The stiffness at 10 Hertz will be used in later analysis when computing the fatigue life.

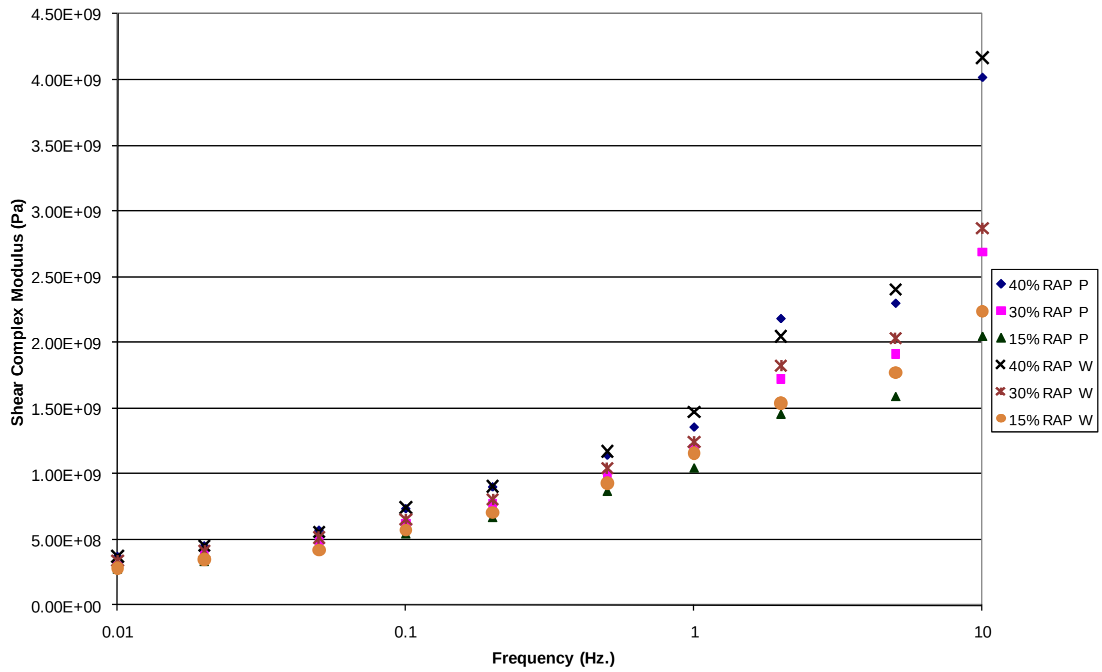


Figure 5.13 19.0 mm Frequency Sweep Comparison for PG 64-22

Figure 5.13 depicts the comparison for the various RAP percentages and both RAP sources using PG 64-22 binder. This data shows expected trends with mixtures containing 15% RAP having the lowest complex modulus and mixtures containing 40% RAP having the highest complex modulus. At each percentage, the mixtures containing Westgate RAP have a larger complex modulus than mixtures containing Pineville RAP. The complex modulus for mixtures containing PG 58-22 binder range from 2.24 X 10^9 Pa to 4.17 X 10^9 Pa at 10 Hz.

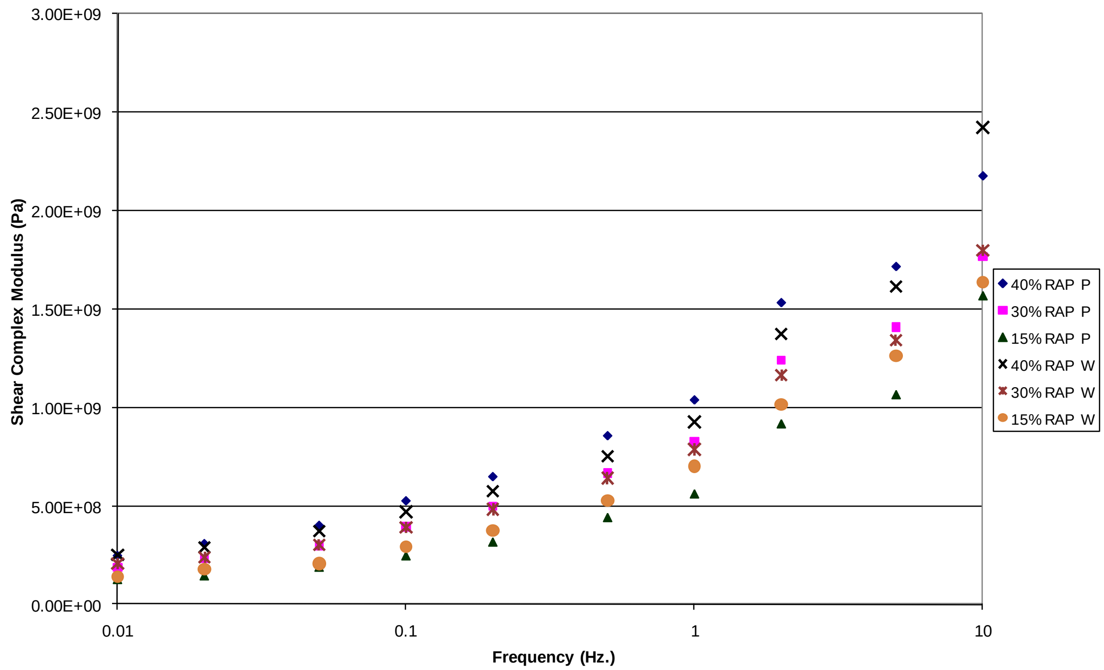


Figure 5.14 19.0 mm Frequency Sweep Comparison for PG 58-22

Figure 5.14 depicts the comparison for the various RAP percentages and both RAP sources using PG 58-22 binder. This data shows expected trends with mixtures containing 15% RAP having the lowest complex modulus and mixtures containing 40% RAP having the highest complex modulus. At each percentage, the mixtures containing Westgate RAP have a larger complex modulus than mixtures containing Pineville RAP. The complex modulus for mixtures containing PG 58-22 binder range from 1.57 X 10^9 Pa to 2.42 X 10^9 Pa at 10 Hz. These values are less than the mixtures containing PG 64-22 binder.

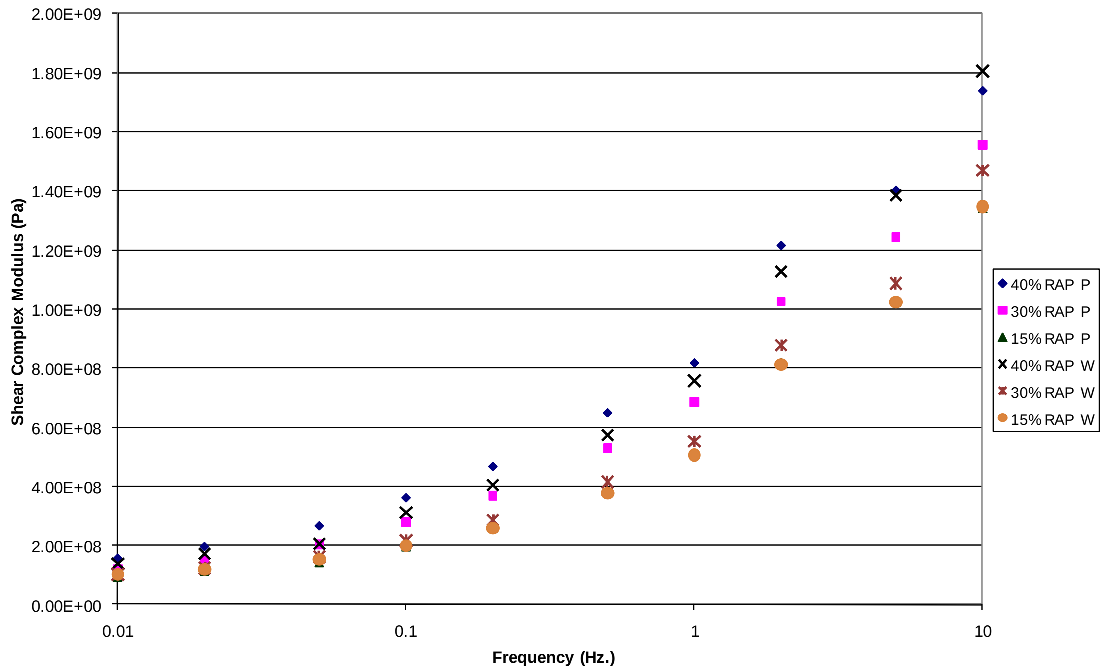


Figure 5.15 19.0 mm Frequency Sweep Comparison for PG 52-28

Figure 5.15 depicts the comparison for the various RAP percentages and both RAP sources using PG 52-28 binder. This data shows expected trends with mixtures containing 15% RAP having the lowest complex modulus and mixtures containing 40% RAP having the highest complex modulus. The complex modulus for mixtures containing PG 52-28 binder range from 1.34 X 10^9 Pa to 1.81 X 10^9 Pa at 10 Hz. These values are less than the mixtures containing PG 64-22 binder and PG 58-22 binder.

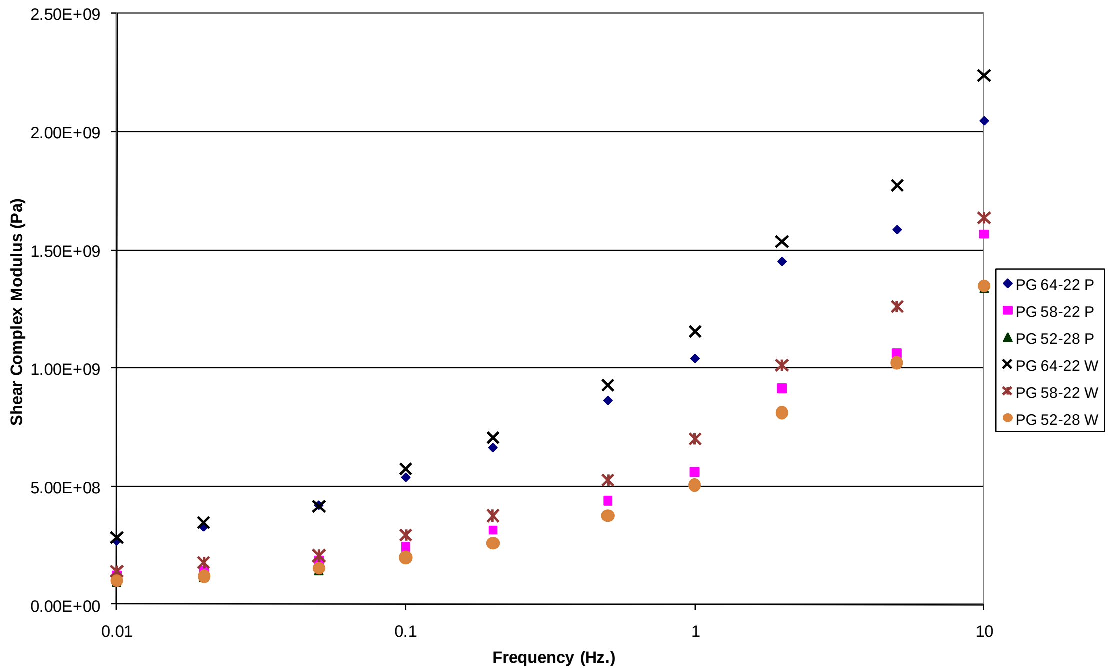


Figure 5.16 19.0 mm Frequency Sweep Comparison with 15% RAP

Figure 5.16 depicts the comparison for the various binder grades and RAP sources using 15% RAP. The mixtures containing PG 64-22 binder have the highest complex modulus followed by mixtures containing PG 58-22 binder and then mixtures containing PG 52-28 binder. This is expected as virgin PG 64-22 binder has a highest complex modulus followed by PG 58-22 binder and then PG 52-28 binder. The complex modulus for mixtures containing 15% RAP range from 1.34 X 10^9 Pa to 2.24 X 10^9 Pa at 10 Hz.

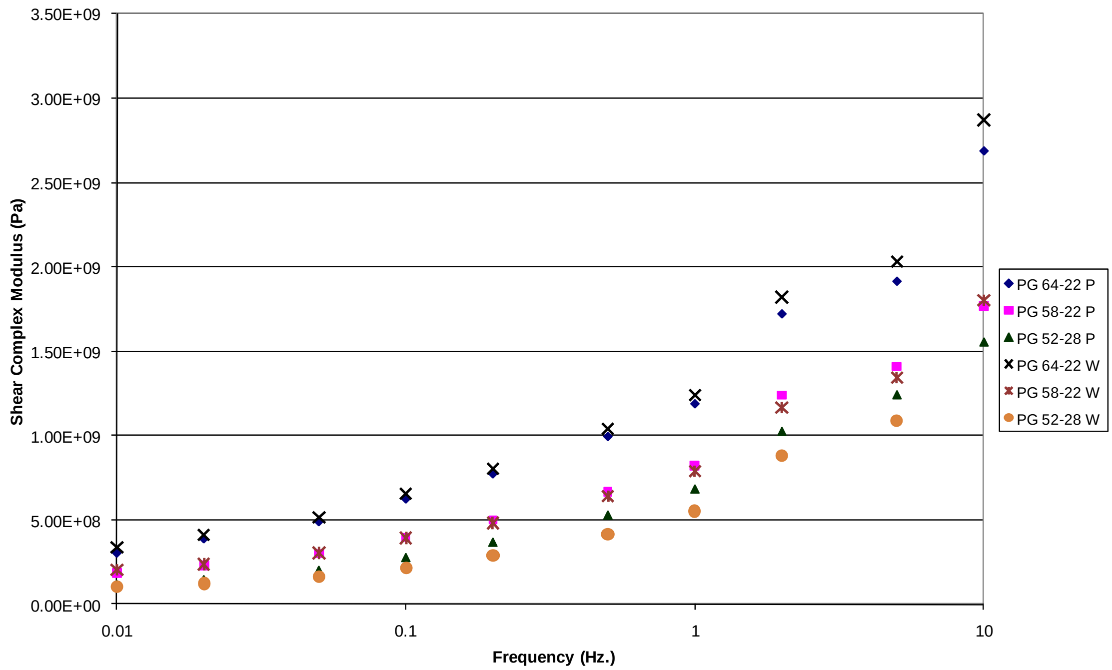


Figure 5.17 19.0 mm Frequency Sweep Comparison with 30% RAP

Figure 5.17 depicts the comparison for the various binder grades and RAP sources using 30% RAP. The mixtures containing PG 64-22 binder have the highest complex modulus followed by mixtures containing PG 58-22 binder and then mixtures containing PG 52-28 binder. This is expected as virgin PG 64-22 binder has a highest complex modulus followed by PG 58-22 binder and then PG 52-28 binder. The complex modulus for mixtures containing 30% RAP range from 1.47 X 10^9 Pa to 2.87 X 10^9 Pa at 10 Hz. These values are larger than the mixtures containing 15% RAP.

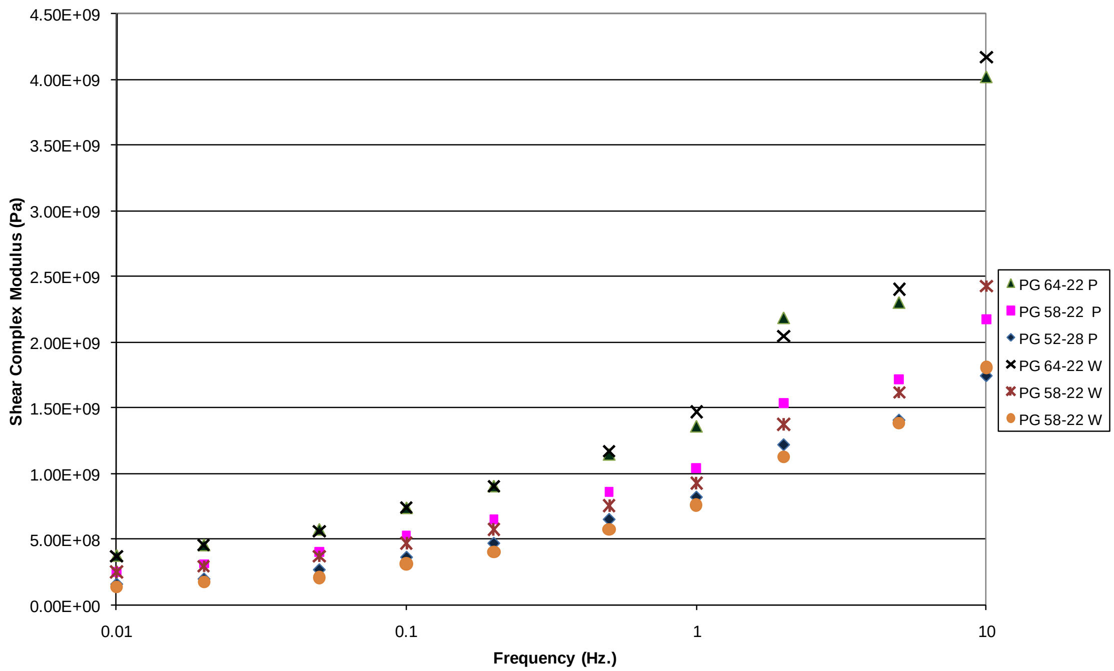


Figure 5.18 19.0 mm Frequency Sweep Comparison with 40% RAP

Figure 5.18 depicts the comparison for the various binder grades and RAP sources using 40% RAP. The mixtures containing PG 64-22 binder have the highest complex modulus followed by mixtures containing PG 58-22 binder and then mixtures containing PG 52-28 binder. This is expected as virgin PG 64-22 binder has a highest complex modulus followed by PG 58-22 binder and then PG 52-28 binder. The complex modulus for mixtures containing 40% RAP range from 1.74 X 10^9 Pa to 4.17 X 10^9 Pa at 10 Hz. These values are larger than the mixtures containing 15% and 30% RAP.

The results outlined above will be used in the next chapter for the pavement performance analysis in order to predict fatigue life.

5.2 Frequency Sweep Statistical Analysis

Statistical Analysis using a one-way Analysis of Variance (ANOVA) was conducted to determine if there was a statistical difference between the mean values of virgin mixtures and mean values of mixtures containing various amounts of RAP at different binder grades. The ANOVA compares the treatment mean square (between groups) to the mean square error (within groups). The F-value is computed as the ratio of the treatment mean square to the mean square error. The F distribution is used to determine a critical F-value based on the degrees of freedom and the alpha (α), or the significance level. If the F-value is greater than the F critical, then the null hypothesis can be rejected. For this case, the null hypothesis is H_o: $\mu_1=\mu_2$ (the mean value of the virgin mixture is equal to the mean value of the mixture containing RAP) where μ_1= average virgin mixture value and μ_2=average value of mixture containing RAP. The alternative hypothesis is H_a: $\mu_1\neq\mu_2$ (the mean value of the virgin mixture differs from the mean value of the mixture containing RAP). The p-value is calculated as the probability of getting an F-value this extreme or more if the null hypothesis is true. If the p-value is less than alpha, then the null hypothesis can be rejected. For this analysis, an alpha of 0.05 was used.

Tables 5.5-5.7 compare the G* values at 10 Hz for 9.5 mm mixtures containing 15%, 30% and 40% RAP, respectively to the virgin mixture containing PG 64-22 binder. The ANOVA shows that at all RAP percentages, the mixtures containing both Westgate and Pineville RAP and PG 64-22 binder show no difference in means from the virgin mixture. However, the ANOVA shows that at all RAP percentages, the mixtures containing both Westgate and Pineville RAP do not have similar means to the virgin mixtures for both PG 58-22 and PG 52-28 binders.

Table 5.5 Analysis of Variance Results of G* at 10 Hz for 9.5 mm Mixtures Containing 15% RAP vs. Virgin

	Treatment Mean Square	F value	p-value	Means Similar?
PG 64-22 P	1.80E+17	4.713	0.096	Yes
PG 64-22 W	1.07E+17	2.809	0.169	Yes
PG 58-22 P	1.40E+18	82.129	0.001	No
PG 58-22 W	1.33E+18	86.303	0.001	No
PG 52-28 P	2.47E+18	187.627	0.000	No
PG 52-28 W	1.90E+18	80.795	0.001	No

Table 5.6 Analysis of Variance Results of G* at 10 Hz for 9.5 mm Mixtures Containing 30% RAP vs. Virgin

	Treatment Mean Square	F value	p-value	Means Similar?
PG 64-22 P	9.37E+16	2.895	0.187	Yes
PG 64-22 W	6.00E+16	2.317	0.203	Yes
PG 58-22 P	1.12E+18	73.715	0.001	No
PG 58-22 W	8.74E+17	65.144	0.001	No
PG 52-28 P	1.19E+18	29.050	0.006	No
PG 52-28 W	1.84E+18	126.114	0.000	No

Table 5.7 Analysis of Variance Results of G* at 10 Hz for 9.5 mm Mixtures Containing 40% RAP vs. Virgin

	Treatment Mean Square	F value	p-value	Means Similar?
PG 64-22 P	7.80E+16	3.533	0.157	Yes
PG 64-22 W	4.68E+16	0.966	0.381	Yes
PG 58-22 P	6.48E+17	32.279	0.011	No
PG 58-22 W	4.27E+17	20.301	0.011	No
PG 52-28 P	1.36E+18	66.772	0.001	No
PG 52-28 W	1.33E+18	34.928	0.004	No

Tables 5.8-5.10 compare the G* values at 10 Hz for 19.0 mm mixtures containing 15%, 30% and 40% RAP, respectively to the virgin mixture containing PG 64-22 binder. The ANOVA shows that for all mixtures containing both Westgate and Pineville RAP at all binder grades (PG 64-22, PG 58-22 and PG 52-28) show no difference in means from the virgin mixture with the exception of the mixtures containing 15% and 30% Westgate RAP and PG 52-28 binder. It can be expected that a mixture containing two binder grades less than the original virgin grade and less RAP (15, 30%) would produce non similar results to the virgin mixture.

Table 5.8 Analysis of Variance Results of G* at 10 Hz for 19.0 mm Mixtures Containing 15% RAP vs. Virgin

	Treatment Mean Square	F value	p-value	Means Similar?
PG 64-22 P	9.76E+15	0.136	0.731	Yes
PG 64-22 W	5.62E+17	4.809	0.116	Yes
PG 58-22 P	5.84E+17	3.705	0.127	Yes
PG 58-22 W	4.42E+17	4.224	0.109	Yes
PG 52-28 P	8.68E+17	9.429	0.055	Yes
PG 52-28 W	1.07E+18	14.978	0.018	No

Table 5.9 Analysis of Variance Results of G* at 10 Hz for 19.0 mm Mixtures Containing 30% RAP vs. Virgin

	Treatment Mean Square	F value	p-value	Means Similar?
PG 64-22 P	3.69E+17	0.948	0.385	Yes
PG 64-22 W	5.54E+17	3.338	0.165	Yes
PG 58-22 P	2.70E+17	3.232	0.147	Yes
PG 58-22 W	2.29E+17	3.112	0.153	Yes
PG 52-28 P	6.03E+17	7.524	0.052	Yes
PG 52-28 W	7.79E+17	8.592	0.043	No

Table 5.10 Analysis of Variance Results of G* at 10 Hz for 19.0 mm Mixtures Containing 40% RAP vs. Virgin

	Treatment Mean Square	F value	p-value	Means Similar?
PG 64-22 P	5.02E+18	3.268	0.145	Yes
PG 64-22 W	8.26E+18	4.022	0.115	Yes
PG 58-22 P	2.94E+14	0.002	0.971	Yes
PG 58-22 W	8.12E+16	0.351	0.585	Yes
PG 52-28 P	3.05E+17	3.592	0.131	Yes
PG 52-28 W	1.62E+17	2.433	0.194	Yes

Statistical analysis using one-way ANOVA was used to determine whether there was a difference in means between the two RAP sources. . For this case, the null hypothesis is H_o: $\mu_1=\mu_2$ (the mean value of the Westgate RAP mixture is equal to the mean value of the Pineville RAP mixture) where μ_1= average Westgate RAP mixture value and μ_2=average Pineville RAP mixture value. The alternative hypothesis is H_a: $\mu_1\neq\mu_2$ (the mean value of the Westgate RAP mixture differs from the mean value of the Pineville RAP mixture). Tables 5.11-5.13 compare the G* values of the two RAP sources at 10 Hz for 9.5 mm mixtures containing 15%, 30% and 40% RAP, respectively. The ANOVA for all mixtures at any RAP percentage and all binder grades (PG 64-22, PG 58-22 and PG 52-28) show no difference in means. This suggests that mixtures containing RAP from either stockpile produce similar results. The variability of RAP stockpiles is often a concern for using higher percentages of RAP since the properties are often unknown. However, these results show that although these two RAP sources that were selected for their differing properties, the differing sources can still produce similar complex modulus.

Table 5.11 Analysis of Variance Results of G* at 10 Hz for 9.5 mm Mixtures Containing 15% RAP (Stockpiles)

	Treatment Mean Square	F value	p-value	Means Similar?
PG 64-22	9.43E+15	0.188	0.687	Yes
PG 58-22	8.17E+14	0.123	0.743	Yes
PG 52-28	3.68E+16	3.398	0.139	Yes

Table 5.12 Analysis of Variance Results of G* at 10 Hz for 9.5 mm Mixtures Containing 30% RAP (Stockpiles)

	Treatment Mean Square	F value	p-value	Means Similar?
PG 64-22	7.58E+15	0.234	0.662	Yes
PG 58-22	1.50E+16	5.590	0.077	Yes
PG 52-28	7.04E+16	2.382	0.198	Yes

Table 5.13 Analysis of Variance Results of G* at 10 Hz for 9.5 mm Mixtures Containing 40% RAP (Stockpiles)

	Treatment Mean Square	F value	p-value	Means Similar?
PG 64-22	2.24E+17	4.286	0.130	Yes
PG 58-22	4.88E+16	3.596	0.154	Yes
PG 52-28	1.50E+14	0.005	0.949	Yes

Tables 5.14-5.16 compare the G* values of the two RAP sources at 10 Hz for 19.0 mm mixtures containing 15%, 30% and 40% RAP, respectively. The ANOVA for all mixtures at any RAP percentage and all binder grades (PG 64-22, PG 58-22 and PG 52-28) show no difference in means. This suggests that mixtures containing RAP from either stockpile produce similar results. The variability of RAP stockpiles is often a concern for using higher percentages of RAP since the properties are often unknown. However, these results show that although these two RAP sources that were selected for their differing

properties, the differing sources can still produce similar complex modulus.

Table 5.14 Analysis of Variance Results of G* at 10 Hz for 19.0 mm Mixtures Containing 15% RAP (Stockpiles)

	Treatment Mean Square	F value	p-value	Means Similar?
PG 64-22	7.02E+17	19.941	0.021	Yes
PG 58-22	9.94E+15	0.077	0.795	Yes
PG 52-28	5.33E+13	0.006	0.945	Yes

Table 5.15 Analysis of Variance Results of G* at 10 Hz for 19.0 mm Mixtures Containing 30% RAP (Stockpiles)

	Treatment Mean Square	F value	p-value	Means Similar?
PG 64-22	4.03E+16	0.080	0.796	Yes
PG 58-22	1.67E+15	0.070	0.804	Yes
PG 52-28	1.13E+16	0.300	0.613	Yes

Table 5.16 Analysis of Variance Results of G* at 10 Hz for 19.0 mm Mixtures Containing 40% RAP (Stockpiles)

	Treatment Mean Square	F value	p-value	Means Similar?
PG 64-22	4.02E+17	0.116	0.750	Yes
PG 58-22	9.13E+16	0.315	0.605	Yes
PG 52-28	2.22E+16	1.212	0.333	Yes

5.3 Repeated Shear Analysis

Using the SST, testing for RSSTCH was completed for the 9.5mm specimens at the various RAP percentages (15%, 30%, and 40%) with PG 64-22 binder, PG 58-22 binder and PG 52-28 binder and both RAP sources (Westgate and Pineville). Figures 5.19-5.24 below depict comparisons among mixtures containing the three various binder grades, various percentages of RAP and both RAP sources for 9.5 mm mixtures for RSSTCH.

After 5000 cycles of repeated shear, the mixtures containing PG 64-22 binder exhibited the least amount of strain at all percentages of RAP. Mixtures with PG 58-22 binder exhibited lesser strain than the mixtures with PG 52-28 binder. This can be expected as mixtures with stiffer binders exhibited less strain.

Comparing mixtures with various percentages of RAP with constant binder grade shows general trends that the strain decreases with increasing RAP. Again, this can be expected as the binder recovered from the RAP was stiffer than the virgin binders due to its aging during its service life. Therefore, mixtures with higher percentages of RAP are going to generally exhibit less strain as a result.

Table 5.17 below compares the values of the plastic shear strain accumulated by the 9.5 mm virgin mixtures to the 9.5 mm mixtures containing various percentages of Westgate RAP. The amount of plastic shear strain reduces for all PG 64-22 mixtures containing RAP varying from 7% to 45% reduction. The PG 58-22 mixtures containing 15% and 30% RAP result in the plastic shear strain increases of 28% and 21%, respectively. This increase is caused by the reduction in binder stiffness of the PG 58-22 binder from the original PG 64-22 virgin binder. However, this reduction in virgin binder stiffness is overcome when 40% RAP is included in the mix and the plastic shear strain reduces 6% from the virgin mixture. With the reduction of two binder grades from the original virgin binder to a PG 52-28 binder, the plastic shear strain increases 100%, 42% and 33% for mixtures containing 15%, 30% and 40% RAP, respectively. For all binder grades, as the percentage of RAP increases, the plastic shear strain reduces. This is because the RAP binder has a higher complex modulus than the virgin binder and results in a stiffer blend.

Table 5.17 Comparison of Plastic Strain Values After RSSTCH for 9.5 mm Mixtures Westgate

Binder Grade	RAP Percentage	Plastic Strain (%) @ 5,000 Cycles	Percent Difference from Virgin Mixtures
PG 64-22	0	1.07	--
PG 64-22	15%	0.99	-7
	30%	0.92	-14
	40%	0.59	-45
PG 58-22	15%	1.37	28
	30%	1.29	21
	40%	1.01	-6
PG 52-28	15%	2.14	100
	30%	1.52	42
	40%	1.42	33

Table 5.18 below compares the values of the plastic shear strain accumulated by the 9.5 mm virgin mixtures to the 9.5 mm mixtures containing various percentages of Pineville RAP. The amount of plastic shear strain reduces for all PG 64-22 mixtures containing RAP varying from 22% to 64% reduction. The PG 58-22 mixtures containing 15% and 30% RAP result in the plastic shear strain increases 53% and 12%, respectively. This increase is caused by the reduction in binder stiffness of the PG 58-22 binder from the original PG 64-22 virgin binder. However, this reduction in virgin binder stiffness is overcome when 40% RAP is included in the mix and the plastic shear strain reduces 24% from the virgin mixture. With the reduction of two binder grades from the original virgin binder to a PG 52-28 binder, the plastic shear strain increases 126%, 55% and 46% for mixtures containing 15%, 30% and 40% RAP, respectively. For all binder grades, as the percentage of RAP increases, the plastic shear strain reduces. This is because the RAP binder has a higher complex modulus than the virgin binder and results in a stiffer blend.

Table 5.18 Comparison of Plastic Strain Values After RSSTCH for 9.5 mm Mixtures Pineville

Binder Grade	RAP Percentage	Plastic Strain (%) @ 5,000 Cycles	Percent Difference from Virgin Mixtures
PG 64-22	0	1.07	--
PG 64-22	15%	0.83	-22
	30%	0.75	-30
	40%	0.39	-64
PG 58-22	15%	1.64	53
	30%	1.20	12
	40%	0.81	-24
PG 52-28	15%	2.42	126
	30%	1.66	55
	40%	1.56	46

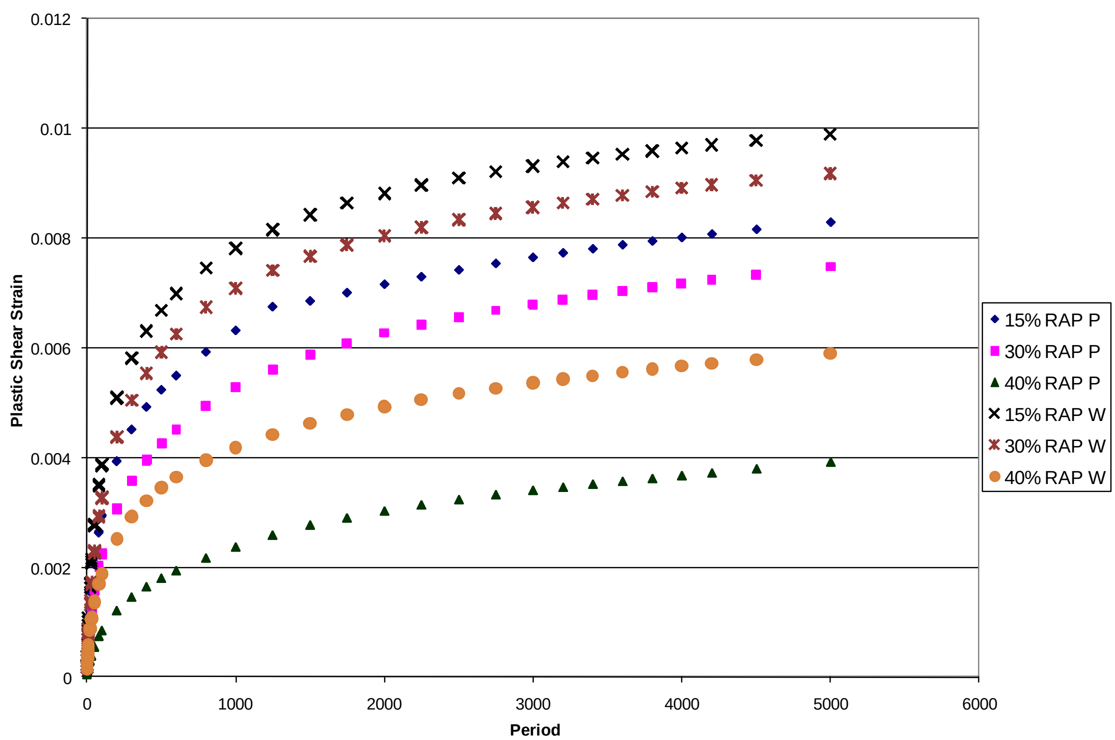


Figure 5.19 9.5 mm Repeated Shear Comparison for PG 64-22

Figure 5.19 depicts the comparison for the various RAP percentages and both RAP sources using PG 64-22 binder. The plastic shear strain for mixtures containing 30% Westgate RAP is larger than the plastic shear strain for mixtures containing 15% Pineville RAP. This is an unexpected result and is probably due to variation in the RAP stockpiles. The plastic shear strain ranges from 0.00829 to 0.005901.

