RESEARCH & DEVELOPMENT

CHARACTERIZATION OF DIFFERENT RAP SOURCES

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by

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Recycling of asphalt pavements is crucial to alleviating the growing demand for paving materials including both asphalt binder and aggregates. For this reason many states have adopted specifications for the use of reclaimed asphalt pavement (RAP) in hot mix asphalt (HMA). These specifications, however, are based on the percentage weight of RAP in the total mix. Because, RAP binder is usually much stiffer than virgin binders and contributes largely to the increased stiffness of the recycled mixture placing emphasis on the recycled binder content would be a more efficient way to optimize use of RAP. The state of North Carolina studied recycled materials with the objective of placing limits on percentage of binder contributed by RAP, instead of percentage by weight of mix replaced. As part of the research, one RAP material was selected and tested with different virgin binders and limits were derived. Since, recycled binders from different RAP sources exhibit different properties, the limits determined for binder from a single RAP source are not directly applicable to all RAP sources.

This research aimed to evaluate the effect of variability in the RAP binders on the recycled binder limits by examining extensively the rheological properties of recycled binders from different RAP sources. RAP stockpiles from different geographical regions were selected and the recycled binder extracted from RAP was characterized using the Dynamic Shear Rheometer and binder limits determined to identify differences among the stockpiles. Statistical inferences were derived from the rheological properties of the different RAP binders and the binder limits obtained for different stockpiles were used to develop draft specifications to select the optimum amount of recycled materials based on the variability between and within stockpiles.</td></tr>
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EXECUTIVE SUMMARY

Recycling of asphalt pavements is crucial to alleviating the growing demand for paving materials including both asphalt binder and aggregates. For this reason many states have adopted specifications for the use of reclaimed asphalt pavement (RAP) in hot mix asphalt (HMA). These specifications, however, are based on the percentage weight of RAP in the total mix. Because, RAP binder is usually much stiffer than virgin binders and contributes largely to the increased stiffness of the recycled mixture placing emphasis on the recycled binder content would be a more efficient way to optimize use of RAP. North Carolina Department of Transportation (NCDOT) projects RP 2012-04 and RP 2013-06 studied recycled materials with the objective of placing limits on percentage of binder contributed by RAP, instead of percentage by weight of mix replaced. As part of the research, one RAP material was selected and tested with different virgin binders and limits were derived. Since, recycled binders from different RAP sources exhibit different properties, the limits determined for binder from a single RAP source are not directly applicable to all RAP sources.

By definition, RAP is the material that gets removed and processed from an existing deteriorated asphalt pavement during resurfacing, rehabilitation, or reconstruction operations. Different pavements age to various degrees during their service life depending on the factors that are responsible for aging: factors such as geographic location, service life, pavement structure, the virgin binder and the aggregates used to construct the initial pavement. Thus, it is safe to assume that RAP from different parts of the state of North Carolina age to varying degrees and would differ in their properties. Therefore, the need exists to investigate the

variability in the properties of recycled binder from different sources of RAP and design a framework for accounting for this variability while recommending a set of specifications for designing recycled mixtures.

The proposed research aimed to evaluate the effect of variability in the RAP binders on the recycled binder limits by examining extensively the rheological properties of recycled binders from different RAP sources. RAP stockpiles from different geographical regions were selected and the recycled binder extracted from RAP was characterized using the Dynamic Shear Rheometer and binder limits determined to identify differences among the stockpiles. As a result, a draft specification was developed to select the optimum amount of recycled material based on the RAP source binder properties.

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CHAPTER 1 : - INTRODUCTION AND PROBLEM STATEMENT

As the population and the economy of the United States continue to grow, there is a continuous rise in demand for better infrastructure. The system of highways and roads serves as a critical resource allowing people and goods to move from one place to another. The United States road network is over 4 million miles long and over 90% of the US highways and roads are constructed with hot mix asphalt (HMA). As these highways and roads age and deteriorate, there will be a need to maintain or rehabilitate these aged pavements. Currently, 32% of America's major roads are in poor or mediocre condition [9]. With the continuous rise in cost of materials and construction, there is a strong interest by both agencies and industry to mitigate cost by incorporating more recyclable materials in asphalt pavements.

The same materials used for construction of the original highway system can be re-used to repair, reconstruct and maintain them. Where appropriate, recycling of aggregates, binder and other highway construction materials makes sound economic, environmental and engineering sense [10]. Extensive studies have been conducted on how the material from aged asphalt pavements can be incorporated into newer constructions and how the long term performance of pavements is affected by its inclusion. With an increased demand in the need for better infrastructure owing to a continuous growth in population and economy with a limited supply of virgin materials, the state of North Carolina has increased the allowance for the use of recycled materials in asphalt pavements.

The research projects RP 2012-04 and RP 2013-06 conducted by NCDOT extensively studied the effects of RAP on S9.5B, S9.5C and S9.5D mixtures. Virgin binders PG 58-28, PG 64-22 and PG 70-22 were blended with RAP binder from a single source and limits were determined for the amount of RAP binder that could be blended with a virgin binder of a known PG grade such that the blended binder qualified for a required PG grade. Subsequently, performance tests and economic analyses were conducted on recycled asphalt mixtures of all the three kinds and; it was determined that the limiting factor in the amounts of recycled materials that could be incorporated into a HMA was the proportion of recycled binder by weight of total binder in the recycled mixtures.

By definition, RAP is the material that is removed and processed from an existing deteriorated asphalt pavement during resurfacing, rehabilitation or reconstruction operations. Different pavements age to various degrees during their service life depending on the factors that are responsible for aging: factors such as geographic location, service life, pavement structure, the virgin binder and the aggregates used to construct the initial pavement. Therefore, it is safe to assume that RAP from different parts of the state