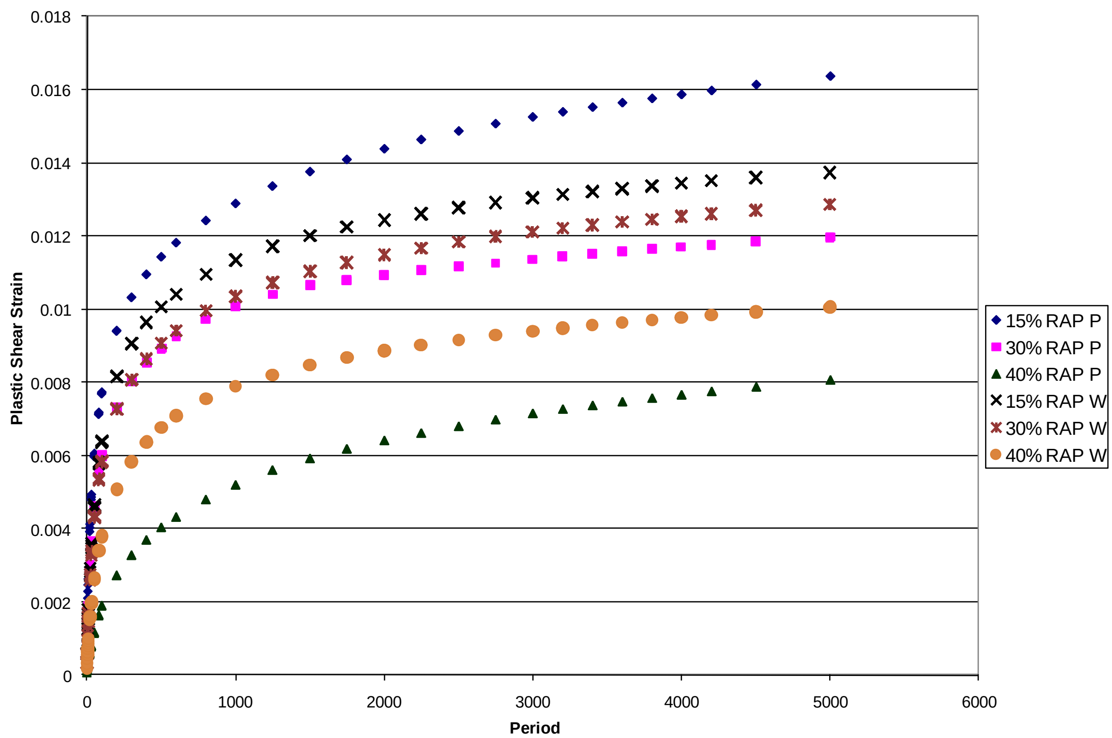


Figure 5.20 9.50 mm Repeated Shear Comparison for PG 58-22

Figure 5.20 depicts the comparison for the various RAP percentages and both RAP sources using PG 58-22 binder. Mixtures containing 15% RAP have the largest plastic shear strain while mixtures containing 40% RAP have the least plastic shear strain. This is expected since mixtures with larger complex modulus, such as mixtures with 40% RAP, should experience less shear strain. The plastic shear strain ranges from 0.013729 to 0.010053. These values are larger than the plastic shear strain experience with mixtures containing PG 64-22 binder. This is a result of using a virgin binder, PG 58-22, with a lower complex modulus.

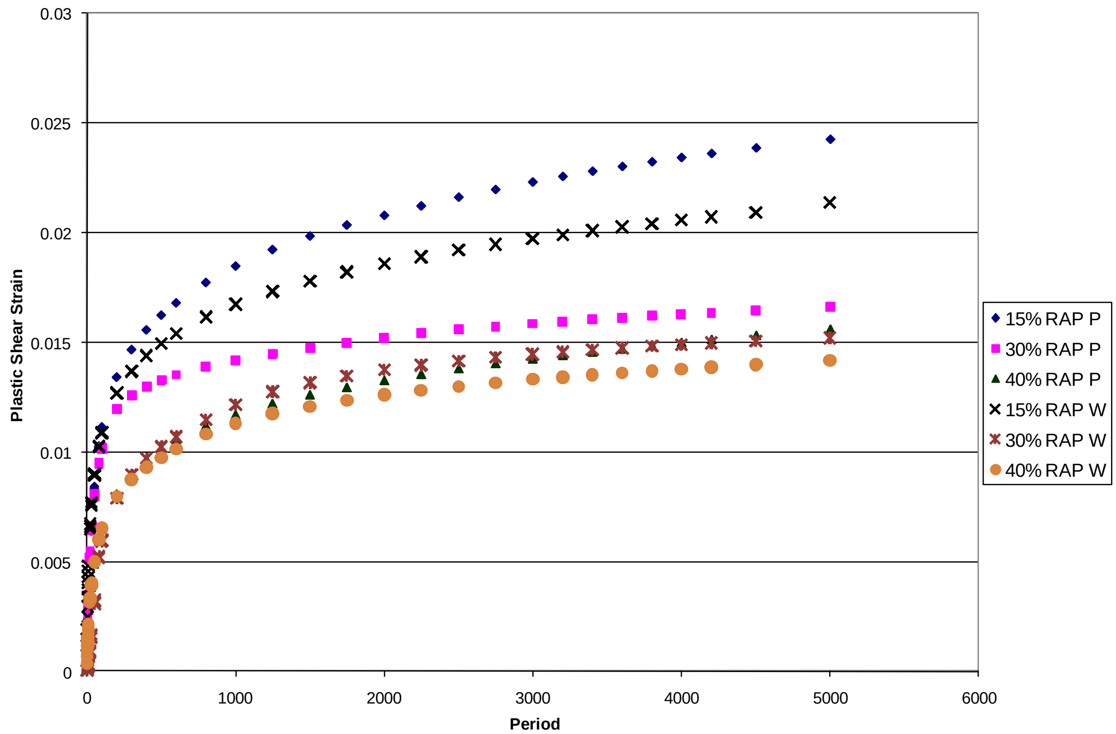


Figure 5.21 9.5 mm Repeated Shear Comparison for PG 52-28

Figure 5.21 depicts the comparison for the various RAP percentages and both RAP sources using PG 52-28 binder. Mixtures containing 15% RAP have the largest plastic shear strain while mixtures containing 40% RAP have the least plastic shear strain. This is expected since mixtures with larger complex modulus, such as mixtures with 40% RAP, should experience less shear strain. However, the mixture containing 40% Pineville RAP experiences slightly more plastic shear strain than the mixture containing 30% Westgate RAP at the end of the loading period. This might be explained by the Pineville RAP containing a softer binder than the Westgate RAP so a higher plastic shear strain is observed. The plastic shear strain ranges from 0.021366 to 0.014164. These values are larger than the plastic shear strain experience with mixtures containing PG 64-22 binder and PG 58-22 binder. This is a result of using a virgin binder, PG 52-28, with a lower complex modulus.

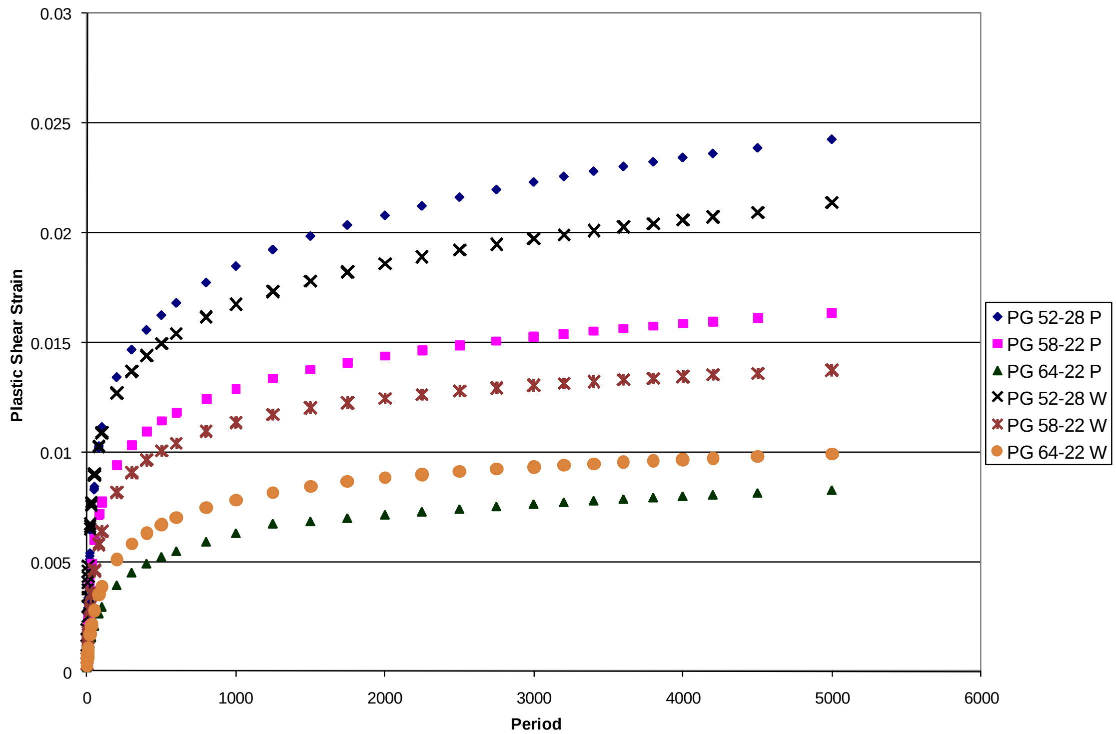


Figure 5.22 9.5 mm Repeated Shear Comparison with 15% RAP

Figure 5.22 depicts the comparison for the various binder grades and RAP sources using 15% RAP. The mixtures containing PG 64-22 binder experience the lowest amount of plastic shear strain followed by mixtures containing PG 58-22 binder and then mixtures containing PG 52-28 binder. This is expected as virgin PG 64-22 binder has a highest complex modulus followed by PG 58-22 binder and then PG 52-28 binder. The plastic shear strain for mixtures containing 15% RAP range from 0.00829 to 0.024246.

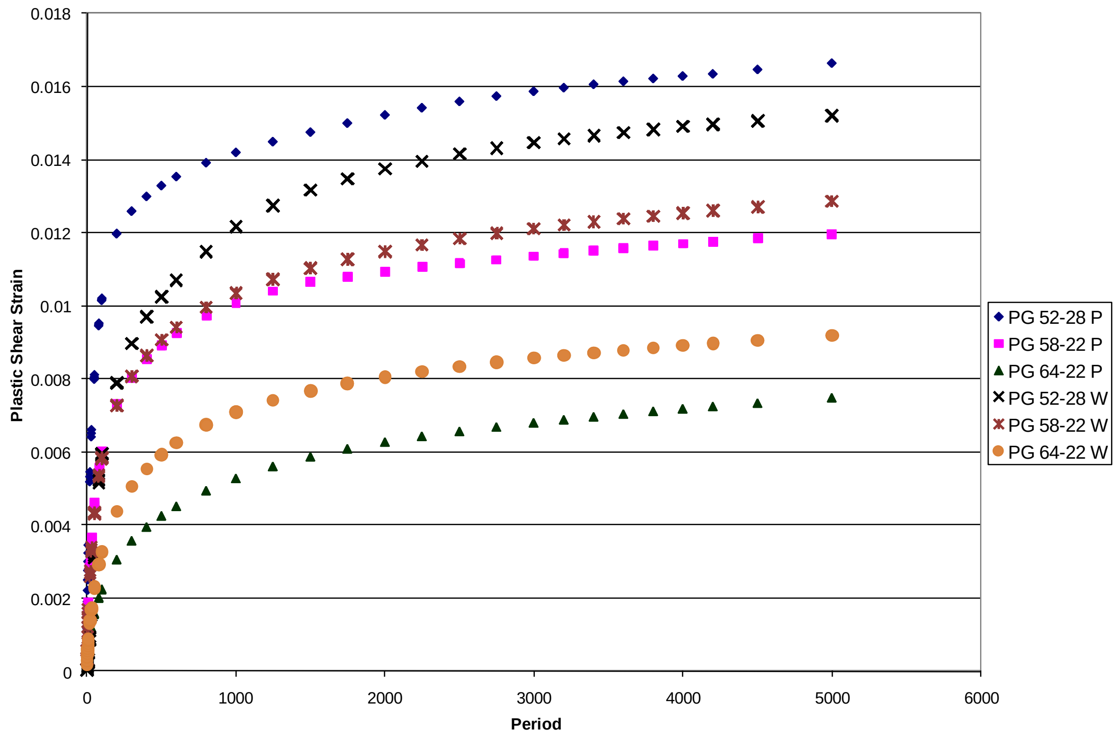


Figure 5.23 9.5 mm Repeated Shear Comparison with 30% RAP

Figure 5.23 depicts the comparison for the various binder grades and RAP sources using 30% RAP. The mixtures containing PG 64-22 binder experience the lowest amount of plastic shear strain followed by mixtures containing PG 58-22 binder and then mixtures containing PG 52-28 binder. This is expected as virgin PG 64-22 binder has a highest complex modulus followed by PG 58-22 binder and then PG 52-28 binder. The plastic shear strain for mixtures containing 30% RAP range from 0.007481 to 0.016626. These values are less than the plastic shear strain values for mixtures containing 15% RAP. This is expected since mixtures containing higher percentages of RAP have higher complex modulus, thus reducing the plastic shear strain.

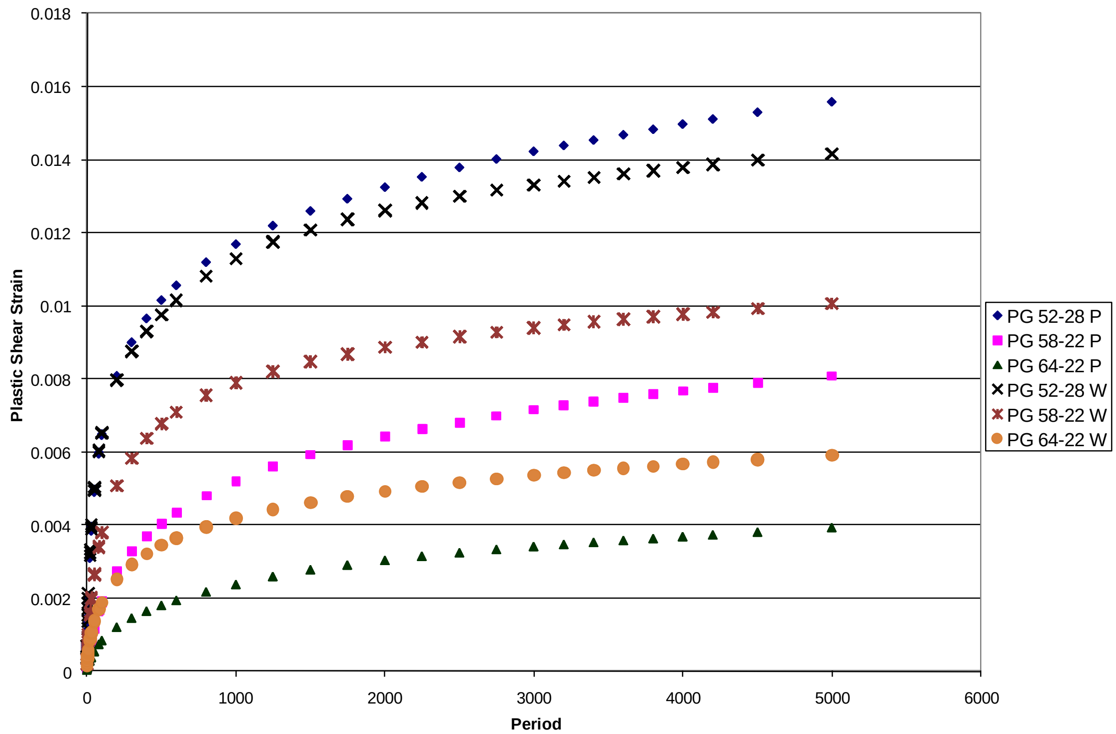


Figure 5.24 9.5 mm Repeated Shear Comparison with 40% RAP

Figure 5.24 depicts the comparison for the various binder grades and RAP sources using 40% RAP. The mixtures containing PG 64-22 binder experience the lowest amount of plastic shear strain followed by mixtures containing PG 58-22 binder and then mixtures containing PG 52-28 binder. This is expected as virgin PG 64-22 binder has a highest complex modulus followed by PG 58-22 binder and then PG 52-28 binder. The plastic shear strain for mixtures containing 40% RAP range from 0.003922 to 0.01558. These values are less than the plastic shear strain values for mixtures containing 15% RAP and 30% RAP. This is expected since mixtures containing higher percentages of RAP have higher complex modulus, thus reducing the plastic shear strain.

Using the SST, testing for RSSTCH was completed for the 19.0 mm specimens at the various RAP percentages (15%, 30%, and 40%) with PG 64-22 binder, PG 58-22 binder and PG 52-28 binder and both RAP sources (Westgate and Pineville). Figures 5.25-5.30 below depict comparisons among mixtures containing the three various binder grades, various percentages of RAP and both RAP sources for 19.0 mm mixtures for RSSTCH.

After 5000 cycles of repeated shear, the mixtures containing PG 64-22 binder exhibited the least amount of strain at all percentages of RAP. Mixtures with PG 58-22 binder exhibited lesser strain than the mixtures with PG 52-28 binder. This can be expected as mixtures with stiffer binders exhibited less strain.

Comparing mixtures with various percentages of RAP with constant binder grade shows general trends that the strain decreases with increasing RAP. Again, this can be expected as the binder recovered from the RAP was stiffer than the virgin binders due to its aging during its service life. Therefore, mixtures with higher percentages of RAP are going to generally exhibit less strain as a result.

Table 5.19 below compares the values of the plastic shear strain accumulated by the 19.0 mm virgin mixtures to the 19.0 mm mixtures containing various percentages of Westgate RAP. The amount of plastic shear strain reduces for all PG 64-22 mixtures containing RAP varying from 27% to 35% reduction. The PG 58-22 mixtures containing 15% RAP result in the plastic shear strain increase of 8%. This increase is caused by the reduction in binder stiffness of the PG 58-22 binder from the original PG 64-22 virgin binder. However, this reduction in binder stiffness is overcome when 30% and 40% RAP is included in the mix and the plastic shear strain reduces 15% and 19%, respectively, from the virgin mixture. With the reduction of two binder grades from the original virgin binder to a PG 52-28 binder, the plastic shear strain increases 23%, 14% and 13% for mixtures containing 15%, 30% and 40% RAP, respectively. For all binder grades, as the percentage of RAP increases, the plastic shear strain reduces. This is because the RAP binder has a higher complex modulus than the virgin binder and results in a stiffer blend.

Table 5.19 Comparison of Plastic Strain Values After RSSTCH for 19.0 mm Mixtures Westgate

Binder Grade	RAP Percentage	Plastic Strain (%) @ 5,000 Cycles	Percent Difference from Virgin Mixtures
PG 64-22	0	1.26	--
PG 64-22	15%	0.92	-27
	30%	0.87	-31
	40%	0.82	-35
PG 58-22	15%	1.36	8
	30%	1.07	-15
	40%	1.02	-19
PG 52-28	15%	1.55	23
	30%	1.44	14
	40%	1.43	13

Table 5.20 below compares the values of the plastic shear strain accumulated by the 19.0 mm virgin mixtures to the 19.0 mm mixtures containing various percentages of Pineville RAP. The amount of plastic shear strain reduces for all PG 64-22 mixtures containing RAP varying from 10% to 38% reduction. With a reduction of one binder grade from the original virgin binder to a PG 58-22 binder, the plastic shear strain increases 37%, 27%, and 19% for mixtures containing 15%, 30%, and 40% RAP, respectively. With the reduction of two binder grades from the original virgin binder to a PG 52-28 binder, the plastic shear strain increases 56%, 39% and 34% for mixtures containing 15%, 30% and 40% RAP, respectively. Mixtures containing Pineville RAP are not as capable in compensating for the grade shifts in virgin binder as mixtures containing Westgate RAP (i.e., PG 58-22 with 30% and 40% Pineville RAP plastic shear strain increases). This can be attributed to the softer binder contained in the Pineville RAP. For all binder grades, as the percentage of RAP increases, the plastic shear strain reduces. This is because the RAP binder has a higher complex modulus than the virgin binder and results in a stiffer blend.

Table 5.20 Comparison of Plastic Strain Values After RSSTCH for 19.0 mm Mixtures Pineville

Binder Grade	RAP Percentage	Plastic Strain (%) @ 5,000 Cycles	Percent Difference from Virgin Mixtures
PG 64-22	0	1.26	--
PG 64-22	15%	1.14	-10
	30%	1.02	-19
	40%	0.78	-38
PG 58-22	15%	1.73	37
	30%	1.60	27
	40%	1.50	19
PG 52-28	15%	1.97	56
	30%	1.75	39
	40%	1.69	34

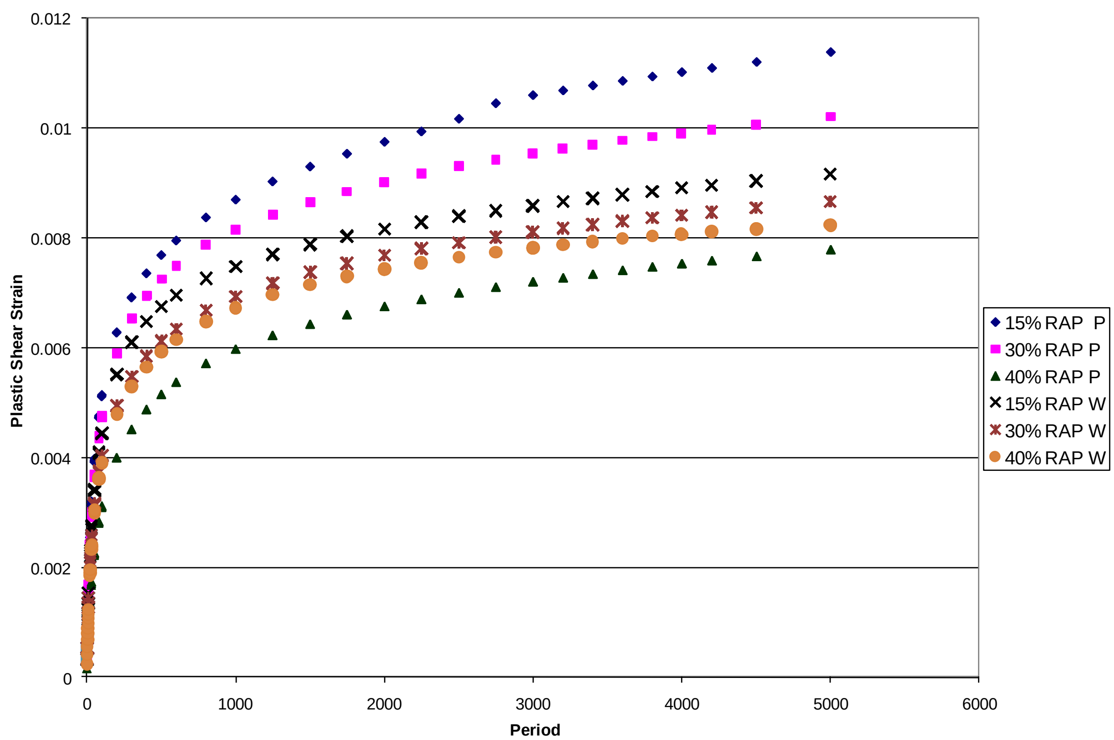


Figure 5.25 19.0 mm Repeated Shear Comparison for PG 64-22

Figure 5.25 depicts the comparison for the various RAP percentages and both RAP sources using PG 64-22 binder. The plastic shear strain for mixtures containing 30% Pineville RAP is larger than the plastic shear strain for mixtures containing 15% Westgate RAP. This may be a result of the less stiff Pineville binder. The plastic shear strain ranges from 0.008235 to 0.009164.

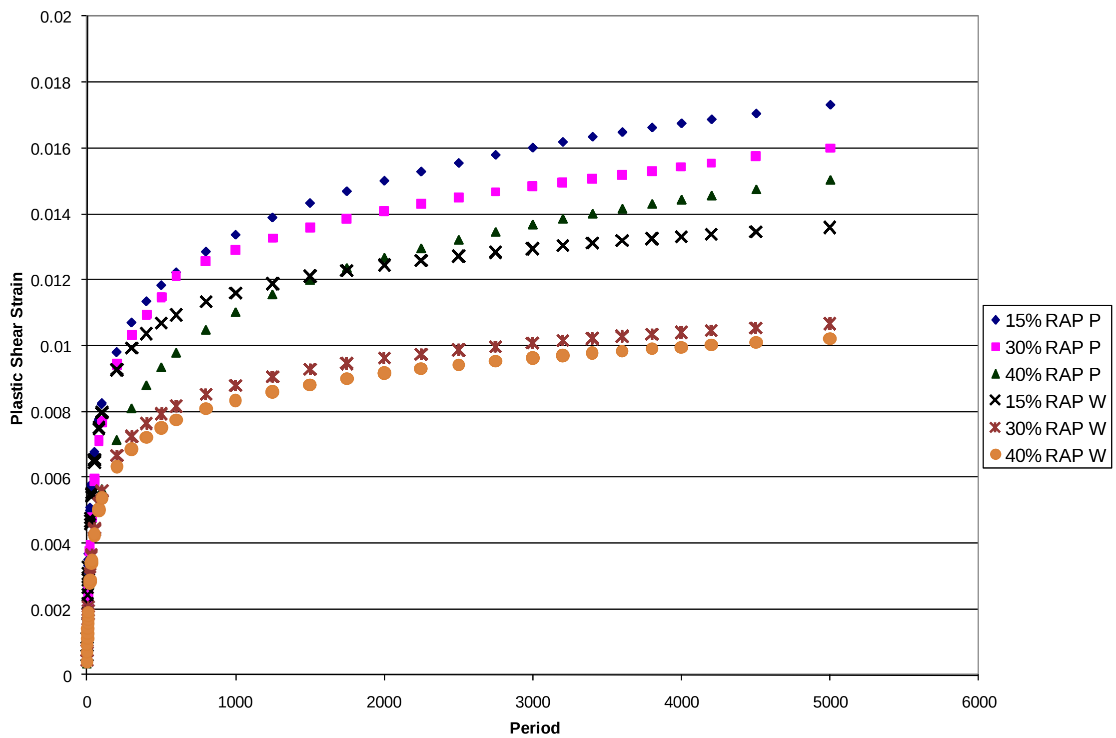


Figure 5.26 19.0 mm Repeated Shear Comparison for PG 58-22

Figure 5.26 depicts the comparison for the various RAP percentages and both RAP sources using PG 58-22 binder. The plastic shear strain for all mixtures containing Pineville RAP is larger than the plastic shear strain for all mixtures containing Westgate RAP. This could be a result of the Westgate RAP having a higher complex modulus than the Pineville RAP thus experiencing less plastic shear strain. The plastic shear strain ranges from 0.013589 to 0.015024. These values are larger than the plastic shear strain experience with mixtures containing PG 64-22 binder. This is a result of using a virgin binder, PG 58-22, with a lower complex modulus.

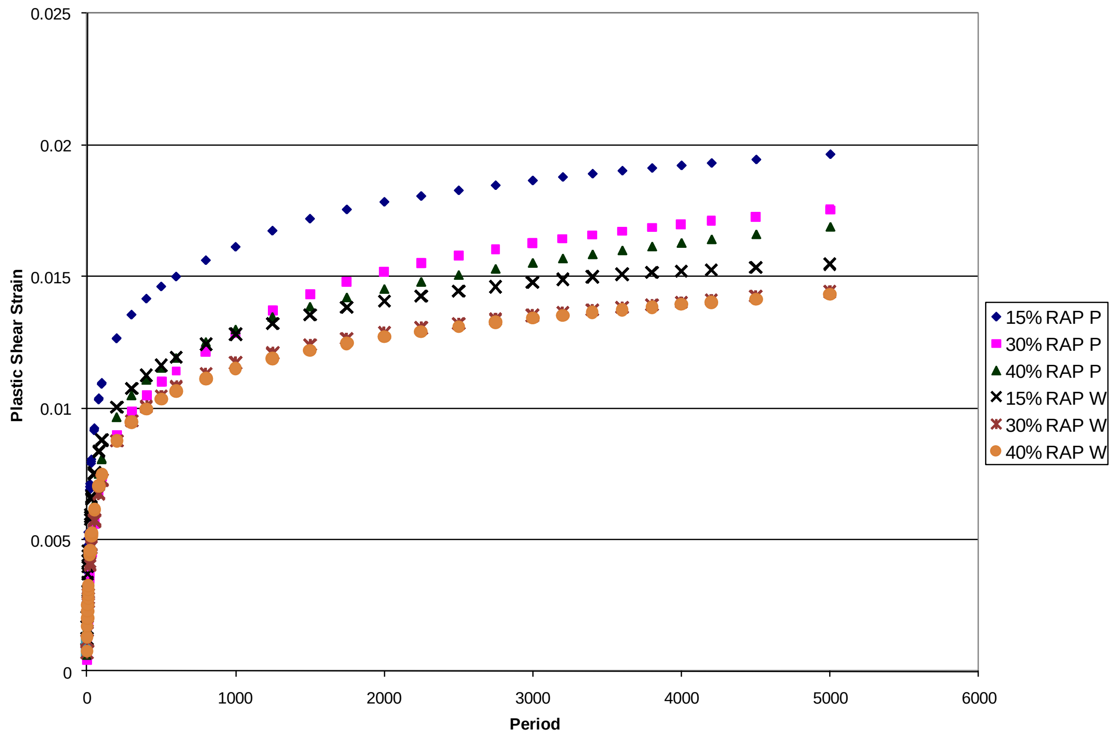


Figure 5.27 19.0 mm Repeated Shear Comparison for PG 52-28

Figure 5.27 depicts the comparison for the various RAP percentages and both RAP sources using PG 52-28 binder. The plastic shear strain for all mixtures containing Pineville RAP is larger than the plastic shear strain for all mixtures containing Westgate RAP. This could be a result of the Westgate RAP having a higher complex modulus than the Pineville RAP thus experiencing less plastic shear strain. The plastic shear strain ranges from 0.014321 to 0.01967. These values are larger than the plastic shear strain experience with mixtures containing PG 64-22 binder and PG 58-22 binder. This is a result of using a virgin binder, PG 52-28, with a lower complex modulus.

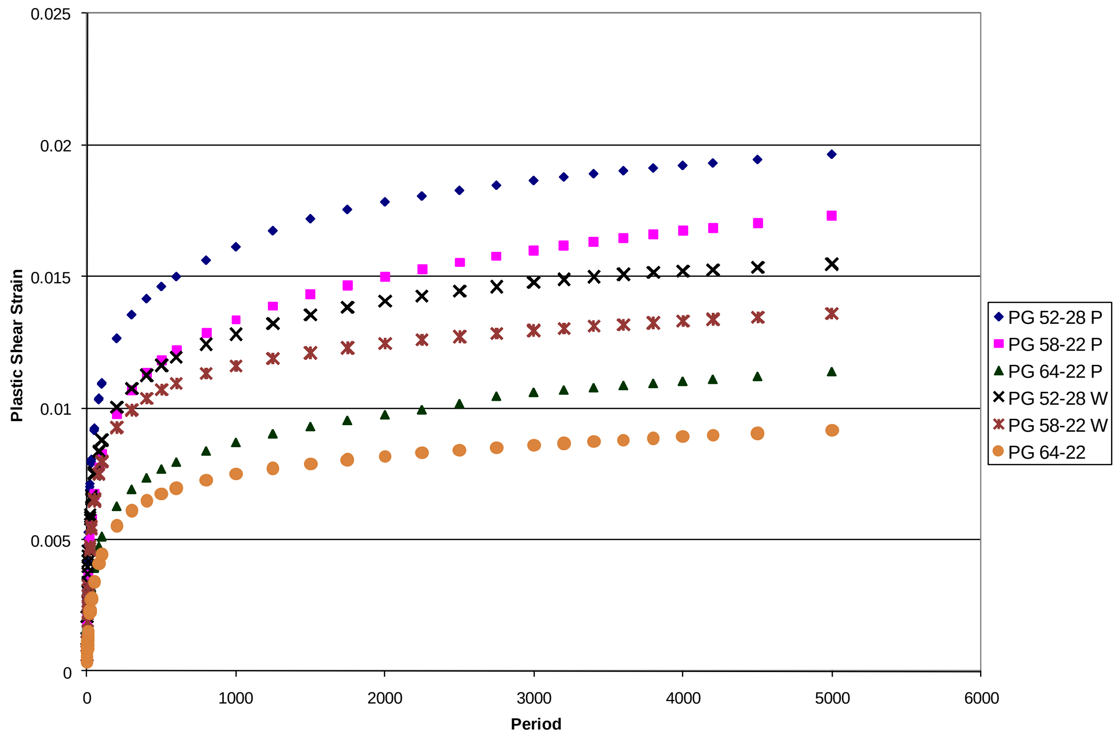


Figure 5.28 19.0 mm Repeated Shear Comparison with 15% RAP

Figure 5.28 depicts the comparison for the various binder grades and RAP sources using 15% RAP. The mixtures containing PG 64-22 binder experience the lowest amount of plastic shear strain. Mixtures containing PG 58-22 binder and Pineville RAP experience more plastic shear strain than mixtures containing PG 52-28 binder and Westgate RAP. This can again be contributed to the Westgate RAP having a higher complex modulus thus resulting in less plastic shear strain. The plastic shear strain for mixtures containing 15% RAP range from 0.009164 to 0.01967.

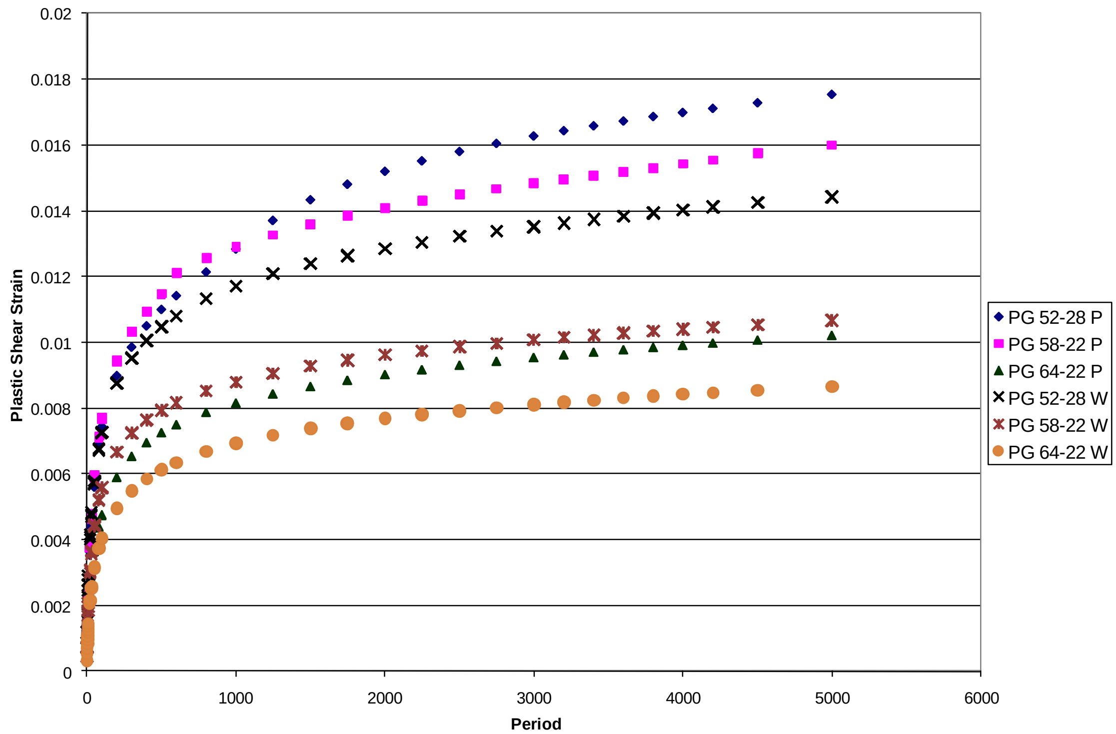


Figure 5.29 19.0 mm Repeated Shear Comparison with 30% RAP

Figure 5.29 depicts the comparison for the various binder grades and RAP sources using 30% RAP. The mixtures containing PG 64-22 binder experience the lowest amount of plastic shear strain. Mixtures containing PG 58-22 binder and Pineville RAP experience more plastic shear strain than mixtures containing PG 52-28 binder and Westgate RAP. This can again be contributed to the Westgate RAP having a higher complex modulus thus resulting in less plastic shear strain. The plastic shear strain for mixtures containing 30% RAP range from 0.008661 to 0.017535. These values are less than the plastic shear strain values for mixtures containing 15% RAP. This is expected since mixtures containing higher percentages of RAP have higher complex modulus, thus reducing the plastic shear strain.

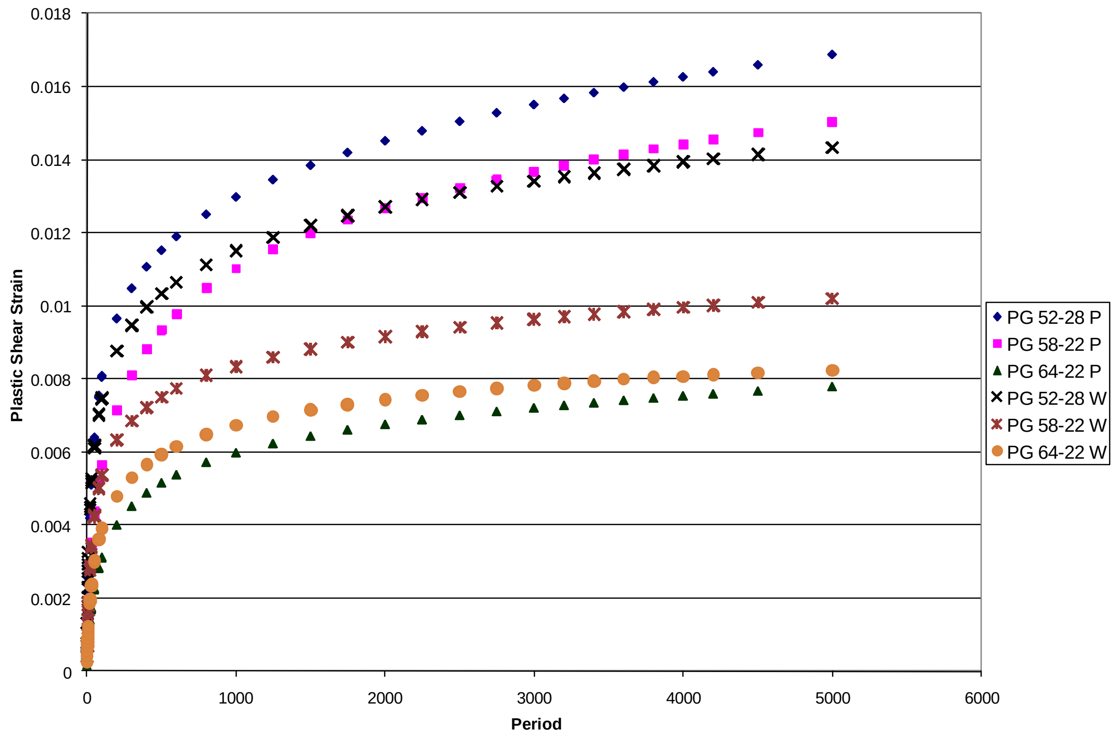


Figure 5.30 19.0 mm Repeated Shear Comparison with 40% RAP

Figure 5.30 depicts the comparison for the various binder grades and RAP sources using 40% RAP. The mixtures containing PG 64-22 binder experience the lowest amount of plastic shear strain. Mixtures containing PG 58-22 binder and Pineville RAP experience more plastic shear strain than mixtures containing PG 52-28 binder and Westgate RAP at the end of the period. This can again be contributed to the Westgate RAP having a higher complex modulus thus resulting in less plastic shear strain. The plastic shear strain for mixtures containing 40% RAP range from 0.007782 to 0.016872. These values are less than the plastic shear strain values for mixtures containing 15% RAP and 30% RAP. This is expected since mixtures containing higher percentages of RAP have higher complex modulus, thus reducing the plastic shear strain.

The results outlined above will be used in the next chapter for the pavement performance analysis in order to predict rut depth and rut life.

5.4 Repeated Shear Statistical Analysis

Statistical Analysis using a one-way ANOVA was conducted to determine if there was a statistical difference between the mean values of virgin mixtures and mean values of mixtures containing various amounts of RAP at different binder grades. The ANOVA compares the treatment mean square (between groups) to the mean square error (within groups). The F-value is computed as the ratio of the treatment mean square to the mean square error. The F distribution is used to determine a critical F-value based on the degrees of freedom and the alpha (α), or the significance level. If the F-value is greater than the F critical, then the null hypothesis can be rejected. For this case, the null hypothesis is H_o: $\mu_1=\mu_2$ (the mean value of the virgin mixture is equal to the mean value of the mixture containing RAP) where μ_1= average virgin mixture value and μ_2=average value of mixture containing RAP. The alternative hypothesis is H_a: $\mu_1 \neq \mu_2$ (the mean value of the virgin mixture differs from the mean value of the mixture containing RAP). The p-value is calculated as the probability of getting an F-value this extreme or more if the null hypothesis is true. If the p-value is less than alpha, then the null hypothesis can be rejected. For this analysis, an alpha of 0.05 was used.

Tables 5.21-5.23 compare the plastic shear strain at 5,000 cycles for 9.5 mm mixtures containing 15%, 30% and 40% RAP, respectively, to the virgin mixture containing PG 64-22 binder. The ANOVA shows that at 15% RAP, only the mixture containing Pineville RAP and PG 64-22 binder had a similar mean to the virgin mixture. The ANOVA shows that at 30% RAP, both mixtures containing PG 64-22 binder as well as the mixtures containing PG 58-22 and PG 52-28 binder and Pineville RAP had means similar to the virgin mixture. At 40% RAP, the ANOVA shows that both mixtures containing PG 64-22 binder as well as the mixture containing PG 58-22 binder and Pineville RAP had means similar to the virgin mixture.

Table 5.21 Analysis of Variance Results of Plastic Shear Strain for 9.5 mm Mixtures Containing 15% RAP vs. Virgin

	Treatment Mean Square	F value	p-value	Means Similar?
PG 64-22 P	8.20E-06	5.334	0.082	Yes
PG 64-22 W	2.33E-05	8.005	0.047	No
PG 58-22 P	1.62E-04	74.915	0.001	No
PG 58-22 W	7.26E-05	21.098	0.019	No
PG 52-28 P	4.02E-04	181.543	0.001	No
PG 52-28 W	3.59E-04	93.124	0.001	No

Table 5.22 Analysis of Variance Results of Plastic Shear Strain for 9.5 mm Mixtures Containing 30% RAP vs. Virgin

	Treatment Mean Square	F value	p-value	Means Similar?
PG 64-22 P	6.37E-06	3.331	0.165	Yes
PG 64-22 W	1.25E-05	5.130	0.108	Yes
PG 58-22 P	5.43E-05	2.217	0.211	Yes
PG 58-22 W	7.40E-05	46.755	0.002	No
PG 52-28 P	6.37E-05	4.345	0.105	Yes
PG 52-28 W	1.03E-04	41.387	0.008	No

Table 5.23 Analysis of Variance Results of Plastic Shear Strain for 9.5 mm Mixtures Containing 40% RAP vs. Virgin

	Treatment Mean Square	F value	p-value	Means Similar?
PG 64-22 P	6.24E-09	0.002	0.967	Yes
PG 64-22 W	4.08E-09	0.002	0.965	Yes
PG 58-22 P	5.41E-06	1.791	0.273	Yes
PG 58-22 W	2.52E-05	13.996	0.020	No
PG 52-28 P	2.57E-04	38.046	0.004	No
PG 52-28 W	2.64E-04	24.706	0.008	No

Tables 5.24-5.26 compare the plastic shear strain at 5,000 cycles for 19.0 mm mixtures containing 15%, 30% and 40% RAP, respectively, to the virgin mixture containing PG 64-22 binder. The ANOVA shows that at 15% RAP, both the mixtures containing PG 64-22 binder and the mixture containing PG 58-22 binder and Westgate RAP had similar means to the virgin mixture. The ANOVA shows that at 30% RAP, all mixtures except the mixtures containing PG 58-22 and PG 52-28 binder and Pineville RAP had similar means to the virgin mixture. The ANOVA shows that at 40% RAP, all mixtures except the mixture containing PG 52-28 binder and Pineville RAP had similar means to the virgin mixture.

Table 5.24 Analysis of Variance Results of Plastic Shear Strain for 19.0 mm Mixtures Containing 15% RAP vs. Virgin

	Treatment Mean Square	F value	p-value	Means Similar?
PG 64-22 P	8.26E-06	2.345	0.200	Yes
PG 64-22 W	4.65E-07	0.141	0.727	Yes
PG 58-22 P	8.61E-05	23.659	0.008	No
PG 58-22 W	2.43E-05	1.387	0.304	Yes
PG 52-28 P	1.48E-04	45.044	0.003	No
PG 52-28 W	4.97E-05	12.319	0.025	No

Table 5.25 Analysis of Variance Results of Plastic Shear Strain for 19.0 mm Mixtures Containing 30% RAP vs. Virgin

	Treatment Mean Square	F value	p-value	Means Similar?
PG 64-22 P	3.63E-07	0.112	0.755	Yes
PG 64-22 W	1.35E-06	0.295	0.625	Yes
PG 58-22 P	5.90E-05	12.181	0.025	No
PG 58-22 W	1.06E-06	0.232	0.663	Yes
PG 52-28 P	9.16E-05	12.724	0.023	No
PG 52-28 W	3.32E-05	5.106	0.087	Yes

Table 5.26 Analysis of Variance Results of Plastic Shear Strain for 19.0 mm Mixtures Containing 40% RAP vs. Virgin

	Treatment Mean Square	F value	p-value	Means Similar?
PG 64-22 P	5.64E-06	1.412	0.300	Yes
PG 64-22 W	3.31E-06	0.732	0.441	Yes
PG 58-22 P	2.11E-05	3.370	0.208	Yes
PG 58-22 W	3.42E-07	0.054	0.828	Yes
PG 52-28 P	7.67E-05	14.734	0.018	No
PG 52-28 W	2.30E-05	5.015	0.089	Yes

Statistical analysis using one-way ANOVA was used to determine whether there was a difference in means between the two RAP sources. . For this case, the null hypothesis is H_o: $\mu_1=\mu_2$ (the mean value of the Westgate RAP mixture is equal to the mean value of the Pineville RAP mixture) where μ_1= average Westgate RAP mixture value and μ_2=average Pineville RAP mixture value. The alternative hypothesis is H_a: $\mu_1\neq\mu_2$ (the mean value of the Westgate RAP mixture differs from the mean value of the Pineville RAP mixture). Tables 5.27-5.29 compare the plastic shear strain values at 5,000 cycles of the two RAP sources for 9.5 mm mixtures containing 15%, 30% and 40% RAP, respectively. The ANOVA for all mixtures at any RAP percentage and all binder grades (PG 64-22, PG 58-22 and PG 52-28) show no difference in means. This suggests that mixtures containing RAP from either stockpile produce similar results. The variability of RAP stockpiles is often a concern for using higher percentages of RAP since the properties are often unknown. However, these results show that although these two RAP sources that were selected for their differing properties, the differing sources can still produce similar plastic shear strain.

Table 5.27 Analysis of Variance Results of Plastic Shear Strain for 9.5 mm Mixtures Containing 15% RAP (Stockpiles)

	Treatment Mean Square	F value	p-value	Means Similar?
PG 64-22	3.84E-06	2.366	0.199	Yes
PG 58-22	8.28E-06	3.220	0.171	Yes
PG 52-28	9.54E-06	2.651	0.202	Yes

Table 5.28 Analysis of Variance Results of Plastic Shear Strain for 9.5 mm Mixtures Containing 30% RAP (Stockpiles)

	Treatment Mean Square	F value	p-value	Means Similar?
PG 64-22	8.52E-07	0.967	0.429	Yes
PG 58-22	1.51E-06	0.065	0.811	Yes
PG 52-28	8.96E-06	0.490	0.534	Yes

Table 5.29 Analysis of Variance Results of Plastic Shear Strain for 9.5 mm Mixtures Containing 40% RAP (Stockpiles)

	Treatment Mean Square	F value	p-value	Means Similar?
PG 64-22	4.79E-10	0.000	0.988	Yes
PG 58-22	4.69E-06	2.823	0.192	Yes
PG 52-28	4.56E-08	0.003	0.958	Yes

Tables 5.30-5.32 compare the plastic shear strain values at 5,000 cycles of the two RAP sources for 19.0 mm mixtures containing 15%, 30% and 40% RAP, respectively. The ANOVA shows no difference in means for all mixtures at any RAP percentage and all binder grades (PG 64-22, PG 58-22 and PG 52-28) except the mixtures containing PG 64-22 binder and PG 52-28 binder at 15% RAP and the mixture containing PG 58-22 binder and 30% RAP. This suggests that most mixtures containing RAP from either stockpile produce similar results. The variability of RAP stockpiles is often a concern for using higher percentages of RAP since the properties are

often unknown. However, these results show that although these two RAP sources that were selected for their differing properties, the differing sources can still produce similar plastic shear strain.

Table 5.30 Analysis of Variance Results of Plastic Shear Strain for 19.0 mm Mixtures Containing 15% RAP (Stockpiles)

	Treatment Mean Square	F value	p-value	Means Similar?
PG 64-22	4.81E-06	8.353	0.045	No
PG 58-22	1.89E-05	1.267	0.323	Yes
PG 52-28	2.64E-05	24.695	0.008	No

Table 5.31 Analysis of Variance Results of Plastic Shear Strain for 19.0 mm Mixtures Containing 30% RAP (Stockpiles)

	Treatment Mean Square	F value	p-value	Means Similar?
PG 64-22	2.89E-06	5.206	0.107	Yes
PG 58-22	3.41E-05	12.686	0.038	No
PG 52-28	1.45E-05	1.950	0.235	Yes

Table 5.32 Analysis of Variance Results of Plastic Shear Strain for 19.0 mm Mixtures Containing 40% RAP (Stockpiles)

	Treatment Mean Square	F value	p-value	Means Similar?
PG 64-22	3.07E-07	0.136	0.731	Yes
PG 58-22	1.75E-05	2.723	0.241	Yes
PG 52-28	1.57E-05	4.437	0.103	Yes

This chapter had characterized the mixtures developed in Chapter 3 using SST. These characterizations were used for comparisons between the various mixtures. The results from this chapter will be used in the next chapter as part of the performance predictions for mixtures.

Chapter 6
Performance Analysis

This chapter predicts the performance of pavements against fatigue cracking and rutting using the results from the Frequency Sweep Test at Constant Height (FSTCH) and Repeated Simple Shear Test at Constant Height (RSSTCH). The surrogate models from the Strategic Highway Research Program's (SHRP) A-003A as well as distress models developed by the Asphalt Institute (AI) were used to perform fatigue and rutting analysis. The models used for analysis are described below. The results from these analyses will then be used to perform an economic analysis.

6.1 Fatigue Model Analysis

The fatigue cracking model from SHRP A-003A considers horizontal tensile strain at the bottom of the pavement layer during loading, the initial flexural loss stiffness of the mixture (S_o") and the voids filled with asphalt (VFA). The shear stiffness measured during the FSTCH at 10Hz and 20^{o}C was used to determine the initial flexural loss stiffness using the following relationships:

$$S_o = 8.56 * (G_o)^{0.913}$$
$$S_o^{"} = 81.125 * (G_o^{"})^{0.725}$$

where,
S_o = initial flexural stiffness at 50th loading cycle (psi)
G_o = shear stiffness at 10Hz (psi)
S_o'' = initial flexural loss stiffness at 50th loading cycle (psi)
G_o'' = shear loss stiffness at 10Hz (psi)

This model requires the principle tensile strain at the bottom of the asphalt concrete layer. This was estimated using EVERSTRESS pavement analysis and design software. For this software, a pavement section must be assumed. Figure 6.1 below depicts the pavement profile used for the analysis. The strain values were assessed at three locations: directly beneath the tire, at the edge of the tire and at the center of the dual tire configuration in order to consider the full loading configuration. The fatigue life of the pavement was estimated by the SHRP A-003A model as follows:

$$N_{supply} = 2.738 * 10^{5} e^{0.077VFA} \varepsilon_{0}^{-3.624} S_{o}^{"-2.72}$$

where,

N_{supply} = estimated fatigue life of the pavement section in 18 kip axles (ESALs)

VFA = voids filled with asphalt for the mixture

ε_o = critical strain at the bottom of the asphalt layer

Figure 6.1 below depicts the simulated pavement cross-section geometry used for estimating the strains for the pavement performance. It contains a four inch thick asphalt concrete surface layer, eight inch thick asphalt concrete base layer, eight inch think aggregate subbase layer and the semi-infinite subgrade. The moduli values for the asphalt concrete layers are estimated by the complex modulus at 10 Hz from the FSTCH. The Poisson's ratio (μ) for all layers and the elastic modulus (E) for the subbase and subgrade layers were assumed. The assumed values are typical for pavement system analysis. The loading configuration consists or dual tires twelve inches on center with 100 psi tire pressure and single axel 18 kip load configuration.

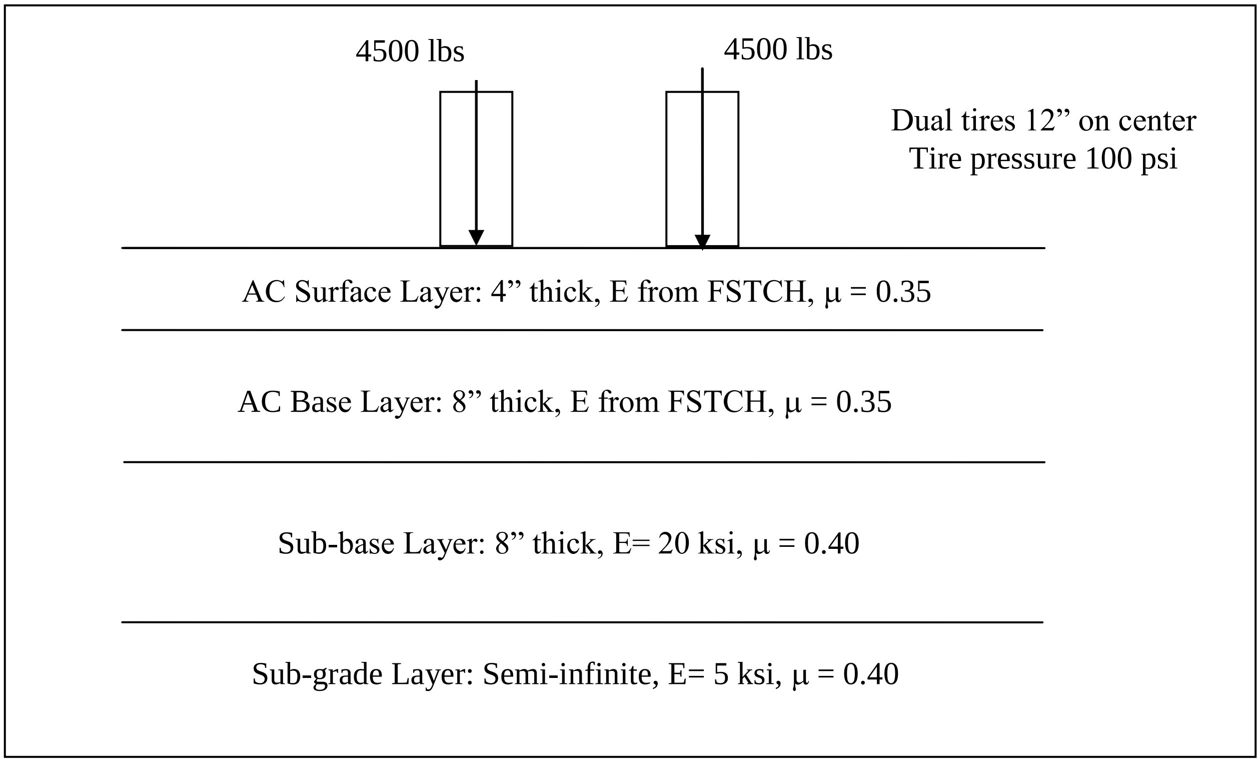


Figure 6.1 Simulated Pavement Cross-Section Geometry

The Asphalt Institute model for determining fatigue life was also considered. Like the surrogate SHRP A-003A fatigue model, the tensile strain at the bottom of the asphalt concrete layer is needed. The AI model for estimating fatigue life follows:

$$N_f = 0.00796 \varepsilon_t^{-3.291} E_1^{-0.854}$$

where,

N_f = number of load applications to fatigue failure (20% cracked area)

ε_t = tensile strain at the bottom of the asphalt layer

E_1 = elastic modulus of asphalt layer (psi)

If the two models give similar fatigue life predictions, the economic analysis will use the average predicted axle loading value. However, if the models differ significantly, the more conservative, or lowest cycles to failure will be used for the economic analysis.

6.1.1 Fatigue Analysis Results From SHRP A-003A

Table 6.1 below contains the initial flexural stiffness (S_o') of the surface and base layer and initial flexural loss stiffness (S_o") of the base layer. The initial flexural stiffness of each layer was used to estimate the elastic modulus of the layer during the simulation of the critical tensile strain at the bottom of the asphalt base layer using EVERSTRESS and the pavement geometry in Figure 6.1. The initial flexural loss stiffness is a variable for the SHRP fatigue model. Each pavement system has two initial flexural loss stiffness values with the surface asphalt layer and the base asphalt layer each having one. However, for the SHRP fatigue model, only one is needed. The base asphalt layer initial flexural loss stiffness was used in the SHRP fatigue model since this value would represent the material where the fatigue crack would initiate and propagate through due to the tensile strain at the bottom of the asphalt layer.

Table 6.1 Flexural Stiffness Properties for Simulated Pavement Systems

	Pavement System	Surface Mixture	Base Mixture	Surface S_o' (psi)	Base S_o' (psi)	Base S_o" (psi)
	1	9.5 B 64 0	19.0 C 64 0	1,009,002	894,102	504,822
Westgate	2	9.5 B 64 15	19.0 C 64 15	889,419	920,847	575,434
	3	9.5 B 64 30	19.0 C 64 30	909,824	1,156,171	595,801
	4	9.5 B 64 40	19.0 C 64 40	1,055,207	1,625,296	732,789
	5	9.5 B 58 15	19.0 C 58 15	630,276	692,410	478,815
	6	9.5 B 58 30	19.0 C 58 30	700,064	755,161	457,421
	7	9.5 B 58 40	19.0 C 58 40	788,289	990,707	514,411
	8	9.5 B 52 15	19.0 C 52 15	558,429	579,416	402,566
	9	9.5 B 52 30	19.0 C 52 30	556,129	627,678	432,256
	10	9.5 B 52 40	19.0 C 52 40	630,276	757,395	437,910
Pineville	11	9.5 B 64 15	19.0 C 64 15	858,555	848,854	453,268
	12	9.5 B 64 30	19.0 C 64 30	880,375	1,088,549	571,161
	13	9.5 B 64 40	19.0 C 64 40	893,818	1,572,658	796,572
	14	9.5 B 58 15	19.0 C 58 15	621,177	665,257	478,815
	15	9.5 B 58 30	19.0 C 58 30	661,379	742,383	457,421
	16	9.5 B 58 40	19.0 C 58 40	710,987	898,214	514,411
	17	9.5 B 52 15	19.0 C 52 15	496,328	576,797	397,249
	18	9.5 B 52 30	19.0 C 52 30	602,288	661,379	400,329
	19	9.5 B 52 40	19.0 C 52 40	650,250	732,146	423,626

Table 6.2 contains the values (Base S_o", VFA, critical strain) needed to determine the resulting fatigue life for each mixture. As expected, the general trend is that as the percentage of RAP increases in the mixtures, the fatigue life increases, all else being constant. This is expected as the increase in RAP increases the stiffness of the pavement, which results in lower critical strain values by better distributing the loads throughout the pavement system. All else being held constant, as the binder grade is reduced from PG 64-22 to PG 52-28, the fatigue life is reduced. This is also expected as the stiffness of the virgin binder reduces with decreasing binder grade and the distribution of loads is less throughout the pavement system resulting in larger critical strains. The results show that maintaining the original binder grade of PG 64-22, the fatigue life increases 12.3% and 23.1% with 30% and 40% RAP, respectively, for mixtures containing Westgate RAP and the fatigue life increases 0.9% and

10.5% with 30% and 40% RAP, respectively, for mixtures containing Pineville RAP. The increase is larger for mixtures containing samples of Westgate RAP since the stiffness of the binder recovered from the Westgate RAP was stiffer than the binder recovered from the Pineville RAP. By reducing the binder grade one grade to PG 58-22, the fatigue life increases 3.0% and 7.9% for mixtures containing 30% and 40% Westgate RAP, respectively. However, the fatigue life decreases 23.5% and 11.4% for mixtures containing 30% and 40% Pineville RAP, respectively. This reduction is due to the combination of the reduced binder grade and the less stiff binder from the Pineville RAP. By reducing the binder grade another grade to PG 52-28, the fatigue life decreases 19.6% and 6.6% for mixtures containing 30% and 40% Westgate RAP, respectively, 22.9% and 5.6% for mixtures containing 30% and 40% Pineville RAP, respectively. This reduction is due to the combination of the reduced binder grade and the less stiff binder from the Pineville RAP.

Table 6.2 Fatigue life of Simulated Pavements by SHRP Model

	Pavement System	Surface Mixture	Base Mixture	Base S_o" (psi)	Base VFA (%)	Critical Stain (10^{-5})	N_{supply} ESALs (10^6)
	1	9.5 B 64 0	19.0 C 64 0	504,822	72.2	4.55	118.8
Westgate	2	9.5 B 64 15	19.0 C 64 15	575,434	76.7	4.55	117.4
	3	9.5 B 64 30	19.0 C 64 30	595,801	73.1	3.97	133.4
	4	9.5 B 64 40	19.0 C 64 40	732,789	70.9	3.16	146.1
	5	9.5 B 58 15	19.0 C 58 15	478,815	75.3	5.63	112.3
	6	9.5 B 58 30	19.0 C 58 30	457,421	74,1	5.29	119.8
	7	9.5 B 58 40	19.0 C 58 40	514,411	74.7	4.44	131.2
	8	9.5 B 52 15	19.0 C 52 15	402,566	75.2	6.33	83.8
	9	9.5 B 52 30	19.0 C 52 30	432,256	76.8	6.06	91.6
	10	9.5 B 52 40	19.0 C 52 40	437,910	74.1	5.36	112.1
Pineville	11	9.5 B 64 15	19.0 C 64 15	453,268	71.1	4.80	120.6
	12	9.5 B 64 30	19.0 C 64 30	571,161	72.4	4.13	122.3
	13	9.5 B 64 40	19.0 C 64 40	796,572	74.4	3.32	128.2
	14	9.5 B 58 15	19.0 C 58 15	478,815	75.1	5.78	88.2
	15	9.5 B 58 30	19.0 C 58 30	457,421	72.3	5.38	95.5
	16	9.5 B 58 40	19.0 C 58 40	514,411	73.1	4.77	110.9
	17	9.5 B 52 15	19.0 C 52 15	397,249	71.0	6.44	58.9
	18	9.5 B 52 30	19.0 C 52 30	400,329	72.1	5.82	90.9
	19	9.5 B 52 40	19.0 C 52 40	423,626	72.8	5.44	105.2

6.1.2 Fatigue Analysis Results from Asphalt Institute Model

Table 6.3 below contains the parameters needed to estimate the fatigue life using the AI model. The base initial flexural stiffness was used to estimate the elastic modulus of the asphalt layer. This value was used since the base layer material will govern the crack initiation and propagation. The critical strain is the same as that calculated and used in the SHRP model above.

Table 6.3 Fatigue life of Simulated Pavements by Asphalt Institute

	Pavement System	Surface Mix	Base Mix	Base E1=So' (psi)	Critical Strain (10^{-5})	N_f ESALs (10^6)
	1	9.5 B 64 0	19.0 C 64 0	894102	4.55E-05	12.8
Westgate	2	9.5 B 64 15	19.0 C 64 15	920847	4.55E-05	12.5
	3	9.5 B 64 30	19.0 C 64 30	1156171	3.97E-05	16.2
	4	9.5 B 64 40	19.0 C 64 40	1625296	3.16E-05	25.5
	5	9.5 B 58 15	19.0 C 58 15	692410	5.63E-05	7.9
	6	9.5 B 58 30	19.0 C 58 30	755161	5.29E-05	9.0
	7	9.5 B 58 40	19.0 C 58 40	990707	4.44E-05	12.7
	8	9.5 B 52 15	19.0 C 52 15	579416	6.33E-05	6.3
	9	9.5 B 52 30	19.0 C 52 30	627678	6.06E-05	6.8
	10	9.5 B 52 40	19.0 C 52 40	757395	5.36E-05	8.6
Pineville	11	9.5 B 64 15	19.0 C 64 15	848854	4.80E-05	11.2
	12	9.5 B 64 30	19.0 C 64 30	1088549	4.13E-05	14.9
	13	9.5 B 64 40	19.0 C 64 40	1572658	3.32E-05	22.4
	14	9.5 B 58 15	19.0 C 58 15	665257	5.78E-05	7.5
	15	9.5 B 58 30	19.0 C 58 30	742383	5.38E-05	8.7
	16	9.5 B 58 40	19.0 C 58 40	898214	4.77E-05	10.9
	17	9.5 B 52 15	19.0 C 52 15	576797	6.44E-05	5.9
	18	9.5 B 52 30	19.0 C 52 30	661379	5.82E-05	7.4
	19	9.5 B 52 40	19.0 C 52 40	732146	5.44E-05	8.5

As is expected, the general trend is that as the percentage RAP increases in the mixtures, the fatigue life increases, all else being constant. This is expected as the increase in RAP increases the stiffness of the pavement, which results in lower critical strain values by better distributing the loads throughout the pavement system. All else being held constant, as the binder grade is reduced from PG 64-22 to PG 52-28, the fatigue life is reduced. This is also expected as the stiffness of the virgin binder reduces with decreasing binder grade and the distribution of loads is less throughout the pavements system creating larger critical strains. The results show that maintaining the original binder grade of PG 64-22, the fatigue life increases 26.2% with 30% RAP and 99.2% with 40% RAP for mixtures containing Westgate RAP and the fatigue life increases 16.2% and 75.1% with 30% and 40% RAP, respectively, for mixtures containing Pineville RAP. Similarly to the SHRP model, the increase is larger for mixtures containing samples of Westgate RAP since the stiffness of the binder recovered from the Westgate RAP was stiffer than the binder recovered from the Pineville RAP. By reducing the binder grade one grade to PG 58-22, the fatigue life reduces 14.9% with 30% RAP and 0.7% with 40% RAP for mixtures containing Westgate RAP and the fatigue life reduces 32.5% and 29.4% with 30% and 40% RAP, respectively, for mixtures containing Pineville RAP. This reduction is due to the reduced stiffness of the reduced binder grade. By reducing the binder grade another grade to PG 52-28, the fatigue life reduces 47.2% with 30% RAP and 32.6% with 40% RAP for mixtures containing Westgate RAP and the fatigue life reduces 42.4% and 33.9% with 30% and 40% RAP, respectively, for mixtures containing Pineville RAP. This reduction is due to the reduced stiffness of the virgin binder grade.

Initially, the vast difference between the estimates for fatigue life between the SHRP model and the AI model may cause suspicion. However, these differences can be attributed to two main reasons. First, the two models define failure differently. The SHRP model defines failure as 50% reduction in flexural stiffness of the pavement while the AI defines failure as cracking cover 20% of the pavement surface area. Secondly, the two models were developed based on different types of testing with the SHRP model using controlled-strain testing and the AI using controlled-stress testing. In order to remain conservative in our estimates of service life and cost savings, the estimates from the AI will be used in further analysis. Therefore, any conclusions could potentially result in more cost savings since this is the most conservative approach.

6.2 Rutting Model Analysis

According to SHRP A-003A, the rut depth is estimated as a function of the maximum permanent shear strain from the RSSTCH test. This relationship is as follows:

*Rut Depth (in) = 11 * Maximum permanent shear strain*

This relationship should hold true for all tire pressures but is expected to decrease with a decrease from the original pavement thickness of 15 inches [7]. The following equation converts the number of RSSTCH test loading cycles to 18-kip equivalent single axle loads (ESALs):

log (cycles) = -4.36 + 1.24 log (ESALs)

where,

cycles = number of cycles obtained from the RSSTCH test,

ESALs = equivalent 18-kip single axle loads

The AI model for rutting was used to estimate the rutting resistance for the pavement systems produced by the various mixtures. However, unlike the SHRP model, the AI model not only considers the mixture properties but also the pavement geometry and pavement system as a whole. The AI model considers the vertical compressive strain at the top of the subgrade layer as part of the model to determine the number of loading repetitions (N_d) required to cause a rut depth of 0.5 inch. The model is as follows:

$$N_d = 1.365 * 10^{-9} \varepsilon_c^{-4.477}$$

where,

ε_c = compression strain at top of the subgrade

Similar to the fatigue cracking analysis, EVERSTRESS pavement analysis software was used to estimate the vertical compressive strain at the top of the subgrade layer using the pavement configuration in Figure 6.1.

6.2.1 Rutting Analysis Results from SHRP A-003A

Table 6.4 below contains the surface mixture strain measured by the RSSTCH which is used in the SHRP model to predict the rut depth. The surface mixture average shear strain for the mixture was used for the prediction as it is assumed that the small rut depths estimated by this model are a result of the surface mixture densification in the wheel paths. As is expected, the general trend is that as the percentage of RAP increases in the mixtures, the rut depth decreases, all else being constant. This is expected as the increase in RAP increases the stiffness of the pavement, which results in lower shear strain. All else being held constant, as the binder grade is reduced from PG 64-22 to PG 52-28, the rut depth increases. This is also expected as the stiffness of the virgin binder reduces with decreasing binder grade and therefore results in larger shear strains. The results show that maintaining the original binder grade of PG 64-22, the rut depth decreases 14.3% and 44.9% with 30% and 40% RAP, respectively, for mixtures containing Westgate RAP and the rut depth decreases 30.18% and 63.40% with 30% and 40% RAP, respectively, for mixtures containing Pineville RAP. By reducing the binder grade one grade to PG 58-22, the rut depth increases 20.0 % and 11.72% with 30% Westgate RAP and Pineville RAP, respectively. The rut depth decreases 6.18% and 24.64% for mixtures containing 40% Westgate RAP and Pineville RAP, respectively. The increase in rut depth for mixtures containing 30% RAP is due to the softer PG 58-22 binder resulting in larger shear strains but this grade shift is overcome when 40% RAP is included in the mixture since the RAP binder is stiffer. By reducing the binder grade another grade to PG 52-28, the rut depth increases 41.9% and 32.2% for mixtures containing 30% and 40% Westgate RAP, respectively, and 55.2% and 45.4% for mixtures containing 30% and 40% Pineville RAP, respectively. This increase in rut depth for mixtures is due to the softer PG 52-28 binder resulting in larger shear strains.

Table 6.4 Rut Depth Estimates of Simulated Pavements by SHRP Model

	Pavement System	Surface Mixture	Base Mixture	Surface Mixture Ave. Shear Strain from RSSTCH	Rut Depth (in)
	1	9.5 B 64 0	19.0 C 64 0	0.01072	0.118
Westgate	2	9.5 B 64 15	19.0 C 64 15	0.00989	0.109
	3	9.5 B 64 30	19.0 C 64 30	0.00918	0.101
	4	9.5 B 64 40	19.0 C 64 40	0.00590	0.065
	5	9.5 B 58 15	19.0 C 58 15	0.01373	0.151
	6	9.5 B 58 30	19.0 C 58 30	0.01286	0.141
	7	9.5 B 58 40	19.0 C 58 40	0.01005	0.111
	8	9.5 B 52 15	19.0 C 52 15	0.02137	0.235
	9	9.5 B 52 30	19.0 C 52 30	0.01520	0.167
	10	9.5 B 52 40	19.0 C 52 40	0.01416	0.156
Pineville	11	9.5 B 64 15	19.0 C 64 15	0.00829	0.091
	12	9.5 B 64 30	19.0 C 64 30	0.00748	0.082
	13	9.5 B 64 40	19.0 C 64 40	0.00392	0.043
	14	9.5 B 58 15	19.0 C 58 15	0.01636	0.180
	15	9.5 B 58 30	19.0 C 58 30	0.01197	0.132
	16	9.5 B 58 40	19.0 C 58 40	0.00808	0.089
	17	9.5 B 52 15	19.0 C 52 15	0.02425	0.267
	18	9.5 B 52 30	19.0 C 52 30	0.01663	0.183
	19	9.5 B 52 40	19.0 C 52 40	0.01558	0.171

6.2.2 Rutting Analysis Results from Asphalt Institute Model

Table 6.5 below contains the compressive strain estimated at the top of the subgrade layer using EVERSTRESS similar to the tensile strain calculated for the fatigue life calculations and the loading cycles to failure which is stated as a rut depth of 0.5 inch. As is expected, the general trend is that as the percentage of RAP increases in the mixtures, the rut life increases, all else being constant. This is expected as the increase in RAP increases the stiffness of the pavement, which results in lower shear strain. All else being held constant, as the binder grade is reduced from PG 64-22 to PG 52-28, the rut life reduces. This is also expected as the stiffness of the virgin binder reduces with decreasing binder grade and therefore results in larger compressive strains in the subgrade. The results show that maintaining the original binder grade of PG 64-22, the rut life increases 41.5% and 210.7% with 30% and 40% RAP, respectively, for mixtures containing Westgate RAP and the rut life increases 22.4% and 141.1% with 30% and 40% RAP, respectively, for mixtures containing Pineville RAP. By reducing the binder grade one grade to PG 58-22, the rut life decreases 50.1 % and 8.6% with 30% and 40% Westgate RAP, respectively, and the rut life decreases 54.6% and 31.4% with 30% and 40% Pineville RAP, respectively. This reduction is rut life is due to the decrease in stiffness of the binder resulting in an increase in compressive strain in the subgrade. By reducing the binder grade another grade to PG 52-28, the rut life decreases 71.6% and 55.3% with 30% and 40% Westgate RAP, respectively, and the rut life decreases 66.2% and 56.3% with 30% and 40% Pineville RAP, respectively. This reduction in rut life is due to the decrease in stiffness of the binder resulting in an increase in compressive strain in the subgrade.

Table 6.5 Loading Cycles to Rutting Failure for Simulated Pavements Using Asphalt Institute Model

	Pavement System	**Surface Mixture**	**Base Mixture**	**ε_c at sub-base layer ($x10^{-5}$)**	**N_f ESALs ($x10^9$)**
	1	9.5 B 64 0	19.0 C 64 0	1.63E-04	0.12
Westgate	2	9.5 B 64 15	19.0 C 64 15	1.66E-04	0.11
	3	9.5 B 64 30	19.0 C 64 30	1.51E-04	0.18
	4	9.5 B 64 40	19.0 C 64 40	1.26E-04	0.39
	5	9.5 B 58 15	19.0 C 58 15	2.02E-04	0.05
	6	9.5 B 58 30	19.0 C 58 30	1.90E-04	0.06
	7	9.5 B 58 40	19.0 C 58 40	1.66E-04	0.11
	8	9.5 B 52 15	19.0 C 52 15	2.22E-04	0.03
	9	9.5 B 52 30	19.0 C 52 30	2.16E-04	0.04
	10	9.5 B 52 40	19.0 C 52 40	1.95E-04	0.06
Pineville	11	9.5 B 64 15	19.0 C 64 15	1.73E-04	0.10
	12	9.5 B 64 30	19.0 C 64 30	1.56E-04	0.15
	13	9.5 B 64 40	19.0 C 64 40	1.34E-04	0.30
	14	9.5 B 58 15	19.0 C 58 15	2.05E-04	0.04
	15	9.5 B 58 30	19.0 C 58 30	1.94E-04	0.06
	16	9.5 B 58 40	19.0 C 58 40	1.77E-04	0.09
	17	9.5 B 52 15	19.0 C 52 15	2.28E-04	0.03
	18	9.5 B 52 30	19.0 C 52 30	2.07E-04	0.04
	19	9.5 B 52 40	19.0 C 52 40	1.96E-04	0.05

6.3 Economic Analysis

An economic analysis for the life cycle cost of the pavements was conducted in order to take into account more than the initial difference in cost between pavements containing RAP material versus pavements containing 100% virgin materials. Although using RAP material for pavement construction will decrease the initial cost of construction, pavements containing RAP may require more maintenance or have a shorter service life than pavements containing 100% virgin materials reducing the initial construction savings or even resulting in more cost than pavements containing 100% virgin materials. For this reason, the life cycle analysis was utilized. It should be noted that this economic analysis is a very conservative estimate of the present cost in order to give a rough estimate of the difference between virgin mixtures and mixtures containing RAP and does not consider the cost savings of using the RAP material which prevents it from being disposed of in landfills.

The binder rheological properties stated in Chapter Four were combined with the pavement performance above. In Chapter Four, Table 4.11 showed that using virgin PG 64-22 binder, the maximum amount of RAP is 24%-27%, using PG 58-22 binder, the maximum amount of RAP is 52-53%, and using PG 52-28 binder, the maximum amount of RAP is 55-57%. Based on these results, the following economic analysis will compare virgin mixtures, PG 64-22 mixtures containing 30% RAP and PG 58-22 mixtures and PG 52-28 mixtures containing 40% RAP. (Note that although the binder analysis states that more than 40% RAP can be used with PG 58-22 and PG 52-28 binder, this data was not available. Also, further performance testing regarding thermal cracking needs to be performed with mixtures containing that amount of RAP before it can be included in the economic analysis.)

6.3.1 Economic Analysis Period

The life cycle cost for the pavement systems will be compared for a 30 year analysis period as per the NCDOT pavement Management Unit. This 30 year analysis period should not be confused with the typical 20 year pavement design life. In order to complete the 30 year analysis period, each pavement system will need to undergo an initial rehabilitation and possibly a second or third rehabilitation.

6.3.2 Estimated Pavement Service Life

The pavement performance analysis above for fatigue life and rutting shows that fatigue cracking is the limiting distress for the pavement service life as the rut life is able to handle many more loading repetitions. Also as stated above, the AI model fatigue life analysis is more conservative and appropriate for this analysis. As a result, the estimated initial service life of the pavement systems are based on the AI model fatigue life calculations. The surface mixture contains a 9.5 B mixture and is designed for 0.3-3 millions ESALs while the base layer contains a 19.0 C mixture and is designed for 3-30 million ESALS. It is assumed that the pavement systems were designed for a rural secondary highway having an annual traffic level of 1,000,000 ESALs. It is also assumed that the growth rate is minimal and, therefore, not considered. Using these assumptions and the predicted number of loadings until fatigue failure based on the AI model, the estimated initial service life was calculated. Table 6.6 below contains the estimated initial service life of the pavement systems. The service life varies from 8.5 to 16.2 years depending on the materials of the mixture.

Table 6.6 Estimated Initial Service Life for Simulated Pavements Systems

Pavement System	Surface Mixture	Base Mixture	Estimated Initial Service Life (years)
1	9.5 B 64 0	19.0 C 64 0	12.8
3	9.5 B 64 30 W	19.0 C 64 30 W	16.2
7	9.5 B 58 40 W	19.0 C 58 40 W	12.7
10	9.5 B 52 40 W	19.0 C 52 40 W	8.6
12	9.5 B 64 30 P	19.0 C 64 30 P	14.9
16	9.5 B 58 40 P	19.0 C 58 40 P	10.9
19	9.5 B 52 40 P	19.0 C 52 40 P	8.5

6.3.3 Material Costs

Table 6.7 below contains the material costs for pavement construction. The costs per ton for the asphalt concrete mixtures were obtained from the NCDOT 2008 bid averages. The RAP screening and processing cost is an average cost from asphalt plants throughout the state.

Table 6.7 Material Costs for Pavement Construction

Material Type and/or Description	Cost (or Savings) Per Ton
Asphalt Concrete Surface Coarse Mixture 9.5 B	41.21
Asphalt Concrete Surface Coarse Mixture 19.0 C	42.51
RAP Screening and/or Processing	12.25

Table 6.8 below contains the estimated cost per ton for each mixture as well as the percentage of RAP by weight of the total mix. The previous percentages used in the mix design (i.e., 15%, 30%, 40%) were the percent of RAP binder in the mix, not the total amount of RAP in the mixture. The percent of RAP of the total mix was calculated using the percent of RAP binder in the mixture, the percent binder from each RAP source and the percent binder for the mixture. Comparing the cost per ton of the mixtures containing RAP to the cost per ton of virgin mixtures, both the surface and base course show roughly a 26-28%% and 35-37% reduction in cost per ton for 30% and 40% RAP, respectively.

Table 6.8 Material Costs for RAP Mixtures

Mixture Designation	%RAP of Total Mix	Cost per Ton
9.5 64 30 W	40	$29.63
9.5 64 30 P	40	$29.63
9.5 58 40 W	53	$25.86
9.5 58 40 P	53	$25.86
9.5 52 40 W	53	$25.86
9.5 52 40 P	53	$25.86
19.0 64 30 W	37	$31.31
19.0 64 30 P	37	$31.31
19.0 58 40 W	50	$27.38
19.0 58 40 P	50	$27.38
19.0 52 40 W	50	$27.38
19.0 52 40 P	50	$27.38

6.3.4 Initial Costs of Pavement Systems

Now that the cost per ton of each mixture has been calculated, these figures need to be translated to pavement systems. For this, several assumptions are applied to all pavement systems. The pavement cross-section contains a two-lane roadway with total width of 28 feet, which consists of two twelve feet travel lanes and two, two feet shoulders. The total volume of material needed was estimated using this road configuration and the pavement's cross section geometry in Figure 6.1. The compacted density for the asphalt pavement was assumed to be 150 lb/ft^3. Since it is desired to determine difference in cost between the different mixtures, the preparation of the subbase and subgrade layers are assumed to be equal for all pavement systems, and therefore, were not included in this analysis. Table 6.9 below contains the estimated material cost per mile for each pavement system. By comparing the material cost per mile of the virgin mixtures to the mixtures containing various percentages of RAP shows that the inclusion of 30% RAP reduces the cost about 27% and the inclusion of 40% RAP reduces the cost about 36%.

Table 6.9 Initial Construction Cost for Pavement Systems

Pavement System	Surface Mixture	Base Mixture	Material Cost per mile
1	9.5 B 64 0	19.0 C 64 0	$466,546
3	9.5 B 64 30 W	19.0 C 64 30 W	$340,956
7	9.5 B 58 40 W	19.0 C 58 40 W	$297,972
10	9.5 B 52 40 W	19.0 C 52 40 W	$297,972
12	9.5 B 64 30 P	19.0 C 64 30 P	$340,956
16	9.5 B 58 40 P	19.0 C 58 40 P	$297,972
19	9.5 B 52 40 P	19.0 C 52 40 P	$297,972

6.3.5 Pavement System Rehabilitation

Once the pavement systems reached the end of their service life, a rehabilitation needed to be performed on the pavement system in order to restore serviceability of the pavement system. For this analysis, the rehabilitation performed on each pavement system was a two inch overlay. It was assumed that the overlay contained the same material as the initial pavement system. In order to determine the service life of the rehabilitated pavement, EVERSTRESS was used to determine the critical strain at the bottom of the asphalt layer in order to determine the new fatigue life of the pavement system. In order to simulate the damage the existing pavements have experienced in the initial service life before the rehabilitation, the moduli for the asphalt surface course and asphalt base course were reduced 50% and 30%, respectively. The Asphalt Institute model was again used to determine the service life of the rehabilitated pavement system.

Table 6.10 below contains the estimated service life for pavement systems after rehabilitation and the cost of the material for the rehabilitation. Pavement systems 1, 7, 10, 16 and 19 still do not meet the total service life of 30 years needed for the analysis after the initial rehabilitation, so a second rehabilitation will be performed on those pavement systems. Pavement Systems 7 and 19 need a third rehabilitation. It is assumed that the first overlay rehabilitation will be milled up and the second rehabilitation will have the same service life as the initial rehabilitation. The cost for the milling was not considered as these costs were assumed to be minimal compared to the cost of the rehabilitation.

Table 6.10 Estimated Service Life for Pavement Systems After Rehabilitation

Pavement System	Surface Mixture	Base Mixture	Initial Service Life (years)	Rehab. Service Life (years)	Total Service life (years)	Rehab. Material Cost (per mile)
1	9.5 B 64 0	19.0 C 64 0	12.8	14.7	27.5	$76,156
3	9.5 B 64 30 W	19.0 C 64 30 W	16.2	17.9	34.1	$54,756
7	9.5 B 58 40 W	19.0 C 58 40 W	10.9	12.1	23.0	$47,789
10	9.5 B 52 40 W	19.0 C 52 40 W	8.6	9.5	18.1	$47,789
12	9.5 B 64 30 P	19.0 C 64 30 P	14.9	16.5	31.4	$54,756
16	9.5 B 58 40 P	19.0 C 58 40 P	12.7	14.1	26.8	$47,789
19	9.5 B 52 40 P	19.0 C 52 40 P	8.5	10.2	18.7	$47,789

Figure 6.2 below contains the pavement system service life and rehabilitation activity. As stated above, it shows that pavement systems 1, 7 and 16 require a second rehabilitation and pavement systems 7 and 19 required a third rehabilitation in order to meet the analysis period of 30 years.

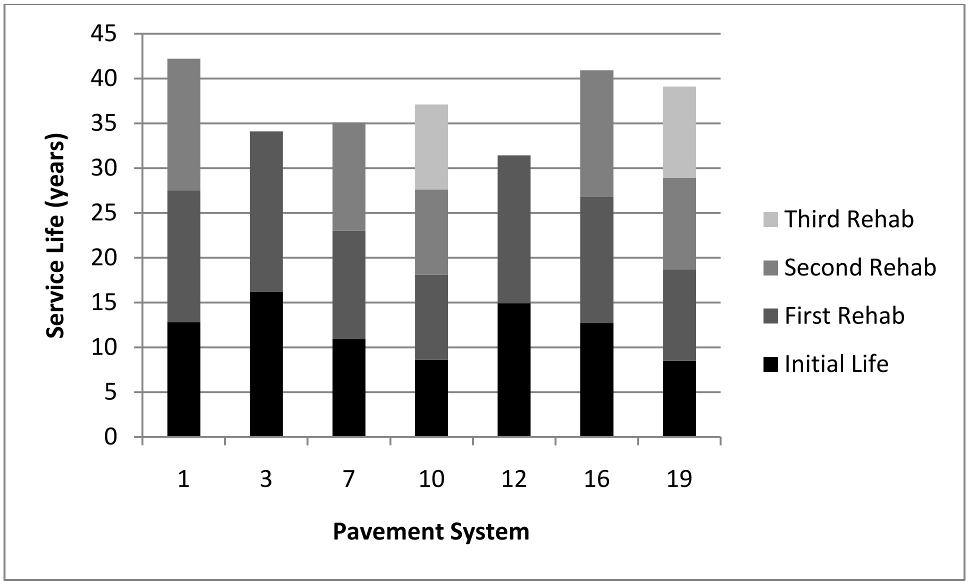


Figure 6.2 Pavement System Service Life and Rehabilitation Activity

6.3.6 Salvage Value of Pavement Systems

Each of the pavement systems had a remaining service life after the initial, second or third rehabilitation beyond the analysis period of 30 years. The remaining service life of the pavement systems after the rehabilitation was converted to a salvage value using the equation [2]:

$$SV = \left(1 - \frac{Y}{Y_e}\right) C$$

Where,

SV = salvage value

Y = the difference of the analysis period and the number of years left before next rehabilitation

Y_e = the service life of the rehabilitated system, and

C = the rehabilitation or initial construction cost of the system.

Table 6.11 below contains the rehabilitation service life, the service life of the rehabilitation used and the calculated salvage value per mile for the pavement systems.

Table 6.11 Salvage Value of Rehabilitated Pavement Systems

Pavement System	Surface Mixture	Base Mixture	Rehab. Service Life (years)	Service Life Used (years)	Salvage Value Per Mile
1	9.5 B 64 0	19.0 C 64 0	14.7	2.5	$63,204
3	9.5 B 64 30 W	19.0 C 64 30 W	17.9	13.8	$12,542
7	9.5 B 58 40 W	19.0 C 58 40 W	12.1	7.0	$20,142
10	9.5 B 52 40 W	19.0 C 52 40 W	9.5	2.4	$35,716
12	9.5 B 64 30 P	19.0 C 64 30 P	16.5	15.1	$4,646
16	9.5 B 58 40 P	19.0 C 58 40 P	14.1	3.2	$36,943
19	9.5 B 52 40 P	19.0 C 52 40 P	10.2	1.1	$42,635

6.3.7 Present Value (Costs) of Pavement Systems

In order to conduct a life cycle cost analysis, it was recommended that either the present worth method or annual cost method be implemented. Both of these methods took into account initial costs of the pavement construction and all future year costs as well as salvage values. The present worth method converts all costs or returns to the present value for analysis. The annual cost method converts all costs and returns to a uniform annual cost for analysis. Both of these methods should result in similar conclusions and the pavement with the lowest life cycle cost should be selected. The following relationship is used for the present worth method.

The present worth of a future sum can be found by:

$$PW = \frac{F}{(1+i)^n}$$

where,

PW = present worth of a sum of money that takes place N years from the base year.

F = future sum of an improvement at the end of year N, and

i = discount rate.

According to the NCDOT Pavement Management life cycle strategies, a discount rate of 4% is used [13]. Table 6.12 below contains the total present cost of the pavement systems and the percent difference from the virgin mixture. Mixtures containing PG 64-22 binder and 30% RAP have a present worth 18.2-18.9% less than the virgin mixture. Mixtures containing PG 58-22 binder and 40% RAP have a present worth 34.1-36.0% less than the virgin mixture. Mixtures containing PG 52-28 binder and 40% RAP have a present worth 30.5-31.1% less than the virgin mixture.

Table 6.12 Total Present Cost of Pavement Systems

Pavement System	Surface Mixture	Base Mixture	Total Present Cost Per Mile	% Difference from Virgin Mixture
1	9.5 B 64 0	19.0 C 64 0	$519,056	--
3	9.5 B 64 30 W	19.0 C 64 30 W	$420,851	18.9
7	9.5 B 58 40 W	19.0 C 58 40 W	$342,316	34.1
10	9.5 B 52 40 W	19.0 C 52 40 W	$360,753	30.5
12	9.5 B 64 30 P	19.0 C 64 30 P	$424,803	18.2
16	9.5 B 58 40 P	19.0 C 58 40 P	$332,327	36.0
19	9.5 B 52 40 P	19.0 C 52 40 P	$357,403	31.1

6.3.8 Annual Value (Costs) of Pavement Systems

The annual cost of a present worth can be calculated by:

$$A = PW * \left[\frac{i(1+i)}{(1+i)^N - 1} \right]$$

where,

A = annual uniform cost,

PW = present worth of a capital investment,

N = number of years in the analysis period, and,

i = discount rate.

Again, the discount rate of 4% was applied to calculate the annual cost of the pavement systems. Table 6.13 below contains the Annual cost of the pavement systems. The annual cost per year for the duration of the 30 year analysis period ranges from $6,162 for the mixture containing PG 58-22 binder and 40% RAP to $9,625 for the virgin mixture.

Table 6.13 Annual Cost of Pavement Systems

Pavement System	Surface Mixture	Base Mixture	Total Present Cost Per Mile
1	9.5 B 64 0	19.0 C 64 0	$9,625
3	9.5 B 64 30 W	19.0 C 64 30 W	$7,804
7	9.5 B 58 40 W	19.0 C 58 40 W	$6,348
10	9.5 B 52 40 W	19.0 C 52 40 W	$6,690
12	9.5 B 64 30 P	19.0 C 64 30 P	$7,877
16	9.5 B 58 40 P	19.0 C 58 40 P	$6,162
19	9.5 B 52 40 P	19.0 C 52 40 P	$6,627

6.4 Modeling and Economic Analysis Summary and Conclusions

This chapter predicted the performance of pavements against fatigue cracking and rutting using the results from the FSTCH and RSSTCH. The surrogate models from the SHRP A-003A as well as distress models developed by the AI were used to perform fatigue and rutting analysis. The results from this analysis were then used to perform an economic analysis.

An economic analysis for the life cycle cost of the pavements was conducted in order to take into account more than the initial difference in cost between pavements containing RAP material versus pavements containing 100% virgin materials. Based on the binder rheological properties stated in Chapter Four and the pavement performance of this chapter, the economic analysis compared virgin mixtures, PG 64-22 mixtures containing 30% RAP and PG 58-22 and PG 52-28 mixtures containing 40% RAP.

The pavement performance analysis for fatigue life and rutting shows that fatigue cracking is the limiting distress for the pavement service life as the rut life is able to handle many more loading repetitions. Also as stated previously, the AI model fatigue life analysis was more conservative and appropriate for this analysis. As a result, the estimated initial service life of the pavement systems were based on the AI model fatigue life calculations. The service life varies from 8.5 years to 16.2 years depending on the materials of the mixture.

In order to determine the initial construction cost and rehabilitation costs, the costs per ton for the asphalt concrete mixtures were obtained from the NCDOT 2008 bid averages. The RAP screening and processing cost is an average cost from asphalt plants throughout the state. These values were used in a present cost comparison and annual cost comparison of the pavement systems. Based on these analyses, the following results have been concluded:

6.4.1Fatigue Life Conclusions

- The general trend is that as the percentage RAP increases in the mixtures, the fatigue life increases, all else being constant.
- All else being held constant, as the binder grade is reduced from PG 64-22 to PG 52-28, the fatigue life is reduced.
- Maintaining the original binder grade of PG 64-22, the fatigue life increases 26.2% with 30% Westgate RAP and 99.2% with 40% Westgate RAP and the fatigue life increases 16.2% and 75.1% with 30% and 40% Pineville RAP, respectively.
- By reducing the binder grade one grade to PG 58-22, the fatigue life reduces 14.9% with 30% Westgate RAP and 0.7% with 40% Westgate RAP and the fatigue life reduces 32.5% and 29.4% with 30% and 40% Pineville RAP, respectively. This reduction is due to the reduced stiffness of the reduced binder grade.
- By reducing the binder grade one grade to PG 52-28, the fatigue life reduces 47.2% with 30% Westgate RAP and 32.6% with 40% Westgate RAP and the fatigue life reduces 42.4% and 33.9% with 30% and 40% Pineville RAP, respectively.

6.4.2 Rut Life Conclusions

- According to the SHRP model, maintaining the original binder grade of PG 64-22, the rut depth decreases 14.3% and 44.9% with 30% and 40% RAP, respectively, for mixtures containing Westgate RAP and the rut depth decreases 30.18% and 63.40% with 30% and 40% RAP, respectively, for mixtures containing Pineville RAP.
- According to the SHRP model, by reducing the binder grade one grade to PG 58-22, the rut depth increases 20.0 % and 11.72% with 30% Westgate RAP and Pineville

RAP, respectively. The rut depth decreases 6.18% and 24.64% for mixtures containing 40% Westgate RAP and Pineville RAP, respectively.

- According to the SHRP model, by reducing the binder grade two grades to PG 52-28, the rut depth increases for mixtures containing Westgate RAP 41.9% and 32.2% for mixtures containing 30% and 40% Rap, respectively, and mixtures containing Pineville RAP 55.2% and 45.4% for mixtures containing 30% and 40% Rap, respectively.
- According to the AI model, the results show that maintaining the original binder grade of PG 64-22, the rut life increases 41.5% and 210.7% with 30% and 40% RAP, respectively, for mixtures containing Westgate RAP and the rut life increases 22.4% and 141.1% with 30% and 40% RAP, respectively, for mixtures containing Pineville RAP.
- According to the AI model, by reducing the binder grade one grade to PG 58-22, the rut life decreases 50.1 % and 8.6% with 30% and 40% RAP, respectively, for mixtures containing Westgate RAP and the rut life decreases 54.6% and 31.4% with 30% and 40% RAP, respectively, for mixtures containing Pineville RAP.
- According to the AI model, by reducing the binder grade two grades to PG 52-28, the rut life decreases 71.6% and 55.3% with 30% and 40% RAP, respectively, for mixtures containing Westgate RAP and the rut life decreases 66.2% and 56.3% with 30% and 40% RAP, respectively, for mixtures containing Pineville RAP.

6.4.3 Economic Analysis Conclusions

- Mixtures containing PG 64-22 binder and 30% RAP have a present worth 18.2-18.9% less than the virgin mixture. Mixtures containing PG 58-22 binder and 40% RAP have a present worth 34.1-36.0% less than the virgin mixture. Mixtures containing PG 52-28 binder and 40% RAP have a present worth 30.5-31.1% less than the virgin mixture.
- The use of mixtures containing one binder grade lower (PG 58-22) than the original virgin binder grade (PG 64-22) and 40% RAP provides the most economical pavement.

Chapter 7
Effect of Warm Mix Asphalt Additive on Binder Rheology

As discussed earlier, the development of warm mix asphalt (WMA) technology over the recent past has sparked interest in many researchers, engineers and government officials. The use of WMA has incentives including fuel savings, lower emissions, longer hauling distances and longer construction seasons since the use of WMA allows for lower production temperatures. Also, another key benefit to lower production temperatures is lowering the oxidative hardening of the asphalt binder that may occur at the higher production temperatures which may reduce thermal cracking, block cracking, and preventing the mix to be tender when placed [10].

Due to this benefit, along with the anticipated benefit of better compactability using WMA, it is thought that WMA can be used in mixes containing higher percentages of RAP since less oxidative hardening of the asphalt binder may occur for the already more stiff RAP binder. Mixtures with higher percentages of RAP often have issues with thermal cracking and block cracking due to the stiff binder from the RAP blending with the virgin binder. Because of this, the percentage of RAP is often limited or requires a grade shift of virgin binder to account for the stiff binder contributed by the RAP.

In this chapter, Dynamic Shear Rheometer (DSR) and Bending Beam Rheometer (BBR) testing were performed on virgin, blended and RAP binders containing Sasobit® in order to determine how the use of WMA additives effect the binder rheology. Sasobit® is a product of Sasol Wax and "is a fine crystalline, long-chain aliphatic polymethylene hydrocarbon produced from coal gasification using the Fischer-Tropsch (FT) process" [10].

7.1 Dynamic Shear Rheometer Testing

DSR testing was completed on the virgin binders, blended binders, and the binder extracted from the RAP, all containing Sasobit® at an amount of 1.5% by weight of the binder. The DSR testing produced rheological properties for the binders including complex modulus (G*) and the phase angle (delta, δ). Each binder was tested at several temperatures in order to form various temperature gradients for the blending charts. The blended binders consisted of a mix of 70% virgin binder and 30% binder extracted from the RAP sources.

Table 7.1 below contain the average G*/sinδ values for the original virgin binders, blended binders, and extracted RAP binder containing Sasobit®. The standard deviation is denoted in the parenthesis.

Table 7.1. G*/sinδ Values for Original Binders Containing Sasobit®

Virgin Binder Grade	RAP Source	Average G*/sinδ kPa (Standard Deviation) At Test Temperature		
		52°C	58 °C	64 °C
PG 52-28	-	2.2 (0.1)	1.0 (0.1)	0.4 (0.03)
PG 58-22	-		2.1 (0.2)	1.0 (0.1)
PG 64-22	-			2.3 (0.2)
PG 52-28	Westgate	5.8 (0.2)	2.5 (0.1)	1.1 (0.1)
PG 58-22	Westgate		6.2 (0.7)	3.1 (0.6)
PG 64-22	Westgate			6.2 (2.5)
-	Westgate	99.7 (4.0)	46.1 (1.2)	20.6 (0.5)

Table 7.2 below contain the average G*/sinδ values for the RTFO aged virgin binders, blended binders and extracted RAP binder containing Sasobit®. The standard deviation is denoted in the parenthesis.

Table 7.2 G*/sinδ Values for RTFO Aged Binders Containing Sasobit®

Virgin Binder Grade	RAP Source	Average G*/sinδ kPa (Standard Deviation) At Test Temperature		
		52°C	58°C	64°C
PG 52-28	**-**	4.3 (0.07)	1.9 (0.03)	0.8 (0.01)
PG 58-22	**-**		6.2 (0.26)	2.9 (0.09)
PG 64-22	**-**			7.0 (0.10)
PG 52-28	**Westgate**	19.4 (0.28)	8.2 (0.30)	3.4 (0.16)
PG 58-22	**Westgate**		17.5 (0.55)	7.9 (0.25)
PG 64-22	**Westgate**			19.0 (0.20)
-	**Westgate**	817.9 (33.61)	379.1 (16.86)	172.5 (8.20)

For both the original and RTFO aged binders, as the temperature increases the value of G*/sinδ decrease while holding the binder constant. Similarly, the value of G*/sinδ increases as the virgin binder grade increases from PG 52-28 to PG64-22 while holding the temperature constant. This is expected because the PG 52-28 is a softer binder than both PG 58-22 and PG 64-22.

Table 7.3 below contains the average G*(sinδ) values for the PAV aged virgin binders, blended binders and extracted RAP binders containing Sasobit®. The standard deviation is denoted in the parenthesis. The table shows that as the temperature increases, the G*(sinδ) decreases. This is expected since at higher temperatures, the G* will decrease since the asphalt binder becomes less stiff and the phase angle increases slightly, which is expected because it acts more viscous. Holding the temperature constant, the G*(sinδ) increases with increasing binder grade and also with the inclusion of RAP. Again, this is expected since lower grade virgin binders are less stiff and have a lower complex modulus. Also, the binder from the RAP as previously explained is much stiffer than the virgin binder, resulting in a higher complex modulus.

Table 7.3 Average G*(sinδ) for PAV Aged Binders Containing Sasobit®

Virgin Binder Grade	RAP Source	Average G*(sinδ) kPa (Standard Deviation) At Test Temperature		
		19°C	22°C	25°C
PG 52-28		2750 (171)	1728 (116)	1051 (77)
PG 58-22		4211 (290)	2881 (166)	1881 (117)
PG 64-22	**-**	8779 (1181)	6266 (956)	4305 (699)
PG 52-28	**Westgate**	4733 (457)	3203 (311)	2069 (213)
PG 58-22	**Westgate**	5535 (902)	3935 (601)	2620 (430)
PG 64-22	**Westgate**	9939 (1236)	7777 (298)	5571 (134)
-	**Westgate**	25095 (2001)	20812 (1597)	16694 (1368)

The above data were compiled together to form blending charts. Once the data was plotted, exponential trendlines were added for each temperature combination. The exponential equations were used to determine the amount of RAP that can be used at certain temperatures and meet the specifications for the given test. Figures 7.1-7.9 below contain the blending charts for each combination of virgin binder. The figures can be used to determine the percentage of RAP necessary to meet the requirement of $G^*/\sin\delta \geq 1.0$ kPa for original binders, $G^*/\sin\delta \geq 2.2$ kPa for RTFO aged binders and $G^*\sin\delta \leq 5000$ kPa for PAV aged binders.

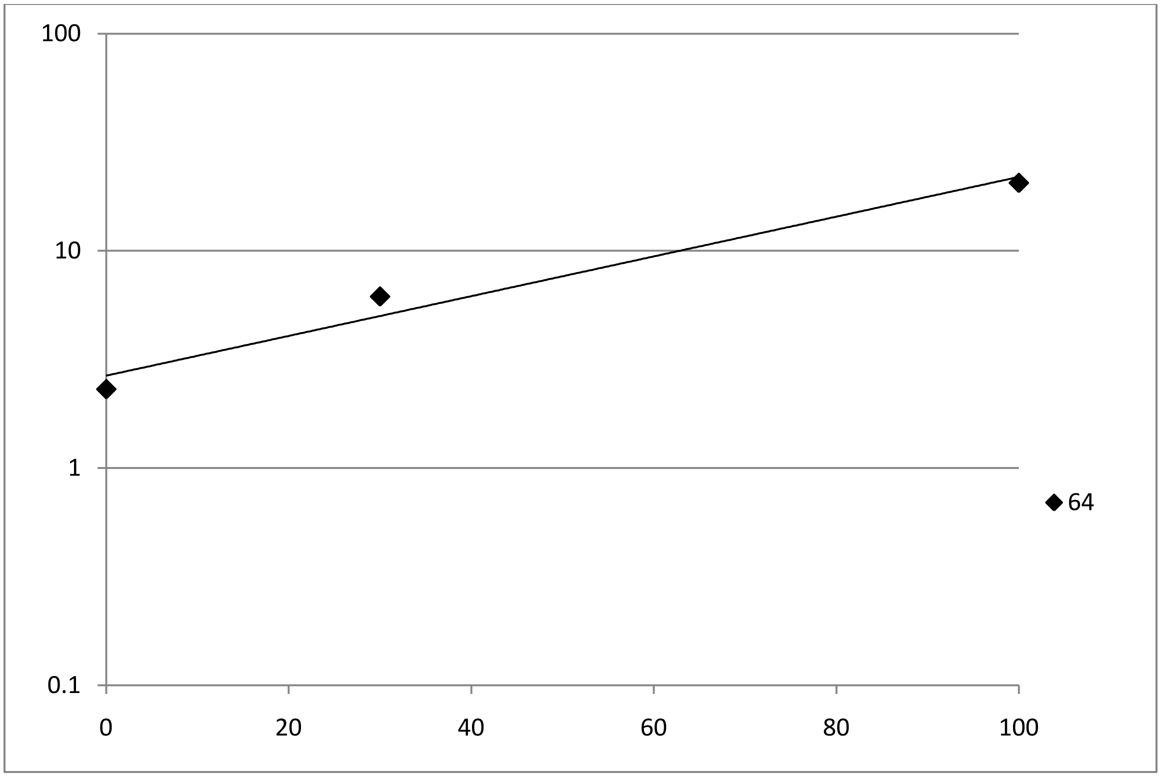


Figure 7.1 DSR Original PG 64-22 Sasobit® Blending Chart

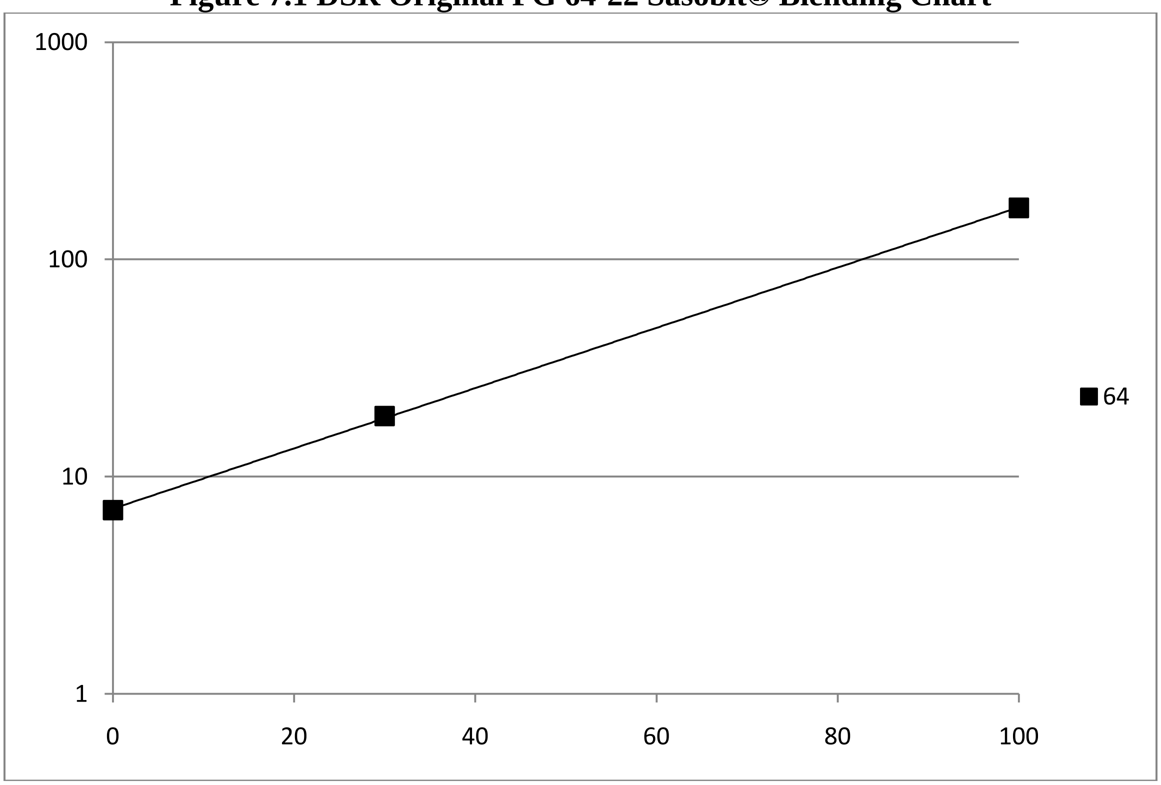


Figure 7.2 DSR RTFO PG 64-22 Sasobit® Blending Chart

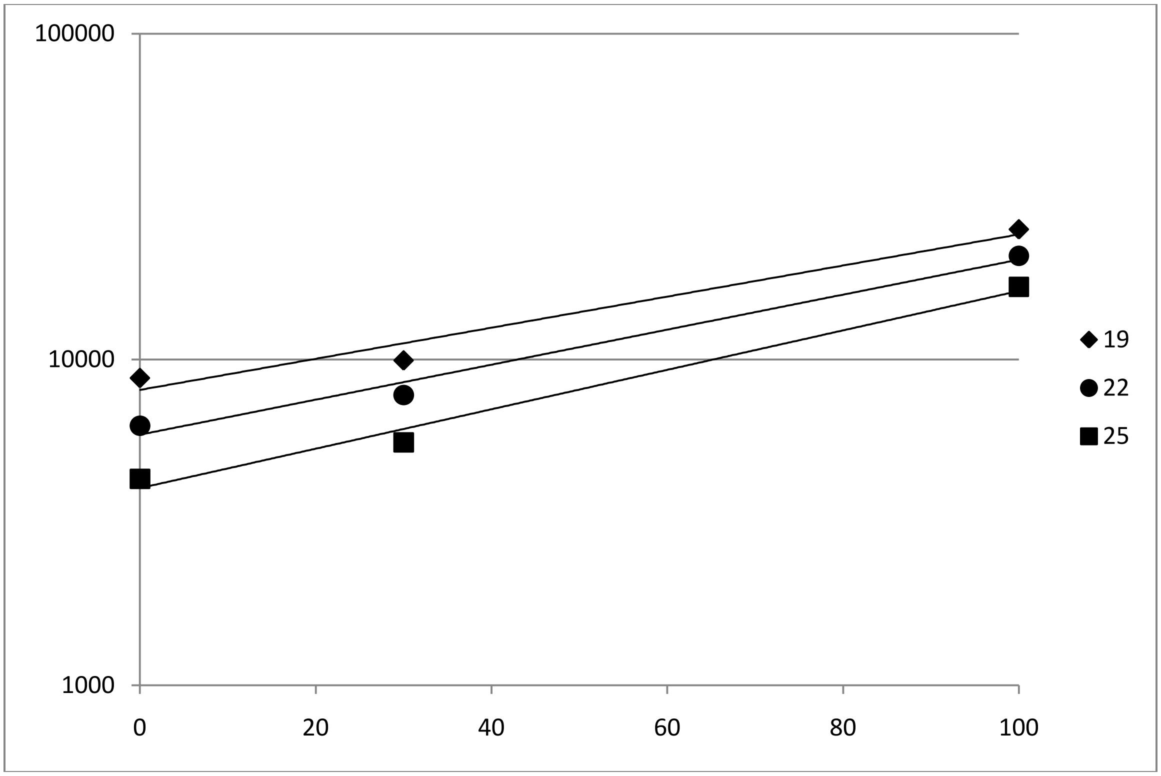


Figure 7.3 DSR PAV PG 64-22 Sasobit® Blending Chart

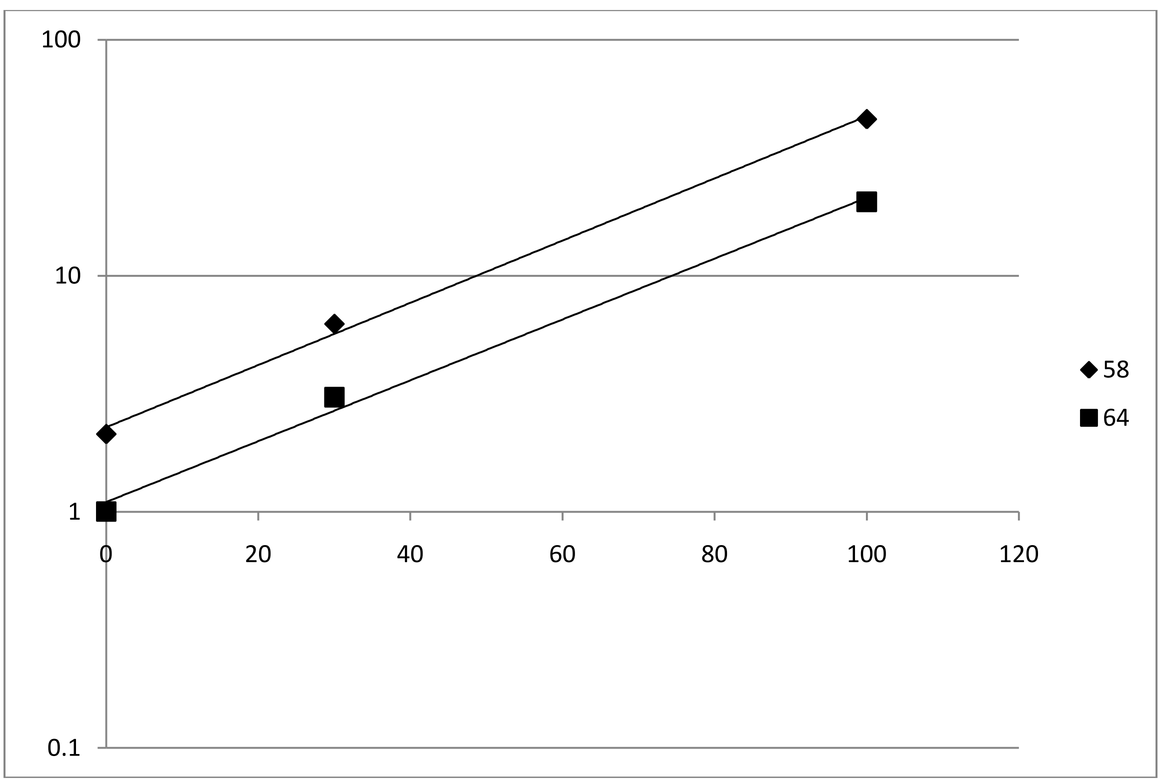


Figure 7.4 DSR Original PG 58-22 Sasobit® Blending Chart

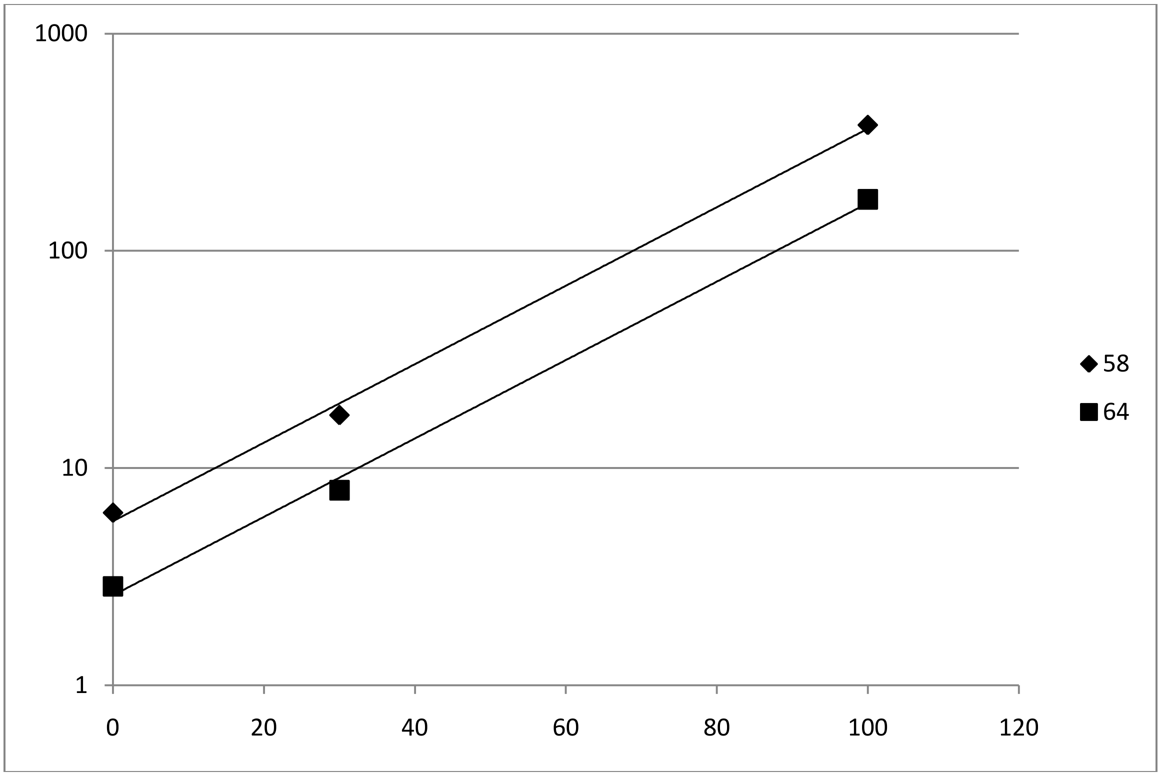


Figure 7.5 DSR RTFO PG 58-22 Sasobit® Blending Chart

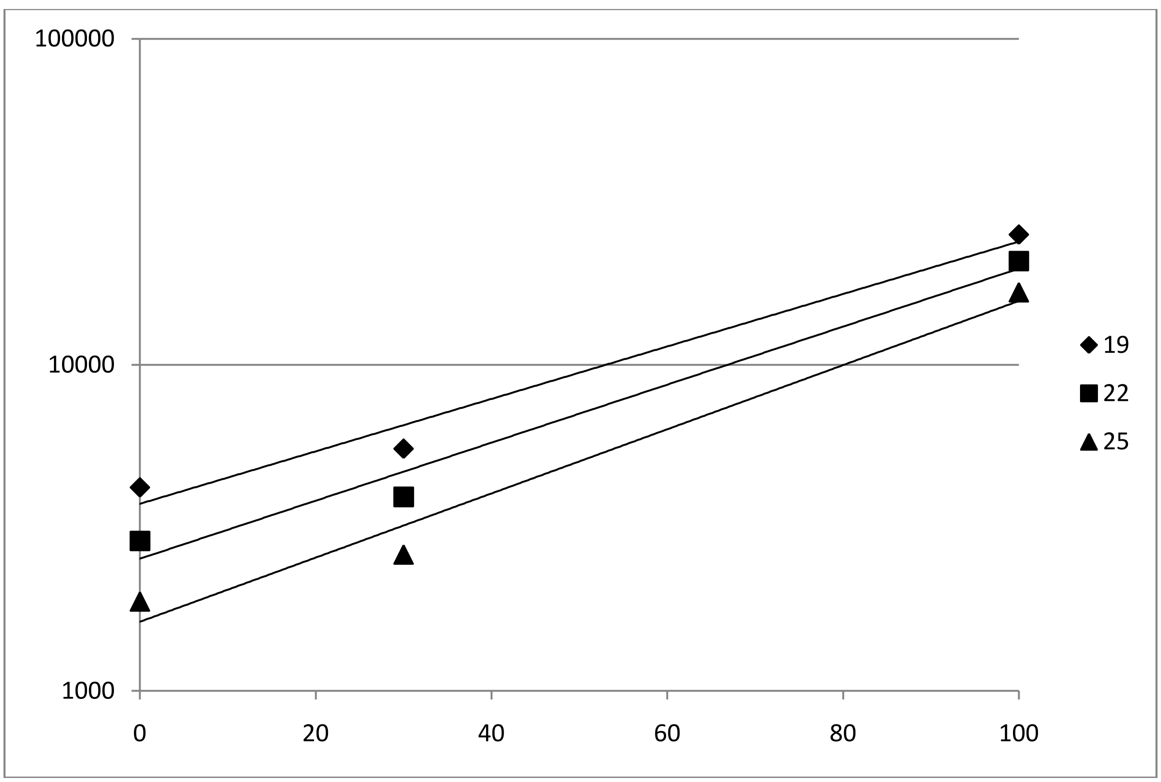


Figure 7.6 DSR PAV PG 58-22 Sasobit® Blending Chart

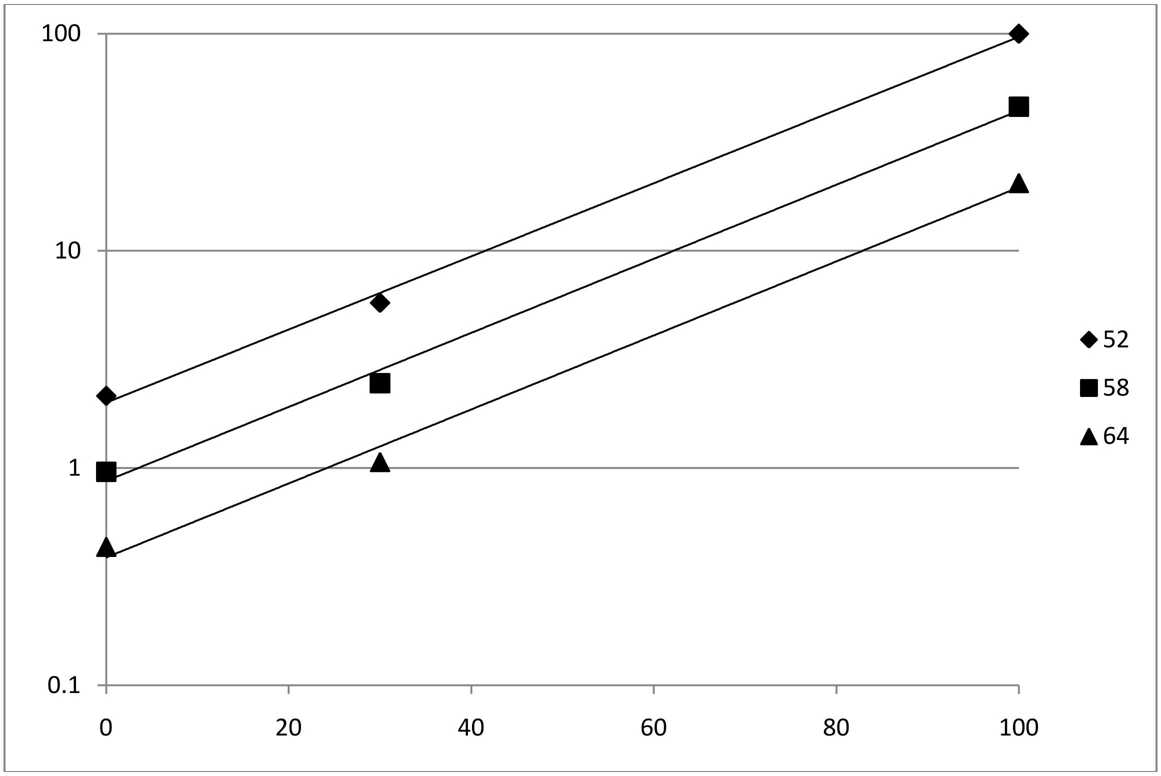


Figure 7.7 DSR Original PG 52-28 Sasobit® Blending Chart

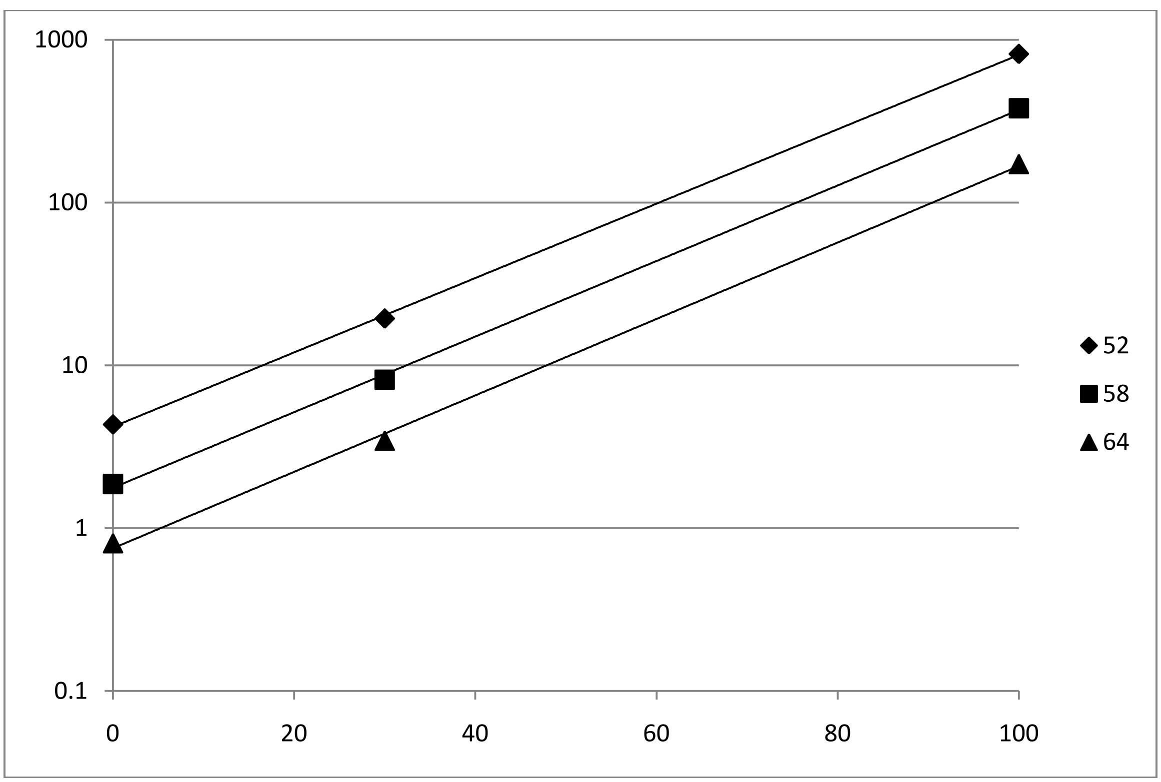


Figure 7.8 DSR RTFO PG 52-28 Sasobit® Blending Chart

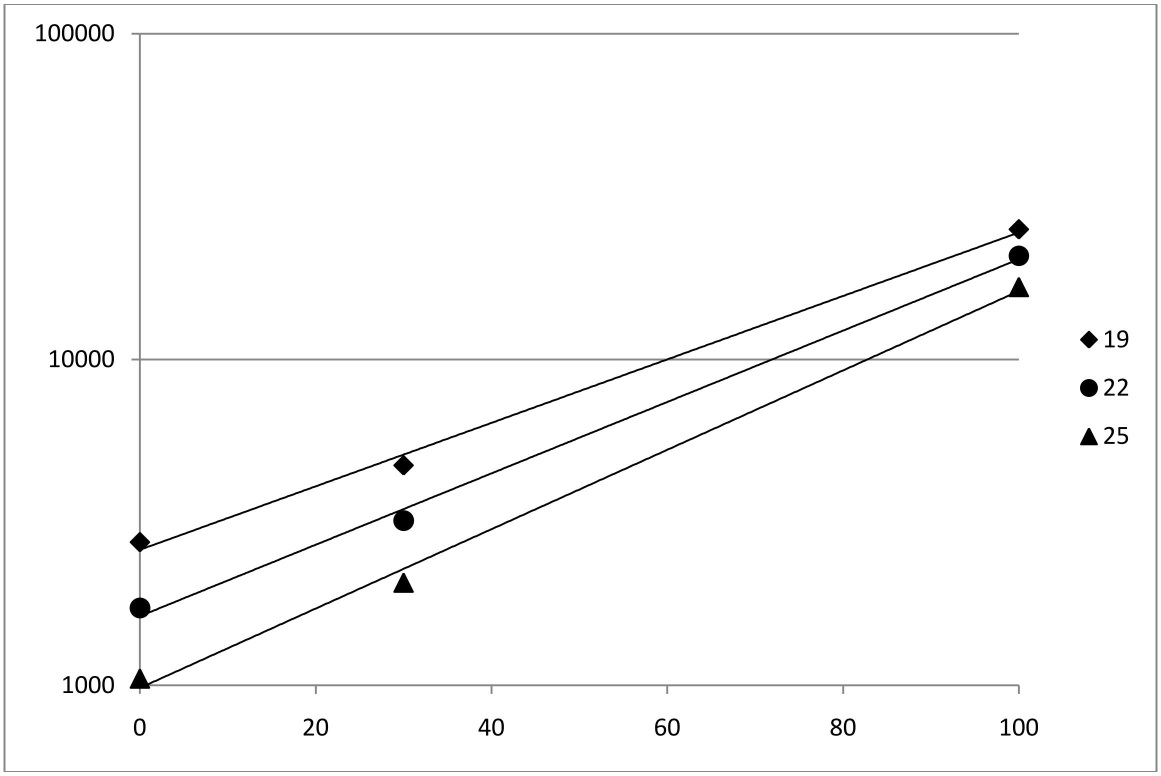


Figure 7.9 DSR PAV PG 52-28 Sasobit® Blending Chart

Table 7.4 and Table 7.5 below contain the minimum percentage of RAP needed to meet the specification of G*/sinδ= 1.0 and G*/sinδ= 2.2 for original and RTFO binders, respectively, based on the exponential equations from the blending charts at the different temperatures. Due to the increased stiffness caused by the RAP binder and the use of Sasobit®, there is only a minimum percentage of RAP when using a virgin binder grade of PG 52-28 in order to meet the specifications for the high temperature grades of 58^{o} and 64^{o}. For example, if a mixture using PG 52-28 virgin binder, blended with Westgate RAP, in order to meet the specification for the high temperature grade of PG 64 and unaged binder, there needs to be a minimum of 24.2 % RAP in the blend to meet the specification of G*/sinδ= 1.0. Similarly, in order to meet the specification of G*/sinδ= 2.2 for RTFO aged binder, there needs to be a minimum of 19.9% RAP for a high temperature grade of PG 64. Therefore, the minimum for the high temperature grade for this blend would be 19.9% RAP.

Table 7.4 Minimum Percentage of RAP Binder to Satisfy G*/sinδ= 1.0 for Unaged Binder

Virgin Binder Grade	Temperature ^oC	$G^*/\sin\delta = Ae^{B(\%RAP)}$		Minimum % RAP
		A	B	
PG 52-28	52	2.0002	0.0388	-
	58	0.8723	0.0392	3.5
	64	0.3879	0.0392	24.2
PG 58-22	58	2.2833	0.0303	-
	64	1.1009	0.0297	-
PG 64-22	64	2.6642	0.0211	-

Table 7.5 Minimum Percentage of RAP Binder to Satisfy G*/sinδ= 2.2 for RTFO Binder

Virgin Binder Grade	Temperature ^oC	$G^*/\sin\delta = Ae^{B(\%RAP)}$		Minimum % RAP
		A	B	
PG 52-28	52	4.1943	0.0526	-
	58	1.7721	0.0534	4.0
	64	0.7528	0.054	19.9
PG 58-22	58	5.6993	0.0416	-
	64	2.5982	0.0416	-
PG 64-22	64	7.1266	0.0319	-

Table 7.6 below contains the maximum percentage of RAP allowed in order to meet the specification G*sinδ= 5000 kPa, based on the exponential equations from the blending charts. For example, if a mixture using PG 52-28 virgin binder is blended with Westgate RAP, in order to meet the specification for the low temperature grade of PG 64-22 binder, there can be a maximum 58.1% RAP to meet the specification of G*sinδ= 5000 kPa. For PG 64 binders, the temperature of 25^{o}C corresponds to a low grade of -22.

Table 7.6 Maximum Percentage of RAP Binder to Satisfy G*sinδ= 5000 kPa for PAV Binder

Virgin Binder Grade	Temperature ^{o}C	$G^*/\sin\delta = Ae^{B(\%RAP)}$		Maximum % RAP
		A	B	
PG 52-28	19	2607.1	0.0224	29.1
	22	1631.5	0.0252	44.4
	25	982.38	0.028	58.1
PG 58-22	19	3749	0.0185	15.6
	22	2543.6	0.0205	33.0
	25	1629.8	0.0227	49.4
PG 64-22	19	8067	0.011	-
	22	5878.3	0.0124	-
	25	4029.9	0.0139	15.5

7.2 Bending Beam Rheometer Testing

Bending Beam Rheometer (BBR) testing was completed on the blended binders containing Sasobit®. The BBR testing produced rheological properties for the binders including creep stiffness (s) and the m-value (slope). Each binder was tested at -12^{o}C. The blended binders consisted of a mix of 70% virgin binder and 30% binder extracted from the RAP sources.

Table 7.7 below contains the average creep stiffness and m-values for the virgin binders and binders recovered from the Westgate RAP including Sasobit®. Table 7.8 below contains the average creep stiffness and m-values for the blended binders including Sasobit®. The addition of 30% RAP to the PG 52-28 virgin binder resulted in an increase in creep stiffness of 66.7%. The addition of 30% RAP to the PG 58-22 virgin binder resulted in an increase in creep stiffness of 41.2%. The addition of 30% RAP to the PG 64-22 virgin binder resulted in an increase in creep stiffness of 18.1%. As the virgin binder grade in the blend increases from PG 52-28 to PG 64-22, the increase in creep stiffness becomes less. This is expected since as the virgin binder creep stiffness increases with increasing binder grade, the higher creep stiffness from the reclaimed RAP binder has less of an effect on the binder blend.

The addition of 30% RAP to the PG 52-28 virgin binder resulted in a decrease in m-value of 16.6%. The addition of 30% RAP to the PG 58-22 virgin binder resulted in a decrease in m-value of 8.1%. The addition of 30% RAP to the PG 64-22 virgin binder resulted in a decrease in m-value of 7.6%. This reduction in m-value is expected since the binder reclaimed from the RAP is stiffer thus likely to need more time to recover, which is what the m-value signifies.

Table 7.7 Creep Stiffness and m-values of Virgin and RAP Binders

Binder	Creep Stiffness (Mpa)	m-value
PG 52-28 Virgin	78	0.428
PG 58-22 Virgin	102	0.357
PG 64-22 Virgin	199	0.316
Westgate RAP	396	0.217

Table 7.8 Creep Stiffness and m-values of Blended Binders

Virgin Binder	Creep Stiffness (Mpa)	m-value
PG 52-28	130	0.357
PG 58-22	144	0.328
PG64-22	235	0.292

The values from Table 7.7 and Table 7.8 were combined in order to produce blending charts for the creep stiffness and m-values in order to determine the maximum allowable amount of RAP in a mixture to pass the BBR specifications to control for thermal cracking. Figures 7.10-7.15 show the blending charts for the creep stiffness and m-values at the various performance grades.

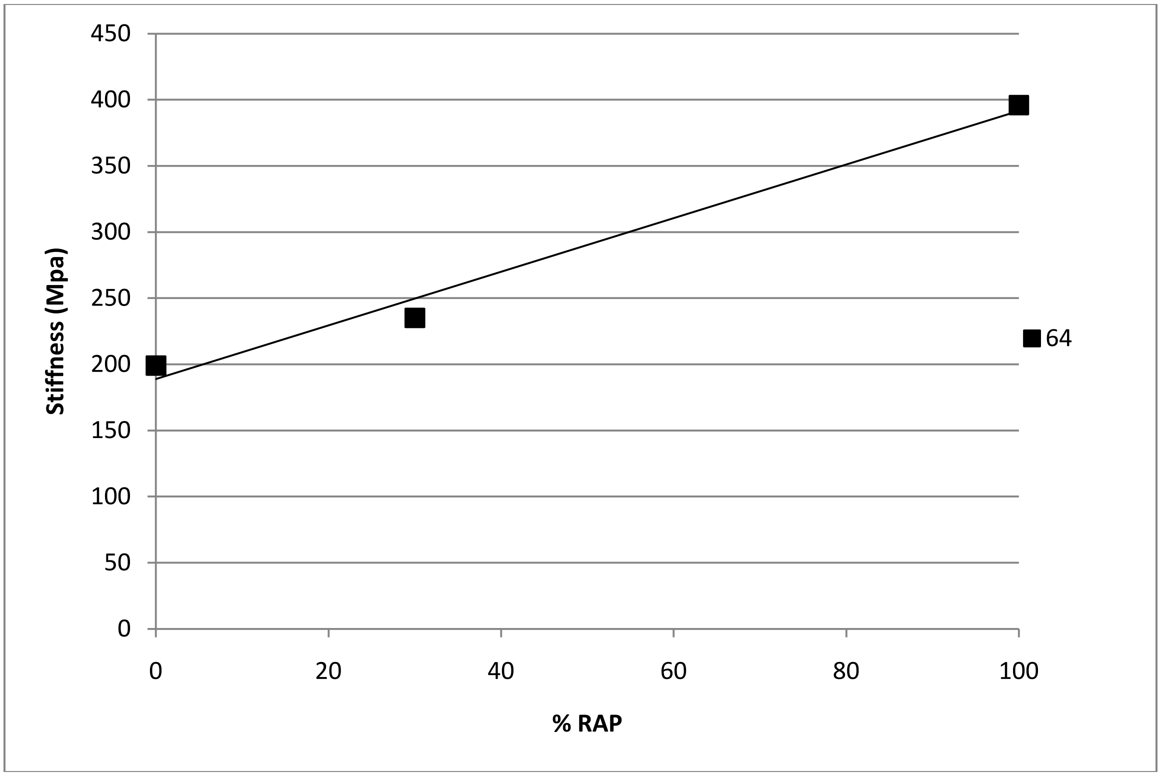


Figure 7.10 BBR PG 64-22 Sasobit® Creep Stiffness Blending Chart

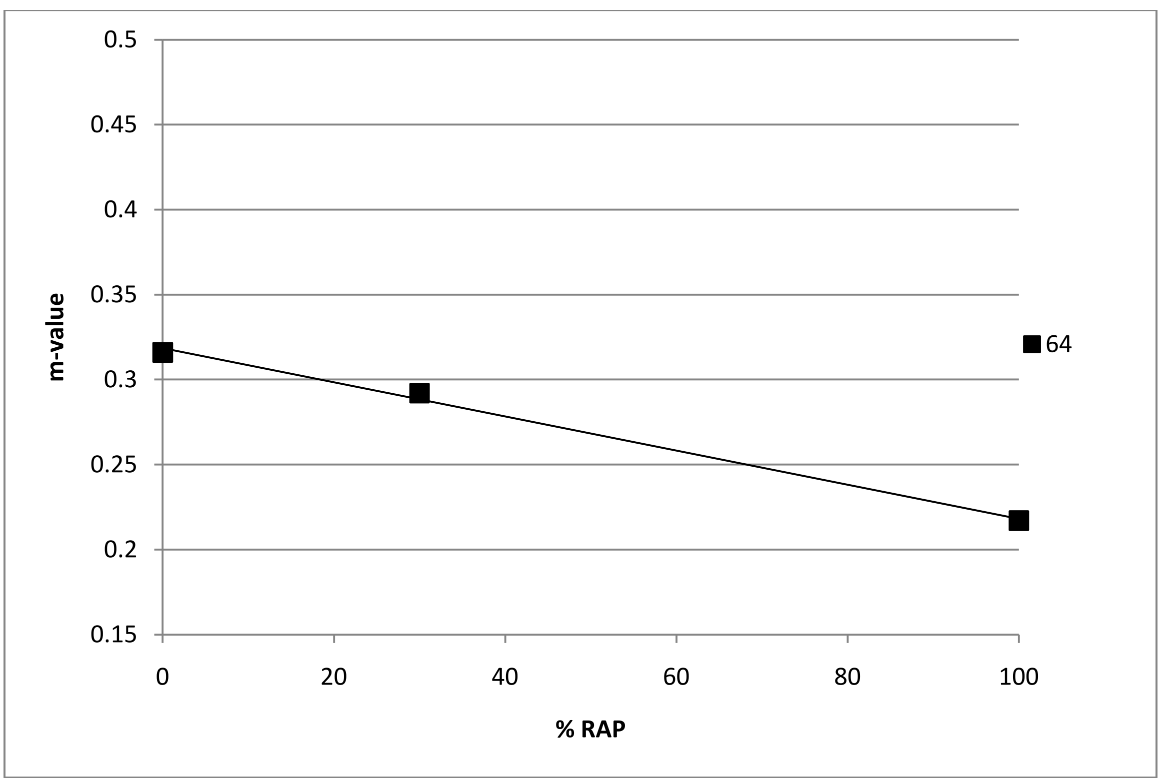


Figure 7.11 BBR PG 64-22 Sasobit® m-value Blending Chart

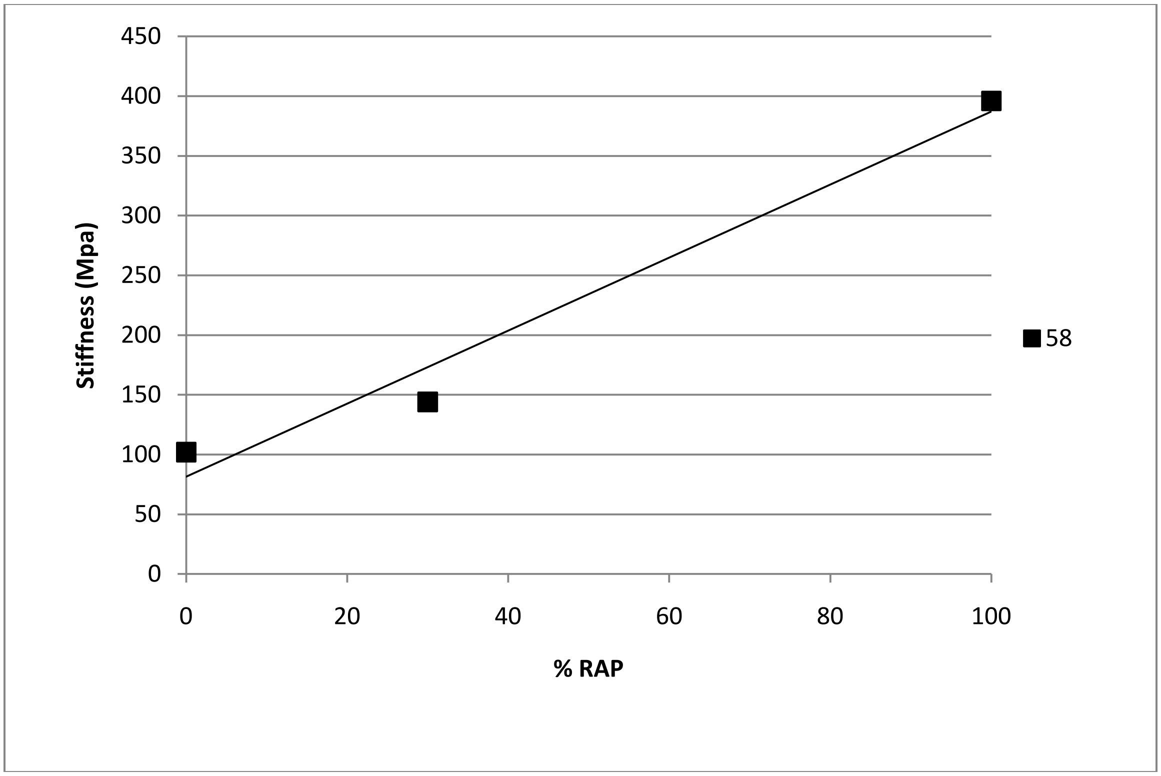


Figure 7.12 BBR PG 58-22 Sasobit® Creep Stiffness Blending Chart

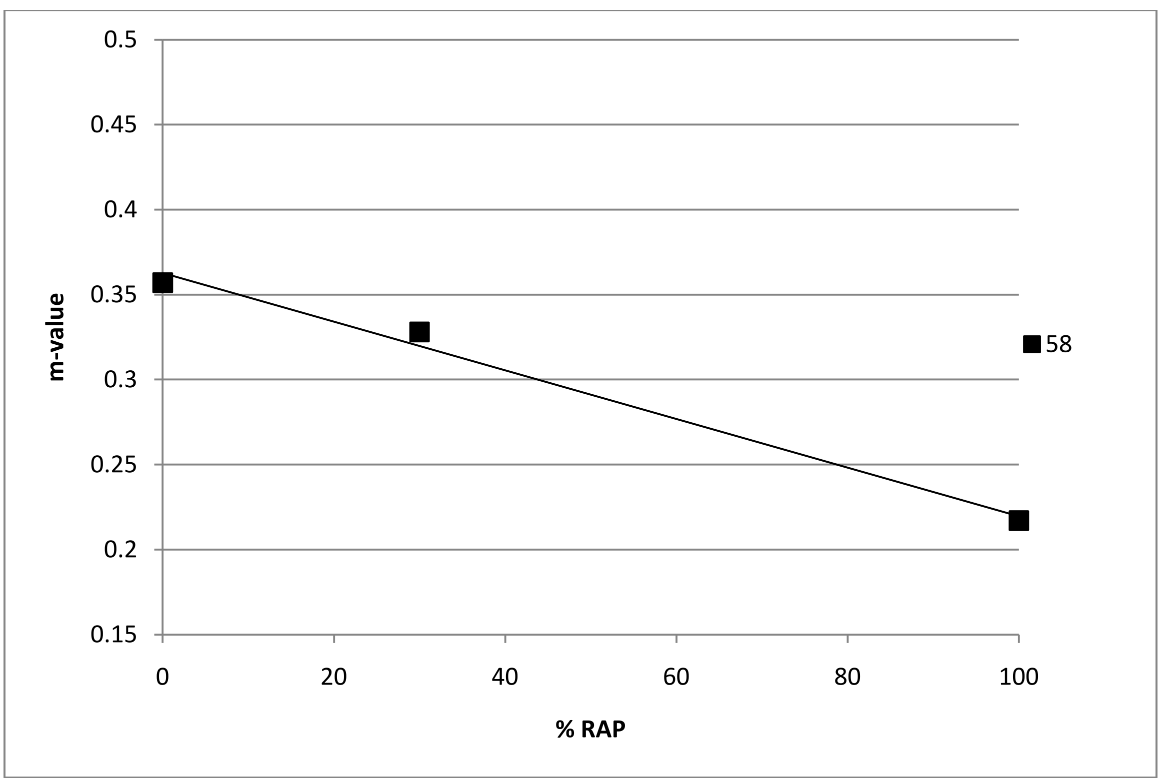


Figure 7.13 BBR PG 58-22 Sasobit® m-value Blending Chart

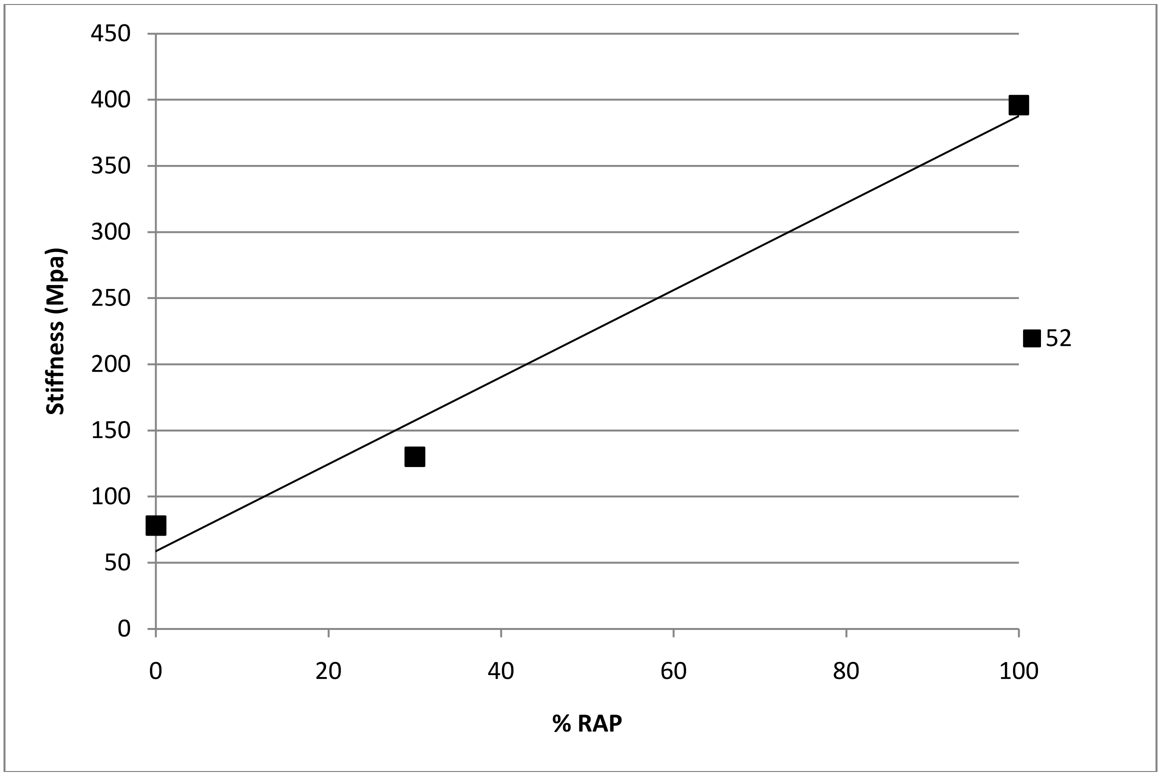


Figure 7.14 BBR PG 52-28 Sasobit® Creep Stiffness Blending Chart

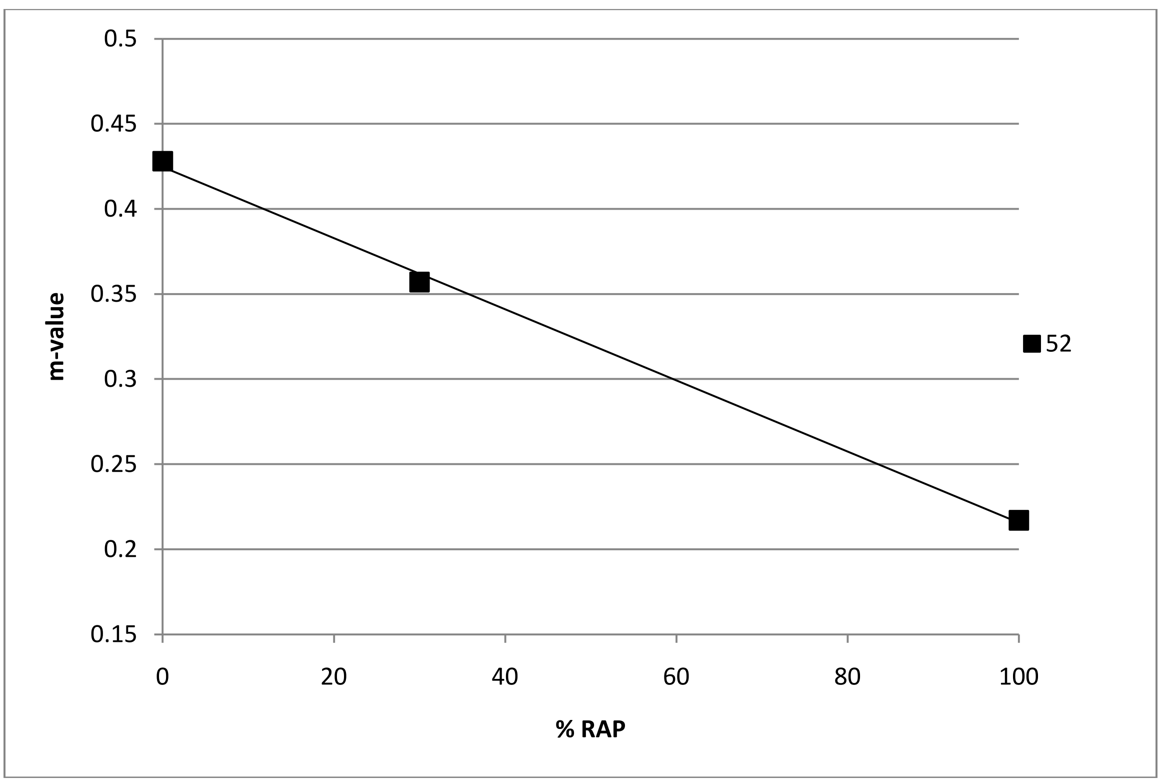


Figure 7.15 BBR PG 52-28 Sasobit® m-value Blending Chart

Table 7.9 and Table 7.10 below contains the maximum percentage of RAP allowed in order to meet the specification S=300 Mpa and m-value= 0.300, respectively, based on the linear equations from the blending charts. Table 7.9 shows that mixtures are able to satisfy the stiffness specification with 54.8-75.3% RAP. However, the controlling variable for thermal cracking from the BBR test is the m-value. Mixtures with PG 64-22 binder are able to contain 18.5% RAP. Mixtures with PG 58-22 binder are able to contain 44.9% RAP. Mixtures with PG 52-28 binder are able to contain 59.3% RAP.

Table 7.9 Maximum Percentage of RAP Binder to Satisfy S = 300 Mpa for PAV Binder

Virgin Binder Grade	S = m*x+b		Maximum % RAP
	m	b	
PG 52-28	3.2899	58.772	73.3
PG 58-22	3.057	81.532	71.5
PG 64-22	2.0285	188.77	54.8

Table 7.10 Maximum Percentage of RAP Binder to Satisfy m-value= 0.300 for PAV Binder

Virgin Binder Grade	m-value = m*x+b		Maximum % RAP
	m	B	
PG 52-28	-0.0021	0.4246	59.3
PG 58-22	-0.0014	0.3628	44.9
PG 64-22	-0.001	0.3185	18.5

Combining the results from Tables 7.4-7.6 and Table 7.9-7.10, the minimum and maximum amount of RAP is determined in order to still pass all specifications for a PG 64-22 binder. Table 7.11 below contains these values. Using virgin PG 64-22 binder, the maximum amount of RAP is 15.5%. Using PG 58-22 binder, the maximum amount of RAP is 44.9%. Using PG 52-28 binder, the maximum amount of RAP is 58.1%.

Table 7.11 Minimum and Maximum Percentage of RAP Binder to Satisfy all PG 64-22 Specifications

Virgin Binder Grade	Minimum Original DSR	Minimum RTFO DSR	Maximum PAV DSR	Maximum BBR S	Maximum BBR m-value
PG 52-28	24.2	19.9	58.1	73.3	59.3
PG 58-22	-	-	49.4	71.5	44.9
PG 64-22	-	-	15.5	54.8	18.5

7.3 Statistical Analysis

In order to determine how the addition of Sasobit® affects the binder rheology, it is important to not only look at the rheological results, but also to compare the rheological results to similar rheological results from binders not containing Sasobit®. In Chapter 4, rheological testing was conducted on virgin binders, blended binders and RAP binders containing no Sasobit®. The results from Chapter 4 will be compared to the above results to determine how the addition of Sasobit® affects the rheological properties. In the analysis, the binders containing no Sasobit® will be considered "HMA" binders and the binders containing Sasobit® will be considered "WMA" binders.

All of the DSR testing consisted of testing three samples at the various temperatures. The DSR testing in this chapter was conducted on a limited amount of temperatures. Therefore, the comparison between the HMA and WMA binders will be limited to the temperatures used in this chapter. It is important to note for the analysis that a temperature sweep was performed on the specimens, meaning that one specimen was used to perform a test at 52^{o}C, 58^{o}C and 64^{o}C, etc. Tables 7.12-7.15 contain the values of G*/sinδ for the original and RTFO aged binders. Tables 7.16 and 7.17 contain the values of G*sinδ for the PAV aged binders. Tables 7.12 and 7.13 shows the addition of Sasobit® to original virgin binders increases the average G*/sinδ for all binders at all temperatures ranging from 5.45% for PG 52 binder at 64^{o}C to 42.18% for PG 64 binder at 64^{o}C. However, the addition of Sasobit® to the binder extracted from the Westgate RAP caused a decrease in average G*/sinδ by about 35%. This reduction in G*/sinδ for Westgate RAP can be seen in the blended binders as well. The blend containing PG 52 binder average G*/sinδ reduces between 32.3-37.4%. The blends containing PG 58 and PG 64 binders, average G*/sinδ increases, but the increase is not as much as was seen with the virgin binders.

Table 7.12 G*/sinδ (kPa) Comparison Between HMA and WMA Original Virgin Binders

Binder	Temperature	HMA	WMA
52	52	1.56	2.29
		1.58	2.01
		1.59	2.16
	58	0.70	1.03
		0.87	0.88
		0.72	0.97
	64	0.43	0.47
		0.42	0.40
		0.38	0.44
58	58	1.75	1.92
		1.51	2.28
		1.59	2.20
	64	0.81	0.91
		0.73	1.08
		0.82	1.02
64	64	1.44	2.38
		1.81	2.13
		1.61	2.40

Table 7.13 G*/sinδ (kPa) Comparison Between HMA and WMA Original Blended Binders

Binder	Temperature	HMA	WMA
52-30	52	8.13	5.62
		9.47	6.01
		7.97	5.67
	58	3.54	2.36
		4.03	2.59
		3.49	2.44
	64	1.71	1.01
		1.79	1.15
		1.63	1.04
58-30	58	6.26	7.03
		6.61	5.53
		5.62	6.19
	64	2.90	3.69
		2.96	2.47
		2.63	3.03
64-30	64	5.21	4.80
		4.57	9.08
		4.82	4.61
Westgate	52	159.34	98.90
		155.54	104.01
		148.99	96.08
	58	71.67	45.91
		71.34	47.40
		67.87	44.92
	64	31.62	21.03
		31.97	20.60
		30.17	20.10

Tables7.14 and 7.15 show the addition of Sasobit® to RTFO aged virgin binders increases average G*/sinδ for all binders at all temperatures, ranging from 12.78% for PG 52 at 64°C to 37.87% for PG 52 at 52°C. The RTFO aged binder extracted from the Westgate RAP average G*/sinδ increases between 5.52%-15.77%. However, the average G*/sinδ for the PG 52 and PG 58 blended binders decrease between 10.8% for PG 52 at 52°C to 23.8% for PG 58 at 64°C.

Since G*/sinδ is an indicator for the resistance of a mixture to rutting, it is desired to have a larger G*/sinδ value since a stiff, elastic binder is needed for rut resistance. This data shows that most mixtures, especially virgin mixtures, improve the rut resistance for mixtures containing Sasobit® compared to similar HMA mixtures with no additives.

Table 7.14 G*/sinδ (kPa) Comparison Between HMA and WMA RTFO Virgin Binders

Binder	Temperature	HMA	WMA
52	52	3.03	4.40
		3.36	4.34
		3.04	4.26
	58	1.41	1.90
		1.47	1.85
		1.40	1.86
	64	0.71	0.82
		0.71	0.81
		0.73	0.80
58	58	4.20	5.99
		5.05	6.50
		5.01	6.18
	64	1.96	2.82
		2.42	2.95
		1.96	2.79
64	64	5.36	6.92
		5.26	7.12
		5.15	7.01

Table 7.15 G*/sinδ (kPa) Comparison Between HMA and WMA RTFO Blended binders

Binder	Temperature	HMA	WMA
52-30	52	23.08	19.62
		19.55	19.09
		22.57	19.46
	58	9.854	8.29
		8.54	7.82
		9.21	8.37
	64	4.22	3.48
		3.87	3.27
		3.85	3.57
58-30	58	20.45	17.68
		24.21	16.89
		22.39	17.95
	64	9.74	7.98
		11.05	7.64
		10.37	8.12
64-30	64	16.94	19.13
		18.64	19.09
		15.77	18.77
Westgate	52	668.44	851.31
		838.33	784.10
		818.54	818.29
	58	300.52	397.00
		378.23	363.52
		366.78	376.73
	64	169.93	181.44
		164.36	165.31
		112.75	170.80

Table 7.16 shows the addition of Sasobit® to PAV aged virgin binders causes an increase in G*sinδ for most cases, except at 25^{o}C for all the binders. Since G*sinδ is an indicator of fatigue cracking, a soft, elastic binder is desired in order to sustain many loads without cracking. Therefore, a decrease of G*sinδ is beneficial. It is also important to note that 25^{o}C is a critical temperature as it is the temperature that corresponds to -22 for PG 64 binders, which is the specification that is trying to be met.

Table 7.16 G*/sinδ (kPa) Comparison Between HMA and WMA PAV Virgin Binders

Binder	Temperature	HMA	WMA
52	19	6.83E+05	2.56E+06
		8.48E+05	2.90E+06
		9.49E+05	2.79E+06
	22	1.11E+06	1.60E+06
		1.37E+06	1.82E+06
		1.53E+06	1.76E+06
	25	1.76E+06	9.63E+05
		2.16E+06	1.11E+06
		2.41E+06	1.08E+06
58	19	1.56E+06	4.01E+06
		1.56E+06	4.07E+06
		1.53E+06	4.54E+06
	22	2.41E+06	2.86E+06
		2.42E+06	2.73E+06
		2.35E+06	3.06E+06
	25	3.69E+06	1.89E+06
		3.68E+06	1.76E+06
		3.55E+06	1.99E+06
64	19	3.71E+06	8.70E+06
		3.86E+06	7.64E+06
		4.12E+06	1.00E+07
	22	5.56E+06	6.20E+06
		5.79E+06	5.34E+06
		6.19E+06	7.25E+06
	25	8.32E+06	4.28E+06
		8.63E+06	3.62E+06
		9.27E+06	5.01E+06

Table 7.17 shows the addition of Sasobit® to PAV aged blended binders causes an increase in average G*sinδ for PG 64 blended binders and binders extracted from the RAP but a decrease in average G*sinδ for PG 52 and PG 58 blended binders. Looking at the critical temperature of 25^{o}C, the average G*sinδ increases 9.45% and 24.1% for the Westgate and PG 64 blend binders, respectively, and decreases 38.74% and 4.68% for the PG 52 and PG 58 blended binders, respectively. Again, a reduced G*sinδ is an indicator of better fatigue cracking resistance.

Table 7.17 G*/sinδ (kPa) Comparison Between HMA and WMA PAV Blended Binders

Binder	Temperature	HMA	WMA
52-30	19	8.08E+06	4.28E+06
		6.58E+06	4.73E+06
		6.41E+06	5.19E+06
	22	5.66E+06	2.89E+06
		4.62E+06	3.21E+06
		4.49E+06	3.51E+06
	25	3.88E+06	1.85E+06
		3.16E+06	2.08E+06
		3.09E+06	2.28E+06
58-30	19	5.91E+06	5.02E+06
		6.05E+06	5.01E+06
		5.98E+06	6.58E+06
	22	4.00E+06	3.53E+06
		4.25E+06	3.65E+06
		4.00E+06	4.63E+06
	25	2.73E+06	2.36E+06
		2.80E+06	2.39E+06
		2.73E+06	3.12E+06
64-30	19	9.18E+06	1.11E+07
		8.22E+06	1.02E+07
		8.78E+06	8.61E+06
	22	6.55E+06	8.11E+06
		5.87E+06	7.54E+06
		6.54E+06	7.68E+06
	25	4.71E+06	5.60E+06
		4.21E+06	5.43E+06
		4.55E+06	5.69E+06
Westgate	19	2.48E+07	2.30E+07
		2.61E+07	2.53E+07
		2.15E+07	2.70E+07
	22	2.00E+07	1.91E+07
		2.10E+07	2.10E+07
		1.75E+07	2.23E+07
	25	1.56E+07	1.53E+07
		1.64E+07	1.68E+07
		1.38E+07	1.80E+07

Table 7.18 shows the addition of Sasobit® to PAV aged binders causes a decrease in m-values of 5.5, 11.7 and 9.3% for virgin PG 52, PG 58 and PG 64 binders, respectively. It also shows that the addition of Sasobit® causes a decrease in m-value of 8.4, 6.4 and 14.2% for blended PG 58 and PG 64 binders and the binder extracted from the Westgate RAP, respectively, while it causes a slight increase of 0.3% for PG 52 blended binders. Table 7.19 shows that the addition of Sasobit® causes an increase in creep stiffness of 7.6, 26.4 and 16.7% for virgin PG 52, PG 58 and PG 64 binders, respectively. It also shows that the addition of Sasobit® causes an increase in creep stiffness of 16.1, 48.7 and 50.6% for blended PG 58 and PG 64 binders and the binder extracted from the Westgate RAP, respectively, while it causes a slight decrease of 8.57% for PG 52 blended binders.

Table 7.18 Comparison Between HMA and WMA m-values

Binder	HMA	WMA
52	0.453	0.428
58	0.4045	0.357
64	0.3485	0.316
52-30	0.356	0.357
58-30	0.358	0.328
64-30	0.312	0.292
Westgate	0.253	0.217

Table 7.19 Comparison Between HMA and WMA Stiffness (MPa)

Binder	HMA	WMA
52	72.5	78
58	80.7	102
64	170.5	199
52-30	142	130
58-30	124	144
64-30	158	235
Westgate	263	396

The experiment consisted of sampling from three different binders (PG 52, PG 58 and PG 64), with testing performed under two competing experimental conditions (method/technique/ procedure) (HMA and WMA), at each binder type, various temperatures were used (52^{o}C, 58^{o}C and 64^{o}C), with these temperatures used depending on the binder type selected. A temperature sweep was performed on the specimens, which resulted in having results for each specimen at the available temperatures (or each specimen being its “own control”). Statistical analysis considered the temperature the test was performed at, nested within the binder. Also, since the same specimen was used for all the temperatures, temperature was considered a repeated measures analysis. A statistical linear model representing the analysis can be found below. The data was divided into subsets according to binder age (original, RTFO and PAV) and RAP content (virgin, or blended). The full SAS code can be found in Appendix A.1.

$y_{ijkl} = \mu + \beta_i + \gamma_j + (\beta\gamma)_{ij} + d_{ijl} + \lambda_{ik} + (\gamma\lambda)_{ijk} + e_{ijkl}$

where,

i = 1, 2, 3 binders

j = 1, 2 methods

l = 1, 2, 3 specimens

k =1,2 3 temperatures for i =1, k =1, 2 for i = 2, and k = 1 for i = 3

l = 1, 2, 3 within ith binder and jth method

β_i =fixed effect of ith binder

γ_j =fixed effect of jth method

λ_{ik} = fixed effect of kth temperature within ith binder

d_{ijl} = random effect of specimen within the ith binder and jth method

e_{ijkl} = residual random effect lth specimen within kth temperature and ith binder and jth method

Hypothesis testing was used to reach a conclusion about the research hypothesis: are the mean response for HMA and WMA similar, is there a difference between all three binders, are there significant differences between the temperature levels within each binder and whether there are significant interaction effects between binder and method, and between temperature and method within each binder level. These hypotheses are as followed in Table 7.20.

Table 7.20 Null and Alternative Hypothesis

Effect	**Null Hypothesis**	**Alternative Hypothesis**
Binder	H_o: $\mu_{52} = \mu_{58} = \mu_{64} = \mu$	H_a: all means are not similar
Method	H_o: $\mu_{HMA} = \mu_{WMA} = \mu$	H_a: all means are not similar
Binder*method	H_o: $\mu_{52HMA} = \mu_{52WMA} = \mu_{58HMA} = \mu_{58WMA} = \mu_{64HMA} = \mu_{64WMA}$	H_a: all means are not similar
Temp(binder)	H_o: $\mu_{T52} = \mu_{T58} = \mu_{T64} = \mu$ (for PG 52 binder) H_o: $\mu_{T58} = \mu_{T64} = \mu$ (for PG 58 binder)	H_a: all means are not similar
Temp*method(binder)	H_o: $\mu_{T52HMA} = \mu_{T52WMA} = \mu_{T58HMA} = \mu_{T58WMA} = \mu_{T64HMA} = \mu_{T64WMA} = \mu$ (for PG 52 binder) H_o: $\mu_{T58HMA} = \mu_{T58WMA} = \mu_{T64HMA} = \mu_{T64WMA} = \mu$ (for PG 58 binder) H_o: $\mu_{T64HMA} = \mu_{T64WMA} = \mu$ (for PG 64 binder)	H_a: all means are not similar

7.3.1 Virgin Binder Original Aged Statistical Analysis

Initial analysis of the data showed trends in the residual plot, so the data was transformed by taking the square root of the data. All of the following analysis will consider data transformed in this manner. Table 7.21 below contains the statistical results for the Type 3 test of Hypothesis associated to the linear model fitted to data from the original virgin binders. As the table shows, all effects except the binder by method interaction are significant ($P<0.05$) at level of $\alpha = 0.05$, which means that the null hypothesis can be rejected. For the binder effect, this means that at least one of the true means of PG 52, PG 58 and PG 64 is not similar to any other. This can be expected since each of the binders has a different grade based on its rheological results. For the method effect, this means that the true mean response of HMA is not the same as the true mean of the WMA, therefore, the use of Sasobit® does have a significant effect on the G*/sinδ for the virgin original data. For the temperature effect, which is nested within the binder, this means that at least one true mean at 52°C, 58°C or 64°C is not similar to the others at each binder. Again, this can be expected, since asphalt binder is a temperature dependent material, so the properties are going to change, maybe significantly, with a change in temperature. For the final temperature by method interaction, at least one true mean at the temperature, method combination is not equal, which again can be expected since the rheological properties will change according to temperature.

Table 7.21 Virgin Original Statistical Analysis

Effect	**Num DF**	**Den DF**	**F-value**	**p-value**
Binder	2	11.3	121.24	<.0001
Method	1	10.8	56.06	<.0001
Binder*method	2	11.3	3.22	0.0784
Temp(binder)	3	11.2	1146.05	<.0001
Temp*method(binder)	3	11.2	18.66	0.0001

Predicted mean values (Least Squares Means) were estimated using least squares which minimizes the sum of the squared residuals (residual= observed-fitted). Table 7.22 below shows the set of least squares means (Estimate column) with associated Standard error. Omitted is information referring to testing of the null hypothesis, $H_o : \widehat{Y}_i = 0$, which is testing whether this particular least squares mean is equal to zero.

Table 7.22 Least Squares Means Virgin Original Binder

Effect	binder	method	temp	Estimate	Standard Error
Binder	52			0.9796	0.01776
Binder	58			1.1545	0.01812
Binder	64			1.3945	0.01987
Method		HMA		1.0914	0.01519
Method		WMA		1.2610	0.01519
Binder*method	52	HMA		0.9236	0.02511
Binder*method	52	WMA		1.0355	0.02511
Binder*method	58	HMA		1.0788	0.02562
Binder*method	58	WMA		1.2303	0.02562
Binder*method	64	HMA		1.2719	0.02811
Binder*method	64	WMA		1.5171	0.02811
Temp(binder)	52		52	1.3611	0.01987
Temp(binder)	52		58	0.9264	0.01987
Temp(binder)	52		64	0.6512	0.01987
Temp(binder)	58		58	1.3652	0.01987
Temp(binder)	58		64	0.9434	0.01987
Temp(binder)	64		64	1.3945	0.01987
Temp*method(binder)	52	HMA	52	1.2554	0.02811
Temp*method(binder)	52	WMA	52	1.4669	0.02811
Temp*method(binder)	52	HMA	58	0.8734	0.02811
Temp*method(binder)	52	WMA	58	0.9793	0.02811
Temp*method(binder)	52	HMA	64	0.6420	0.02811
Temp*method(binder)	52	WMA	64	0.6604	0.02811
Temp*method(binder)	58	HMA	58	1.2709	0.02811
Temp*method(binder)	58	WMA	58	1.4596	0.02811
Temp*method(binder)	58	HMA	64	0.8866	0.02811
Temp*method(binder)	58	WMA	64	1.0010	0.02811
Temp*method(binder)	64	HMA	64	1.2719	0.02811
Temp*method(binder)	64	WMA	64	1.5171	0.02811

In order to check whether the linear model fits the data well, the model assumptions should be checked and to determine if there are any outliers. The model assumptions are that the errors are independent and identically distributed with a mean of zero and a variance of σ_e^2. In order to determine if the y_i's are approximately normal, then the residuals ($\left(y_{ijkl} - \hat{y}_{ijk}\right)$ should be approximately normal. To check this, a histogram of the residuals was plotted. The plot should be bell-shaped and centered about zero. Figure 7.16 shows this plot and that is it

roughly bell-shaped and centered about zero. To determine if there are any outliers, check if any observations have a Studentized residual with a magnitude of ± 3.5. Figure 7.17 contains the residual versus predicted plot. Figure 7.17 shows the transformation of the data helped to increase homogeneity of residual variance and normality. This transformation is also used on all of the following analysis.

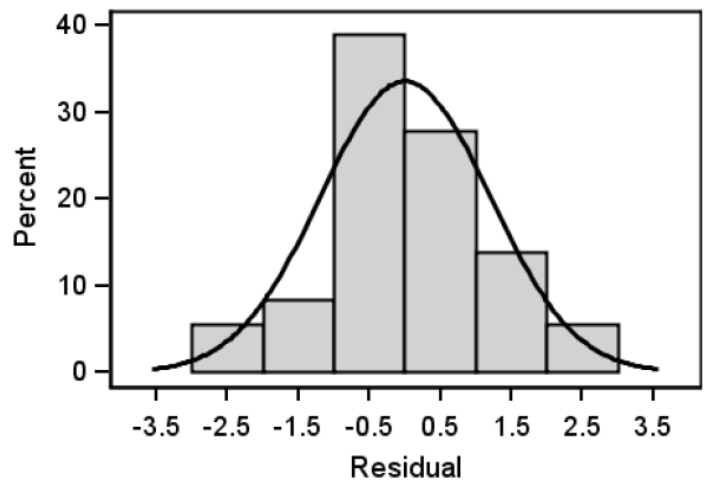


Figure 7.16 Histogram of Residuals (Original Virgin Sqrt)

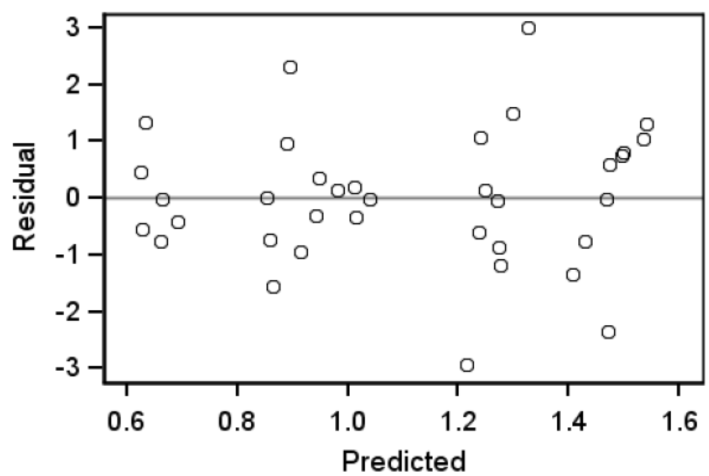


Figure 7.17 Residuals Versus Predicted Values (Original Virgin Sqrt)

7.3.2 Blended Binder Original Aged Statistical Analysis

Initial analysis of the data showed trends in the residual plot, so the data was transformed by taking the square root of the data. All of the following analysis will consider data transformed in this manner. An outlier was also found with a residual greater than 3.5 so this data point was removed after inspection. Table 7.23 below contains the statistical results for the Type 3 test of Hypothesis associated to the linear model fitted to data from the original blended binders. As the table shows, all effects are significant ($P<0.05$) at level of $\alpha = 0.05$, which means that the null hypothesis can be rejected. Similar to the original virgin data, a significant binder effect means that at least one of the true means of PG 52, PG 58 and PG 64 is not similar to any other. This can be expected since each of the binders has a different grade based on its rheological results. For the method effect, this means that the true mean of HMA is not the same as the true mean of the WMA, therefore, the use of Sasobit® does have a significant effect on the $G^*/\sin\delta$ for the blended original data. For the binder by method interaction, this means that at least one true mean of the binder method combinations is not similar to any other, which is expected since there is a difference between binders as well as the method. For the temperature effect, which is nested within the binder, this means that at least one true mean at 52^{o}C, 58^{o}C or 64^{o}C is not similar to the others at each binder. Again, this can be expected, since asphalt binder is a temperature dependent material, so the properties are going to change, maybe significantly, with a change in temperature. For the final temperature by method interaction, at least one true mean at the temperature, method combination is not equal, which again can be expected since the rheological properties will change according to temperature.

Table 7.23 Blended Original Statistical Analysis

Effect	Num DF	Den DF	F-value	p-value
Binder	2	11.1	18.90	0.0003
Method	1	11	10.08	0.0089
Binder*method	2	11.1	8.67	0.0054
Temp(binder)	3	12	1896.50	<.0001
Temp*method(binder)	3	12	9.52	0.0017

Predicted mean values (Least Squares Means) were estimated using least squares which minimizes the sum of the squared residuals (residual= observed-fitted). Table 7.24 below shows the set of least squares means (Estimate column) with associated Standard error. Omitted is information referring to testing of the null hypothesis, $H_o : \widehat{Y}_i = 0$, which is testing whether this particular least squares mean is equal to zero.

Table 7.24 Least Squares Means Original Blended Binder

Effect	binder	method	temp	Estimate	Standard Error
Binder	52			1.8576	0.03726
Binder	58			2.1010	0.03804
Binder	64			2.1872	0.04369
Method		HMA		2.1114	0.03114
Method		WMA		1.9858	0.03375
Binder*method	52	HMA		2.0476	0.05269
Binder*method	52	WMA		1.6676	0.05269
Binder*method	58	HMA		2.0812	0.05380
Binder*method	58	WMA		2.1207	0.05380
Binder*method	64	HMA		2.2054	0.05526
Binder*method	64	WMA		2.1690	0.06768
Temp(binder)	52		52	2.6589	0.03908
Temp(binder)	52		58	1.7441	0.03908
Temp(binder)	52		64	1.1698	.03908
Temp(binder)	58		58	2.4891	0.03908
Temp(binder)	58		64	1.7128	0.03908
Temp(binder)	64		64	2.1872	0.04369
Temp*method(binder)	52	HMA	52	2.9167	0.05526
Temp*method(binder)	52	WMA	52	2.4011	0.05526
Temp*method(binder)	52	HMA	58	1.9189	0.05526
Temp*method(binder)	52	WMA	58	1.5692	0.05526
Temp*method(binder)	52	HMA	64	1.3071	0.05526
Temp*method(binder)	52	WMA	64	1.0324	0.05526
Temp*method(binder)	58	HMA	58	2.4812	0.05526
Temp*method(binder)	58	WMA	58	2.4970	0.05526
Temp*method(binder)	58	HMA	64	1.6813	0.05526
Temp*method(binder)	58	WMA	64	1.7444	0.05526
Temp*method(binder)	64	HMA	64	2.2054	0.05526
Temp*method(binder)	64	WMA	64	2.1690	0.06768

In order to check whether the linear model fits the data well, the model assumptions should be checked and to determine if there are any outliers. The model assumptions are that the errors are independent and identically distributed with a mean of zero and a variance of σ_e^2. In order to determine if the y_i's are approximately normal, then the residuals ($\left(y_{ijkl} - \hat{y}_{ijk}\right)$ should be approximately normal. To check this, a histogram of the residuals was plotted. The plot should be bell-shaped and centered about zero. Figure 7.18 shows this plot and that is it roughly bell-shaped and centered about zero. To determine if there are any outliers, check if any observations have a Studentized residual with a magnitude of ± 3.5. Figure 7.19 contains the residual versus predicted plot. Figure 7.19 shows the transformation of the data helped to increase homogeneity of residual variance and normality.

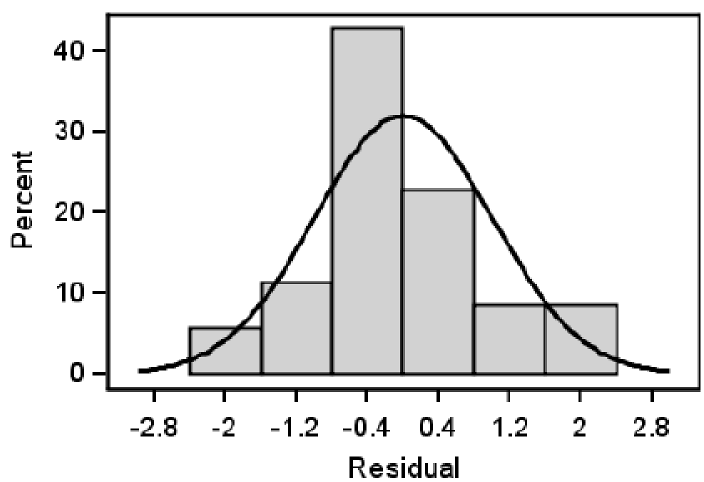


Figure 7.18 Histogram of Residuals (Original Blend Sqrt)

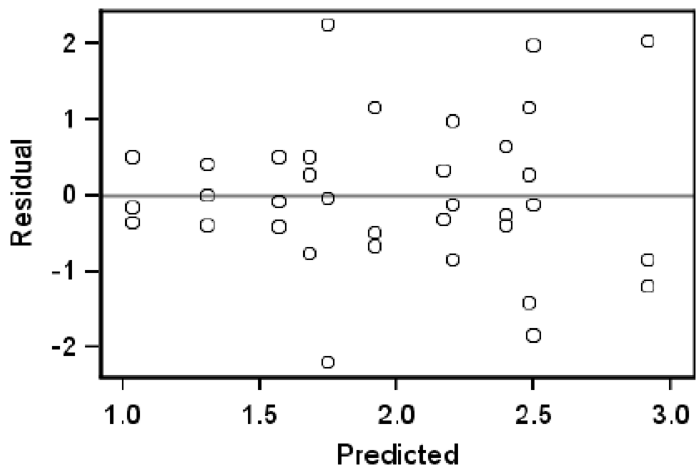


Figure 7.19 Residuals Versus Predicted Values (Original Blend Sqrt)

7.3.3 Virgin Binder RTFO Aged Statistical Analysis

Initial analysis of the data showed trends in the residual plot, so the data was transformed by taking the square root of the data. All of the following analysis will consider data transformed in this manner. Table 7.25 below contains the statistical results for the Type 3 test of Hypothesis associated with the linear model fitted to data from the RTFO aged virgin binders. As the table shows, all effects are significant ($P<0.05$) at level of $\alpha = 0.05$, which means that the null hypothesis can be rejected. Similar to the original binder data, a significant binder effect means that at least one of the true means of PG 52, PG 58 and PG 64 is not similar to any other. This can be expected since each of the binders has a different grade based on its rheological results. For the method effect, this means that the true mean of HMA is not the same as the true mean of the WMA, therefore, the use of Sasobit® does have a significant effect on the $G^*/\sin\delta$ for the RTFO aged virgin data. For the binder by method interaction, this means that at least one true mean of the binder method combinations is not similar to any other, which is expected since there is a difference between binders as well as the method. For the temperature effect, which is nested within the binder, this means that at least one true mean at 52^oC, 58^oC or 64^oC is not similar to the others at each binder. Again, this can be expected, since asphalt binder is a temperature dependent material, so the properties are going to change, maybe significantly, with a change in temperature. For the final temperature by method interaction, at least one true mean at the temperature, method combination is not equal, which again can be expected since the rheological properties will change according to temperature.

Table 7.25 Virgin RTFO Statistical Analysis

Effect	Num DF	Den DF	F-value	p-value
Binder	2	12.6	1027.83	<.0001
Method	1	11.9	172.97	<.0001
Binder*method	2	12.6	6.69	0.0104
Temp(binder)	3	12.2	1070.66	<.0001
Temp*method(binder)	3	12.2	9.78	0.0014

Predicted mean values (Least Squares Means) were estimated using least squares which minimizes the sum of the squared residuals (residual= observed-fitted). Table 7.26 below shows the set of least squares means (Estimate column) with associated Standard error. Omitted is information referring to testing of the null hypothesis, $H_o : \widehat{Y_i} = 0$, which is testing whether this particular least squares mean is equal to zero.

Table 7.26 Least Squares Means Virgin RTFO Binder

Effect	binder	method	temp	Estimate	Standard Error
Binder	52			1.3606	0.01515
Binder	58			1.9536	0.01701
Binder	64			2.4705	0.01979
Method		HMA		1.7931	0.01423
Method		WMA		2.0634	0.01423
Binder*method	52	HMA		1.2715	0.02143
Binder*method	52	WMA		1.4497	0.02143
Binder*method	58	HMA		1.8155	0.02406
Binder*method	58	WMA		2.0917	0.02406
Binder*method	64	HMA		2.2922	0.02798
Binder*method	64	WMA		2.6489	0.02798
Temp(binder)	52		52	1.9270	0.01979
Temp(binder)	52		58	1.2817	0.01979
Temp(binder)	52		64	0.8732	0.01979
Temp(binder)	58		58	2.3363	0.01979
Temp(binder)	58		64	1.5708	0.01979
Temp(binder)	64		64	2.4705	0.01979
Temp*method(binder)	52	HMA	52	1.7723	0.02798
Temp*method(binder)	52	WMA	52	2.0816	0.02798
Temp*method(binder)	52	HMA	58	1.1959	0.02798
Temp*method(binder)	52	WMA	58	1.3675	0.02798
Temp*method(binder)	52	HMA	64	0.8463	0.02798
Temp*method(binder)	52	WMA	64	0.9000	0.02798
Temp*method(binder)	58	HMA	58	2.1783	0.02798
Temp*method(binder)	58	WMA	58	2.4943	0.02798
Temp*method(binder)	58	HMA	64	1.4526	0.02798
Temp*method(binder)	58	WMA	64	1.6891	0.02798
Temp*method(binder)	64	HMA	64	2.2922	0.02798
Temp*method(binder)	64	WMA	64	2.6489	0.02798

In order to check whether the linear model fits the data well, the model assumptions should be checked and to determine if there are any outliers. The model assumptions are that the errors are independent and identically distributed with a mean of zero and a variance of σ_e^2. In order to determine if the y_i's are approximately normal, then the residuals ($\left(y_{ijkl} - \hat{y}_{ijk}\right)$ should be approximately normal. To check this, a histogram of the residuals was plotted. The plot should be bell-shaped and centered about zero. Figure 7.20 shows this plot and that is it

roughly bell-shaped and centered about zero. To determine if there are any outliers, check if any observations have a Studentized residual with a magnitude of ± 3.5. Figure 7.21 contains the residual versus predicted plot. Figure 7.21 shows the transformation of the data helped to increase homogeneity of residual variance and normality.

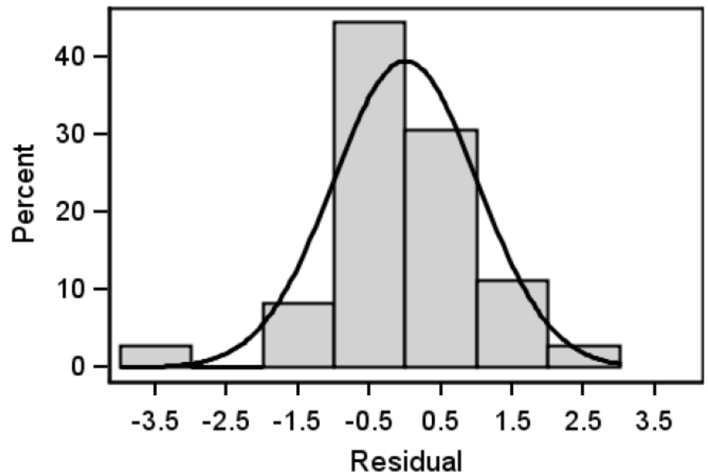


Figure 7.20 Histogram of Residuals (RTFO Virgin Sqrt)

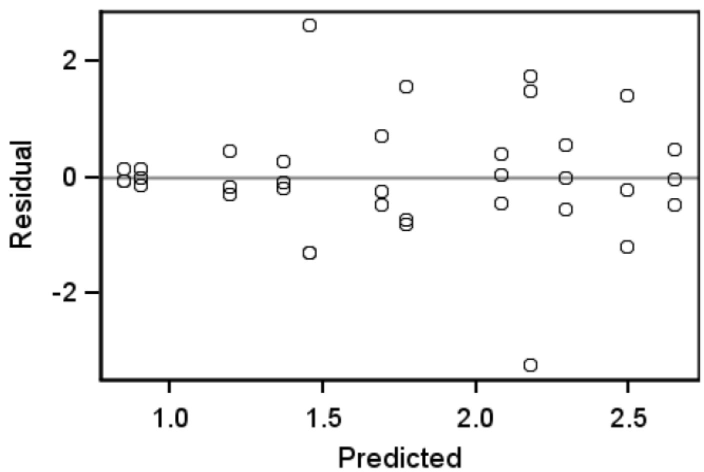


Figure 7.21 Residuals Versus Predicted Values (RTFO Virgin Sqrt)

7.3.4 Blended Binder RTFO Aged Statistical Analysis

Initial analysis of the data showed trends in the residual plot, so the data was transformed by taking the square root of the data. All of the following analysis will consider data transformed in this manner. Table 7.27 below contains the statistical results for the Type 3 test of Hypothesis associated to the linear model fitted to data from the RTFO aged blended binders. As the table shows, all effects except the temperature by method interaction are significant ($P<0.05$) at level of $\alpha = 0.05$, which means that the null hypothesis can be rejected. Similar to the original binder data, a significant binder effect means that at least one of the true means of PG 52, PG 58 and PG 64 is not similar to any other. This can be expected since each of the binders has a different grade based on its rheological results. For the method effect, this means that the true mean of HMA is not the same as the true mean of the WMA, therefore, the use of Sasobit® does have a significant effect on the $G^*/\sin\delta$ for the RTFO aged blended data. For the binder by method interaction, this means that at least one true mean of the binder method combinations is not similar to any other, which is expected since there is a difference between binders as well as the method. For the temperature effect, which is nested within the binder, this means that at least one true mean at 52°C, 58°C or 64°C is not similar to the others at each binder. Again, this can be expected, since asphalt binder is a temperature dependent material, so the properties are going to change, maybe significantly, with a change in temperature. Since the temperature by method interaction was not significant, the true means at all temperature, method combination are equal.

Table 7.27 RTFO Blended Statistical Analysis

Effect	Num DF	Den DF	F-value	p-value
Binder	2	11.8	154.64	<.0001
Method	1	11.4	12.27	0.0047
Binder*method	2	11.8	14.57	0.0006
Temp(binder)	3	11.6	2078.93	<.0001
Temp*method(binder)	3	11.6	2.25	0.1361

Predicted mean values (Least Squares Means) were estimated using least squares which minimizes the sum of the squared residuals (residual= observed-fitted). Table 7.28 below shows the set of least squares means (Estimate column) with associated Standard error. Omitted is information referring to testing of the null hypothesis, $H_o : \widehat{Y}_i = 0$, which is testing whether this particular least squares mean is equal to zero.

Table 7.28 Least Squares Means RTFO Blended Binder

Effect	binder	method	temp	Estimate	Standard Error
Binder	52			3.1335	0.04269
Binder	58			3.7358	0.04460
Binder	64			4.2465	0.04718
Method		HMA		3.7789	0.03663
Method		WMA		3.6316	0.03663
Binder*method	52	HMA		3.2289	0.06037
Binder*method	52	WMA		3.0380	0.06037
Binder*method	58	HMA		3.9733	0.06308
Binder*method	58	WMA		3.4983	0.06308
Binder*method	64	HMA		4.1345	0.06673
Binder*method	64	WMA		4.3585	0.06673
Temp(binder)	52		52	4.5314	0.04718
Temp(binder)	52		58	2.9442	0.04718
Temp(binder)	52		64	1.9248	0.04718
Temp(binder)	58		58	4.4543	0.04718
Temp(binder)	58		64	3.0173	0.04718
Temp(binder)	64		64	4.2465	0.04718
Temp*method(binder)	52	HMA	52	4.6594	0.06673
Temp*method(binder)	52	WMA	52	4.4033	0.06673
Temp*method(binder)	52	HMA	58	3.0321	0.06673
Temp*method(binder)	52	WMA	58	2.8563	0.06673
Temp*method(binder)	52	HMA	64	1.9952	0.06673
Temp*method(binder)	52	WMA	64	1.8544	0.06673
Temp*method(binder)	58	HMA	58	4.7248	0.06673
Temp*method(binder)	58	WMA	58	4.1837	0.06673
Temp*method(binder)	58	HMA	64	3.2218	0.06673
Temp*method(binder)	58	WMA	64	2.8128	0.06673
Temp*method(binder)	64	HMA	64	4.1345	0.06673
Temp*method(binder)	64	WMA	64	4.3585	0.06673

In order to check whether the linear model fits the data well, the model assumptions should be checked and to determine if there are any outliers. The model assumptions are that the errors are independent and identically distributed with a mean of zero and a variance of σ_e^2. In order to determine if the y_i's are approximately normal, then the residuals ($\left(y_{ijkl} - \hat{y}_{ijk}\right)$ should be approximately normal. To check this, a histogram of the residuals was plotted. The plot should be bell-shaped and centered about zero. Figure 7.22 shows this plot and that is it

roughly bell-shaped and centered about zero. To determine if there are any outliers, check if any observations have a Studentized residual with a magnitude of ± 3.5. Figure 7.23 contains the residual versus predicted plot. Figure 7.23 shows the transformation of the data helped to increase homogeneity of residual variance and normality.

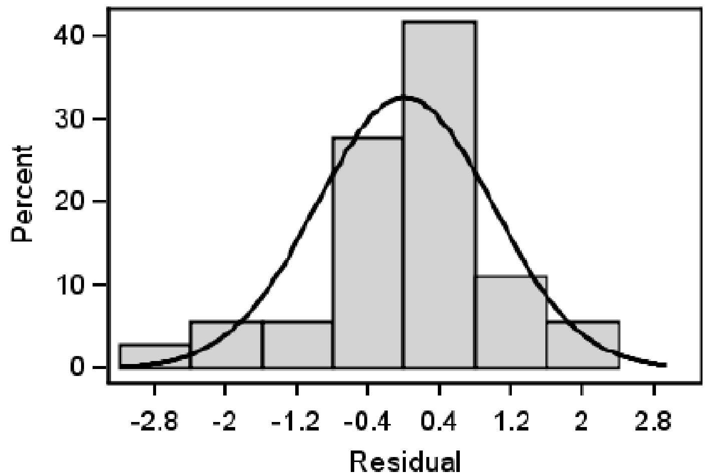


Figure 7.22 Histogram of Residuals (RTFO Blend Sqrt)

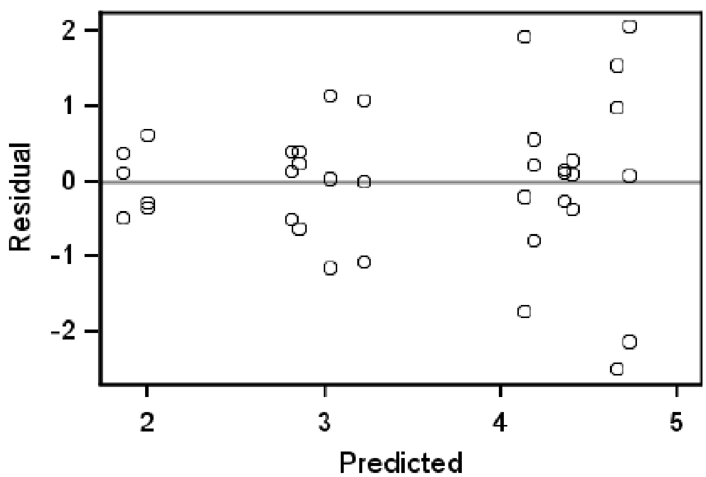


Figure 7.23 Residuals Versus Predicted Values (RTFO Blend Sqrt)

7.3.5 Virgin Binder PAV Aged Statistical Analysis

Initial analysis of the data showed trends in the residual plot, so the data was transformed by taking the square root of the data. All of the following analysis will consider data transformed in this manner. Table 7.29 below contains the statistical results for the Type 3 test of Hypothesis associated to the linear model fitted to data from the PAV aged virgin binders. As the table shows, all effects except the binder by method interaction are significant ($P<0.05$) at level of $\alpha = 0.05$, which means that the null hypothesis can be rejected. Similar to the original and RTFO binder data, a significant binder effect means that at least one of the true means of PG 52, PG 58 and PG 64 is not similar to any other. This can be expected since each of the binders has a different grade based on its rheological results. For the method effect, this means that the true mean of HMA is not the same as the true mean of the WMA, therefore, the use of Sasobit® does have a significant effect on the $G^*\sin\delta$ for the PAV aged virgin data. For the binder by method interaction, this means that at least one true mean of the binder method combinations is not similar, which is expected since there is a difference between binders as well as the method. For the temperature effect, which is nested within the binder, this means that at least one true mean at 52^{o}C, 58^{o}C or 64^{o}C is not similar to the others at each binder. Again, this can be expected, since asphalt binder is a temperature dependent material, so the properties are going to change, maybe significantly, with a change in temperature. For the temperature by method interaction, this means that at least one true mean at the temperature, method combination is not equal, which again can be expected since the rheological properties will change according to temperature.

Table 7.29 Virgin PAV Statistical Analysis

Effect	Num DF	Den DF	F-value	p-value
Binder	2	12.1	266.86	<.0001
Method	1	12.1	7.16	0.0201
Binder*method	2	12.1	0.47	0.6353
Temp(binder)	6	24	15.98	<.0001
Temp*method(binder)	6	24	2013.03	<.0001

Predicted mean values (Least Squares Means) were estimated using least squares which minimizes the sum of the squared residuals (residual= observed-fitted). Table 7.22 below shows the set of least squares means (Estimate column) with associated Standard error.

Omitted is information referring to testing of the null hypothesis, $H_o : \widehat{Y_i} = 0$, which is testing whether this particular least squares mean is equal to zero.

Table 7.30 Least Squares Means Virgin PAV Binder

Effect	binder	method	temp	Estimate	Standard Error
Binder	52			1251.07	38.4178
Binder	58			1638.95	38.4178
Binder	64			2478.81	38.4178
Method		HMA		1730.24	31.3680
Method		WMA		1848.98	31.3680
Binder*method	52	HMA		1170.13	54.3310
Binder*method	52	WMA		1332.00	54.3310
Binder*method	58	HMA		1571.75	54.3310
Binder*method	58	WMA		1706.16	54.3310
Binder*method	64	HMA		2448.84	54.3310
Binder*method	64	WMA		2508.78	54.3310
Temp(binder)	52		19	1282.46	38.8205
Temp(binder)	52		22	1233.60	38.8205
Temp(binder)	52		25	1237.15	38.8205
Temp(binder)	58		19	1647.60	38.8205
Temp(binder)	58		22	1622.29	38.8205
Temp(binder)	58		25	1646.98	38.8205
Temp(binder)	64		19	2466.09	38.8205
Temp(binder)	64		22	2457.60	38.8205
Temp(binder)	64		25	2512.76	38.8205
Temp*method(binder)	52	HMA	19	907.16	54.9005
Temp*method(binder)	52	WMA	19	1657.76	54.9005
Temp*method(binder)	52	HMA	22	1153.66	54.9005
Temp*method(binder)	52	WMA	22	1313.54	54.9005
Temp*method(binder)	52	HMA	25	1449.59	54.9005
Temp*method(binder)	52	WMA	25	1024.71	54.9005
Temp*method(binder)	58	HMA	19	1244.98	54.9005
Temp*method(binder)	58	WMA	19	2050.22	54.9005
Temp*method(binder)	58	HMA	22	1547.01	54.9005
Temp*method(binder)	58	WMA	22	1697.57	54.9005
Temp*method(binder)	58	HMA	25	1923.26	54.9005
Temp*method(binder)	58	WMA	25	1370.70	54.9005
Temp*method(binder)	64	HMA	19	1973.53	54.9005
Temp*method(binder)	64	WMA	19	2958.64	54.9005
Temp*method(binder)	64	HMA	22	2417.39	54.9005
Temp*method(binder)	64	WMA	22	2497.80	54.9005
Temp*method(binder)	64	HMA	25	2955.60	54.9005
Temp*method(binder)	64	WMA	25	2069.92	54.9005

In order to check whether the linear model fits the data well, the model assumptions should be checked and to determine if there are any outliers. The model assumptions are that the errors are independent and identically distributed with a mean of zero and a variance of σ_e^2. In order to determine if the y_i's are approximately normal, then the residuals ($\left(y_{ijkl} - \hat{y}_{ijk}\right)$ should be approximately normal. To check this, a histogram of the residuals was plotted. The plot should be bell-shaped and centered about zero. Figure 7.24 shows this plot and that is it roughly bell-shaped and centered about zero. To determine if there are any outliers, check if any observations have a Studentized residual with a magnitude of ± 3.5. Figure 7.25 contains the residual versus predicted plot. Figure 7.25 shows the transformation of the data helped to increase homogeneity of residual variance and normality.

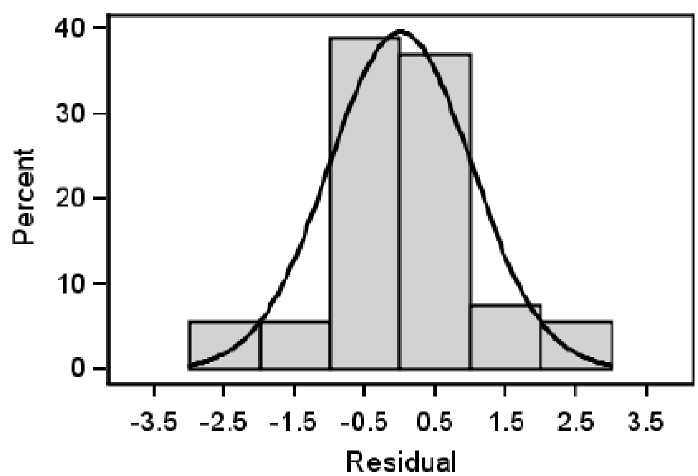


Figure 7.24 Histogram of Residuals (PAV Virgin Sqrt)

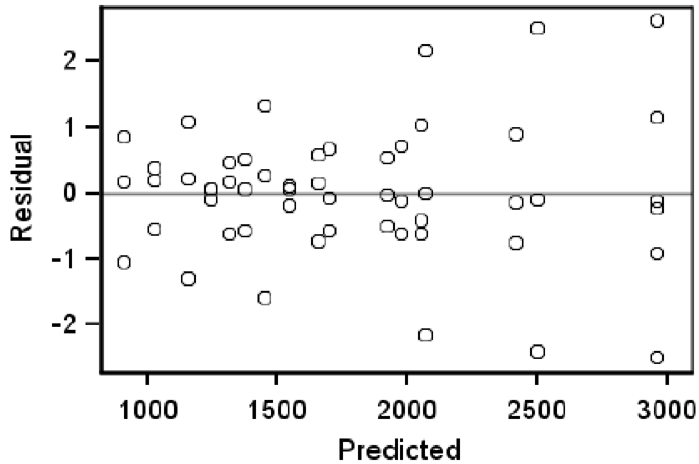


Figure 7.25 Residuals Versus Predicted Values (PAV Virgin Sqrt)

7.3.6 Blended Binder PAV Aged Statistical Analysis

Initial analysis of the data showed trends in the residual plot, so the data was transformed by taking the square root of the data. All of the following analysis will consider data transformed in this manner. Table 7.31 below contains the statistical results for the Type 3 test of Hypothesis associated to the linear model fitted to data from the PAV aged blended binders. As the table shows, the binder effect, binder by method interaction and the temperature effect are significant ($P<0.05$) at level of $\alpha = 0.05$, which means that the null hypothesis can be rejected. However, the method effect and the temperature by method interaction are not significant. Similar to the original and RTFO binder data, a significant binder effect means that at least one of the true means of PG 52, PG 58 and PG 64 is not similar to any other. This can be expected since each of the binders has a different grade based on its rheological results. For the method effect, this means that the true mean of HMA is not statistically different as the true mean of the WMA, therefore, the use of Sasobit® does not have a significant effect on the $G^*\sin\delta$ for the blended PAV data. For the binder by method interaction, this means that at least one true mean oh the binder method combinations is not similar, which is expected since there is a difference between binders as well as the method. For the temperature effect, which is nested within the binder, this means that at least one true mean at 52^{o}C, 58^{o}C or 64^{o}C is not similar to the others at each binder. Again, this can be expected, since asphalt binder is a temperature dependent material, so the properties are going to change, maybe significantly, with a change in temperature. For the temperature by method interaction, this means that there is not a statistically significant difference between any of the temperature method interactions.

Table 7.31 PAV Blended Statistical Analysis

Effect	Num DF	Den DF	F-value	p-value
Binder	2	12	69.24	<.0001
Method	1	12	2.77	0.1220
Binder*method	2	12	14.63	0.0006
Temp(binder)	6	23.6	253.46	<.0001
Temp*method(binder)	6	23.6	0.83	0.5575

Predicted mean values (Least Squares Means) were estimated using least squares which minimizes the sum of the squared residuals (residual= observed-fitted). Table 7.22 below shows the set of least squares means (Estimate column) with associated Standard error. Omitted is information referring to testing of the null hypothesis, $H_o : \widehat{Y_i} = 0$, which is testing whether this particular least squares mean is equal to zero.

Table 7.32 Least Squares Means PAV Blended Binder

Effect	binder	method	temp	Estimate	Standard Error
Binder	52			2016.19	43.9858
Binder	58			2011.62	43.9858
Binder	64			2647.85	43.9858
Method		HMA		2267.49	35.9143
Method		WMA		2182.95	35.9143
Binder*method	52	HMA		2232.47	62.2053
Binder*method	52	WMA		1799.92	62.2053
Binder*method	58	HMA		2041.73	62.2053
Binder*method	58	WMA		1981.51	62.2053
Binder*method	64	HMA		2528.29	62.2053
Binder*method	64	WMA		2767.41	62.2053
Temp(binder)	52		19	2410.22	47.0328
Temp(binder)	52		22	2002.10	47.0328
Temp(binder)	52		25	1636.26	47.0328
Temp(binder)	58		19	2396.69	47.0328
Temp(binder)	58		22	2000.44	47.0328
Temp(binder)	58		25	1637.73	47.0328
Temp(binder)	64		19	3053.28	47.0328
Temp(binder)	64		22	2650.74	47.0328
Temp(binder)	64		25	2239.53	47.0328
Temp*method(binder)	52	HMA	19	2646.49	66.5144
Temp*method(binder)	52	WMA	19	2173.94	66.5144
Temp*method(binder)	52	HMA	22	2215.82	66.5144
Temp*method(binder)	52	WMA	22	1788.08	66.5144
Temp*method(binder)	52	HMA	25	1835.08	66.5144
Temp*method(binder)	52	WMA	25	1437.44	66.5144
Temp*method(binder)	58	HMA	19	2445.38	66.5144
Temp*method(binder)	58	WMA	19	2348.00	66.5144
Temp*method(binder)	58	HMA	22	2020.52	66.5144
Temp*method(binder)	58	WMA	22	1980.36	66.5144
Temp*method(binder)	58	HMA	25	1659.29	66.5144
Temp*method(binder)	58	WMA	25	1616.18	66.5144
Temp*method(binder)	64	HMA	19	2953.34	66.5144
Temp*method(binder)	64	WMA	19	3153.23	66.5144
Temp*method(binder)	64	HMA	22	2513.15	66.5144
Temp*method(binder)	64	WMA	22	2788.33	66.5144
Temp*method(binder)	64	HMA	25	2118.38	66.5144
Temp*method(binder)	64	WMA	25	2360.68	66.5144

In order to check whether the linear model fits the data well, the model assumptions should be checked and to determine if there are any outliers. The model assumptions are that the errors are independent and identically distributed with a mean of zero and a variance of σ_e^2. In order to determine if the y_i's are approximately normal, then the residuals ($\left(y_{ijkl} - \hat{y}_{ijk}\right)$ should be approximately normal. To check this, a histogram of the residuals was plotted. The plot should be bell-shaped and centered about zero. Figure 7.26 shows this plot and that is it roughly bell-shaped and centered about zero. To determine if there are any outliers, check if any observations have a Studentized residual with a magnitude of ± 3.5. Figure 7.27 contains the residual versus predicted plot. Figure 7.27 shows the transformation of the data helped to increase homogeneity of residual variance and normality.

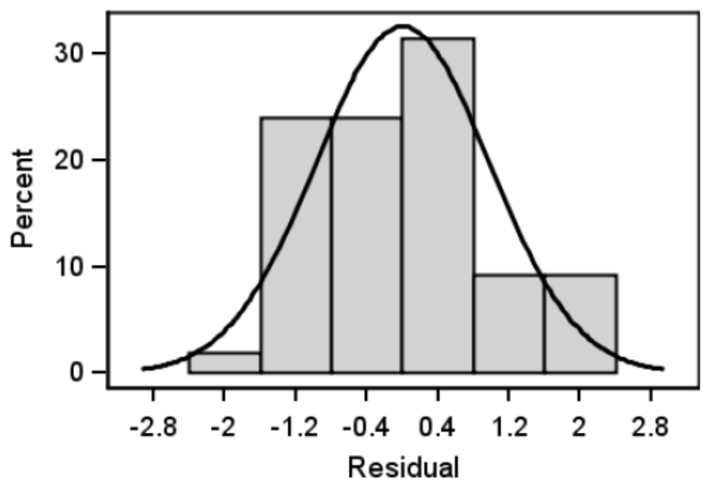


Figure 7.26 Histogram of Residuals (PAV Blend Sqrt)

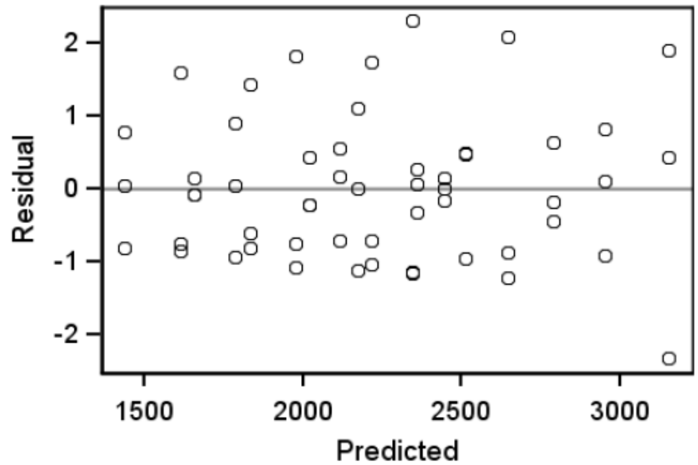


Figure 7.27 Residuals Versus Predicted Values (PAV Blend Sqrt)

7.4 WMA Binder Rheology Conclusions

This chapter used DSR and BBR testing performed on virgin, blended and RAP binders containing Sasobit® in order to determine how the use of WMA additives effect the binder rheology. Statistical analysis was then used to determine whether these effects were significant. Based on the analysis, the following results have been concluded:

- There is only a minimum percentage of RAP when using a virgin binder grade of PG 52-28 in order to meet the specifications for the high temperature grades of 58^{o} and 64^{o} for high temperature DSR testing.
- Mixture using PG 52-28 virgin binder, blended with Westgate RAP, in order to meet the specification for the high temperature grade of PG 64 and unaged binder, there needs to be a minimum of 24.2 % RAP in the blend to meet the specification of G*/sinδ= 1.0.
- In order to meet the specification of G*/sinδ= 2.2 for RTFO aged binder, there needs to be a minimum of 19.9% RAP for a high temperature grade of PG 64 for mixtures using PG 52-28.
- Mixtures are able to satisfy the stiffness specification with 54.8-75.3% RAP.
- The controlling variable for thermal cracking from the BBR test is the m-value. Mixtures with PG 64-22 binder are able to contain 18.5% RAP. Mixtures with PG 58-

22 binder are able to contain 44.9% RAP. Mixtures with PG 52-28 binder are able to contain 59.3% RAP.

- Combining all rheological results, using virgin PG 64-22 binder, the maximum amount of RAP is 15.5%. Using PG 58-22 binder, the maximum amount of RAP is 44.9%. Using PG 52-28 binder, the maximum amount of RAP is 58.1%.
- The addition of Sasobit® to original virgin binders increases the G*/sinδ for all binders at all temperatures ranging from 5.45% for PG 52 binder at 64^{o}C to 42.18% for PG 64 binder at 64^{o}C. However, the addition of Sasobit® to the binder extracted from the Westgate RAP caused a decrease in G*/sinδ by about 35% compared to HMA binders.
- The blend containing PG 52 binder G*/sinδ reduces between 32.3-37.4%. The blends containing PG 58 and PG 64 binders, G*/sinδ increases, but the increase is not as much as was seen with the virgin binders.
- The addition of Sasobit® to RTFO aged virgin binders increases average G*/sinδ for all binders at all temperatures, ranging from 12.78% for PG 52 at 64^{o}C to 37.87% for PG 52 at 52^{o}C. The RTFO aged binder extracted from the Westgate RAP average G*/sinδ increases between 5.52%-15.77%. The average G*/sinδ for the PG 52 and PG 58 blended binders decrease between 10.8% for PG 52 at 52^{o}C to 23.8% for PG 58 at 64^{o}C.
- The addition of Sasobit® to PAV aged virgin binders causes an increase in average G*sinδ for most cases, except at 25^{o}C for all the binders.
- The addition of Sasobit® to PAV aged blended binders causes an increase in average G*sinδ for PG 64 blended binders and binders extracted from the RAP but a decrease in average G*sinδ for PG 52 and PG 58 blended binders. Looking at the critical temperature of 25^{o}C, the G*sinδ increases 9.45% and 24.1% for the Westgate and PG 64 blend binders, respectively, and decreases 38.74% and 4.68% for the PG 52 and PG 58 blended binders, respectively.
- The addition of Sasobit® to PAV aged binders causes a decrease in m-values of 5.5, 11.7 and 9.3% for virgin PG 52, PG 58 and PG 64 binders, respectively. It also shows

that the addition of Sasobit® causes a decrease in m-value of 8.4, 6.4 and 14.2% for blended PG 58 and PG 64 binders and the binder extracted from the Westgate RAP, respectively, while it causes a slight increase of 0.3% for PG 52 blended binders.

- The addition of Sasobit® causes an increase in creep stiffness of 7.6, 26.4 and 16.7% for virgin PG 52, PG 58 and PG 64 binders, respectively. It also shows that the addition of Sasobit® causes an increase in creep stiffness of 16.1, 48.7 and 50.6% for blended PG 58 and PG 64 binders and the binder extracted from the Westgate RAP, respectively, while it causes a slight decrease of 8.57% for PG 52 blended binders.
- Statistical analysis showed that the addition of Sasobit® had a significant effect on the mean compared to HMA binders for all aged binders (original, RTFO, PAV) and RAP content (virgin, blended) except for PAV aged blended binders.
- Based on rheological testing, the addition of Sasobit® improves the rutting resistance, while it may slightly decrease the fatigue cracking resistance on some binders (PG 58-22 and PG 64-22) and decrease the thermal cracking resistance.

Chapter 8
Summary of Results and Conclusions

The recycling of asphalt pavements has become a very routine procedure throughout the country. With the increasing cost of asphalt binder and the growing concern over the availability of quality aggregates, the use of higher percentages of reclaimed asphalt pavements (RAP) has become of much interest across the country. Research has shown that the RAP recovered from construction sites still contains usable materials, both in the recycled aggregates and recycled binder. However, since the RAP binder has been aged during its service life, the use of RAP in new pavement construction may cause the stiffness of the blended binder to increase. Due to this increased stiffness, it is sometimes necessary for a "grade shift" in the virgin binder in order to result in the specifications for the desired performance grade. These specification limits make it cost prohibitive for contractors to use higher RAP contents in their mixes. This practice has led to vast quantities of RAP going unused and stockpiled. Research was needed to show that RAP materials can be used successfully in higher percentages.

The development of warm mix asphalt (WMA) technology over the recent past has sparked interest in many researchers, engineers and government officials. The use of WMA has incentives including fuel savings, lower emissions, longer hauling distances and longer construction seasons since the use of WMA allows for lower production temperatures. Research has also shown that the reduced production temperatures may reduce the amount of oxidative hardening which may help reduce thermal cracking and block cracking. Due to this benefit, along with the anticipated benefit of better compactability using WMA, it is thought that WMA can be used in mixes containing higher percentages of RAP since less oxidative hardening of the asphalt binder may occur for the already more stiff RAP binder. Mixtures with higher percentages of RAP often have issues with thermal cracking and block cracking due to the stiff binder from the RAP blending with the virgin binder.

In order to investigate the effects of RAP in the design and performance of new asphalt concrete mixtures, the specific research objectives were:

- Evaluate the performance of mix designs using higher RAP percentages
- Determine which layers of the pavement structure could contain higher percentage of RAP without any significant reduction in performance life
- Perform a life cycle cost analysis showing the cost savings that could be realized if higher percentages of RAP are allowed.
- Determine how the addition of Sasobit® affects the binder rheology of mixtures containing RAP.

The research found the following conclusions:

8.1 Binder Rheology Conclusions:

- The addition of 30% RAP increases the stiffness of the binder grade. To determine the high temperature grade for unaged binders, determine the highest temperature that $G^*/\sin\delta \geq 1.0$ kPa. PG 52 binders become PG 64, PG 58 binders become PG 70 and PG 64 binders become PG76. This shows that the addition of 30% RAP increases the original binder by two grades.
- To determine the high temperature grade for RTFO aged binders, determine the highest temperature that $G^*/\sin\delta \geq 2.2$ kPa. The PG 52 Pineville blended binder becomes PG 58, the PG 52 Westgate blended binder becomes PG 64, the PG 58 Pineville blended binder becomes PG 70, the PG 58 Westgate blended binder becomes PG 76 and the PG 64 binders become PG76. This shows that the addition of 30% RAP increases the original binder by at least two grades, with the exception of the PG 52 Pineville binder blend.
- The performance grade of the binder can be determined by selecting the temperature that satisfies the $G^*\sin\delta \leq 5000$ kPa requirement for PAV aged binders. The PG 52 Westgate blend and PG 58 binders satisfy the requirement at 22^{o}C while the PG 52 Pineville blend and PG 64 binders satisfy the requirement at 25^{o}C. The PG 58 and PG 64 binders passing at these temperatures translate to a low binder grade of -22, the same as the virgin binder. However, the PG 52 Pineville blend and PG 52 Westgate

blend pass at temperatures that translate to a lower binder grade of -10 and -16, respectively.

- The addition of 30% RAP to the PG 52-28 virgin binder resulted in an increase in creep stiffness of 95.9% and 90.3% for Westgate and Pineville blends, respectively. The addition of 30% RAP to the PG 58-22 virgin binder resulted in an increase in creep stiffness of 53.7% and 59.9% for Westgate and Pineville blends, respectively. The addition of 30% RAP to the PG 64-22 virgin binder actually resulted in a decrease in creep stiffness of 7.3% and 0.3% for Westgate and Pineville blends, respectively. This result is not expected.
- As the virgin binder grade in the blend increases from PG 52-28 to PG 64-22, the increase in creep stiffness becomes less. This is expected since as the virgin binder creep stiffness increases with increasing binder grade, the higher creep stiffness from the reclaimed RAP binder has less of an effect on the binder blend.
- The addition of 30% RAP to the PG 52-28 virgin binder resulted in a decrease in m-value of 21.4% and 20.3% for Westgate and Pineville blends, respectively. The addition of 30% RAP to the PG 58-22 virgin binder resulted in a decrease in m-value of 11.5% and 10.0% for Westgate and Pineville blends, respectively. The addition of 30% RAP to the PG 64-22 virgin binder resulted in a decrease in m-value of 10.5% and 9.0% for Westgate and Pineville blends, respectively. This reduction in m-value is expected since the binder reclaimed from the RAP is stiffer thus likely to need more time to recover, which is what the m-value signifies.
- Mixtures are able to satisfy the creep stiffness specification with 91%-100% RAP. However, the controlling variable for thermal cracking from the BBR test is the m-value. Mixtures with PG 64-22 binder are able to contain 41%-50% RAP. Mixtures with PG 58-22 binder are able to contain 64%-69% RAP. Mixtures with PG 52-28 binder are able to contain 67%-71% RAP.
- Using virgin PG 64-22 binder, the maximum amount of RAP is 24%-27%. Using PG 58-22 binder, the maximum amount of RAP is 52-53%. Using PG 52-28 binder, the maximum amount of RAP is 55-57%.

8.2 Mixture Characterization Conclusions

- The results from the FSTCH indicate trends of increasing complex modulus with increasing frequency. Also, as the binder grade increases, from PG 52-28 to PG 64-22, the complex modulus increases. This would be expected as the complex modulus of PG 64-22 binder is larger than the complex modulus of PG 52-28 binder when temperature is constant.
- The complex modulus of mixtures with higher percentages of RAP increases while holding the binder grade constant. Again, this can be expected since the complex modulus of the RAP binder is greater due to its aging caused during its service life.
- After 5000 cycles of repeated shear, the mixtures containing PG 64-22 binder exhibited the least amount of strain for both virgin 9.5mm mixtures and 19.0 mm mixtures. Mixtures with PG 58-22 binder exhibited less strain than the mixtures with PG 52-28 binder. This can be expected as mixtures with stiffer binders exhibited less strain.
- Comparing mixtures with various percentages of RAP with constant binder grade shows general trends that the strain decreases with increasing RAP. Again, this can be expected as the binder recovered from the RAP was stiffer than the virgin binders due to its aging during its service life. Therefore, mixtures with higher percentages of RAP are going to generally exhibit less strain as a result.
- For 9.5 mm mixtures containing Westgate RAP compared to virgin mixtures, the amount of plastic shear strain reduces for all PG 64-22 mixtures containing RAP varying from 7% to 45% reduction. The PG 58-22 mixtures containing 15% and 30% RAP result in the plastic shear strain increases of 28% and 21%, respectively. This increase is caused by the reduction in binder stiffness of the PG 58-22 binder from the original PG 64-22 virgin binder. However, this reduction in virgin binder stiffness is overcome when 40% RAP is included in the mix and the plastic shear strain reduces 6% from the virgin mixture. With the reduction of two binder grades from the original virgin binder to a PG 52-28 binder, the plastic shear strain increases 100%, 42% and 33% for mixtures containing 15%, 30% and 40% RAP, respectively.

- For 9.5 mm mixtures containing Pineville RAP compared to virgin mixtures, the amount of plastic shear strain reduces for all PG 64-22 mixtures containing RAP varying from 22% to 64% reduction. The PG 58-22 mixtures containing 15% and 30% RAP result in the plastic shear strain increases 53% and 12%, respectively. This increase is caused by the reduction in binder stiffness of the PG 58-22 binder from the original PG 64-22 virgin binder. However, this reduction in virgin binder stiffness is overcome when 40% RAP is included in the mix and the plastic shear strain reduces 24% from the virgin mixture. With the reduction of two binder grades from the original virgin binder to a PG 52-28 binder, the plastic shear strain increases 126%, 55% and 46% for mixtures containing 15%, 30% and 40% RAP, respectively.
- For 19.0 mm mixtures containing Westgate RAP compared to virgin mixtures, the amount of plastic shear strain reduces for all PG 64-22 mixtures containing RAP varying from 27% to 35% reduction. The PG 58-22 mixtures containing 15% RAP result in the plastic shear strain increase of 8%. This increase is caused by the reduction in binder stiffness of the PG 58-22 binder from the original PG 64-22 virgin binder. However, this reduction in binder stiffness is overcome when 30% and 40% RAP is included in the mix and the plastic shear strain reduces 15% and 19%, respectively, from the virgin mixture. With the reduction of two binder grades from the original virgin binder to a PG 52-28 binder, the plastic shear strain increases 23%, 14% and 13% for mixtures containing 15%, 30% and 40% RAP, respectively.
- For 19.0 mm mixtures containing Pineville RAP compared to virgin mixtures, the amount of plastic shear strain reduces for all PG 64-22 mixtures containing RAP varying from 10% to 38% reduction. With a reduction of one binder grade from the original virgin binder to a PG 58-22 binder, the plastic shear strain increases 37%, 27%, and 19% for mixtures containing 15%, 30%, and 40% RAP, respectively. With the reduction of two binder grades from the original virgin binder to a PG 52-28 binder, the plastic shear strain increases 56%, 39% and 34% for mixtures containing 15%, 30% and 40% RAP, respectively.

8.3 Pavement Performance Conclusions

- The pavement performance analysis for fatigue life and rutting showed that fatigue cracking was the limiting distress for the pavement service life as the rut life is able to handle many more loading repetitions. The Asphalt Institute (AI) fatigue life analysis was more conservative and appropriate for the analysis. As a result, the estimated initial service life of the pavement systems were based on the AI fatigue life calculations. The service life varies from 8.5 years to 16.2 years depending on the materials of the mixture.
- The general trend is that as the percentage RAP increases in the mixtures, the fatigue life increases, all else being constant.
- All else being held constant, as the binder grade is reduced from PG 64-22 to PG 52-28, the fatigue life is reduced.

8.4 Economic Analysis Conclusions

- Comparing the cost per ton of the mixtures containing RAP to the cost per ton of virgin mixtures, both the surface and base course show roughly a 26-28%% and 35-37% reduction in cost per ton for 30% and 40% RAP, respectively.
- By comparing the material cost per mile of the virgin mixtures to the mixtures containing various percentages of RAP shows that the inclusion of 30% RAP reduces the cost about 27% and the inclusion of 40% RAP reduces the cost about 36%.

8.5 WMA General Conclusions

- There is only a minimum percentage of RAP required when using a virgin binder grade of PG 52-28 in order to meet the specifications for the high temperature grades of 58^o and 64^o for high temperature DSR testing.
- Mixtures using PG 52-28 virgin binder, blended with Westgate RAP, in order to meet the specification for the high temperature grade of PG 64 and unaged binder, there needs to be a minimum of 24.2 % RAP in the blend to meet the specification of $G^*/\sin\delta = 1.0$.

- In order to meet the specification of G*/sinδ= 2.2 for RTFO aged binder, there needs to be a minimum of 19.9% RAP for a high temperature grade of PG 64 for mixtures using PG 52-28.
- Mixtures are able to satisfy the stiffness specification with 54.8-75.3% RAP.
- The controlling variable for thermal cracking from the BBR test is the m-value. Mixtures with PG 64-22 binder are able to contain 18.5% RAP. Mixtures with PG 58-22 binder are able to contain 44.9% RAP. Mixtures with PG 52-28 binder are able to contain 59.3% RAP.
- Combining all rheological results, using virgin PG 64-22 binder, the maximum amount of RAP is 15.5%. Using PG 58-22 binder, the maximum amount of RAP is 44.9%. Using PG 52-28 binder, the maximum amount of RAP is 58.1%.
- Statistical analysis showed that the addition of Sasobit® had a significant effect on the mean compared to HMA binders for all aged binders (original, RTFO, PAV) and RAP content (virgin, blended) except for PAV aged blended binders.

8.6 Major Conclusions

- The general trend is that as the percentage RAP increases in the mixtures, the fatigue life and rut life increase, all else being constant.
- Since the binder rheological properties are the limiting variable in the amount of RAP allowable in mixtures, there is no difference between which pavement layer could contain more RAP.
- Mixtures containing PG 64-22 binder and 30% RAP have a present worth 18.2-18.9% less than the virgin mixture. Mixtures containing PG 58-22 binder and 40% RAP have a present worth 34.1-36.0% less than the virgin mixture. Mixtures containing PG 52-28 binder and 40% RAP have a present worth 30.5-31.1% less than the virgin mixture.
- The use of mixtures containing one binder grade lower (PG 58-22) than the original virgin binder grade (PG 64-22) and 40% RAP provides the most economical pavement.

- Based on rheological testing, the addition of Sasobit® improves the rutting resistance, while it may slightly decrease the fatigue cracking resistance on some binders (PG 58-22 and PG 64-22) and decrease the thermal cracking resistance.

8.7 Recommendations For Future Research

The following future research is recommended:

- Investigation of how the use of WMA technology affects the amount of RAP allowable in the mixture. Determine how the decreased mixing temperatures affect the blending of the RAP binder with the virgin binder. Determine the performance of mixtures based on the rheological results discussed above. Consider using other additives besides Sasobit®.
- Investigation of rejuvenators to add to mixtures to increase the amount of allowable RAP. The limiting factor to the amount of RAP allowable in mixtures is the specification for $G^*\sin\delta \leq 5000$ kPa. Determine if there is a rejuvenator that can reduce the $G^*\sin\delta$ value of the blends containing RAP so that more RAP can be used.

Chapter 9
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APPENDIX

Appendix A.1

SAS code for statistical analysis

```
data ao52;
   do type="Original"  ; *"RTFO", "PAV";
         do binder= "52";*, "58", "64";
            do temp = 52, 58, 64;
    do specimen =1 ,2,3 ;
                do method ="HMA", "WMA";
                   input response @@;
output;
end;
end;
end;
end;
end;
datalines;
 1.563 2.29
 1.576  2.01
 1.589 2.16
  0.703  1.03
  0.8744 0.88
  0.717  0.97
  0.4327  0.47
  0.422  0.40
   0.3825  0.44
 ;
 proc print data=ao52;
 run;
data ao58;
   do type="Original"  ; *"RTFO", "PAV";
         do binder= "58";*, "58", "64";
            do temp = 58, 64;
    do specimen =1 ,2,3 ;
                do method ="HMA", "WMA";
                   input response @@;
output;
```

```
end;
end;
end;
end;
end;
datalines;
  1.75  1.92
  1.51  2.28
  1.59  2.20
  0.81  0.91
  0.73  1.08
  0.82  1.02
 ;
 proc print data=ao58;
 run;
data ao64;
   do type="Original"  ; *"RTFO", "PAV";
          do binder= "64";*, "58", "64";
             do temp = 64;
    do specimen =1 ,2,3 ;
                  do method ="HMA", "WMA";
                     input response @@;
output;
end;
end;
end;
end;
end;
datalines;
  1.43985  2.38
 1.81  2.13
  1.614  2.40
;
 data all;
  set ao52 ao58 ao64;
  sqrt_response=sqrt(response);
```

```
  run;
  proc sort data= all;
    by binder method specimen temp;
run;
ods listing close;
ods pdf style=journal file ="BinderA_MIXED_NOSPPOW_SQRT_Response.pdf";
ods graphics on;
title "data";
 proc print data=all;
 run;
data all2;
  set all;
  * if binder =  and  temp =  and method= and  specimen= then response =.; *** uniquely identify the
point "outlier";
  sqrt_response=sqrt(response);
  run;
 title "Mixed model fitting Sqrt(Response)";
proc mixed data= all2 plots(only) = StudentPanel;
 class binder temp method specimen;
 model  sqrt_response= binder| method  temp(binder) method*temp(binder)/outp=outmx4 residual
ddfm=kr;
 random specimen(method*binder);
repeated temp/sub=specimen(method*binder)  type= sp(pow)(temp)  ;
 lsmeans binder method  /diff cl;
 lsmeans method*binder /diff slice=(method binder) cl;
 lsmeans  temp(binder)  /diff slice=(  binder) cl;
 lsmeans method*temp(binder)/diff slice=method*binder cl;
 ods exclude diffs;
 ods output lsmeans = lsmnds diffs=diffds;
 run;
 title "Outiers - extreme values - ";
 proc print data= outmx4;
   where  abs(StudentResid) gt 3.5;
   run;
 title "means differences - Binder";
 proc print data= diffds;
```

```
  where effect ="binder";
  run;
 title "means differences - Method";
 proc print data= diffds;
  where effect ="method";
  run;
  proc sort data=lsmnds;
    by binder method;
 run;
title "Binder*method interaction lsmeans";
 proc gchart data=lsmnds;
  where effect ="binder*method"  ;
  vbar method/ group=binder sumvar=estimate type=mean discrete;
  run;
symbol i=join v=star c=red;
symbol2 i=join v=star c=blue;
symbol3 i=join v=star c=green;
title "binder*method lsmeans";
 proc gplot data=lsmnds;
  where effect ="binder*method"  ;
  plot estimate*method=binder;run;
***;
 title "means differences - Binder*Method";
 proc print data= diffds;
  where effect ="binder*method" and binder=_binder;
  run;
 title "means differences - Binder*Method";
 proc print data= diffds;
  where effect ="binder*method"  and method=_method;
  run;
 title "means differences - TEMP(Binder)";
 proc print data= diffds;
  where effect ="temp(binder)" and binder=_binder;
  run;

  proc sort data=lsmnds;
```

```
    by binder method;
 run;

symbol i=join v=star c=red;
symbol2 i=join v=star c=blue;
symbol3 i=join v=star c=green;
title "temp*method(binder) lsmeans";
 proc gplot data=lsmnds;  by binder;
   where effect = "temp*method(binder)";
   plot estimate*method=temp;run;
***;

 title "means differences - TEMP*METHOD(Binder)";
 proc print data= diffds;
   where effect ="temp*method(binder)"  and binder=_binder and method=_method;
   run;
symbol i=none v=star c=red;
symbol2 i=none v=star c=blue;
symbol3 i=none v=star c=green;
title "residual checking";
 proc gplot data=outmx4;
   plot StudentResid*pred=method;
   plot StudentResid*pred=binder;
   plot StudentResid*pred=temp;
   run;
****;
   quit;
  ods graphics off;
  ods pdf close;
  ods listing;
```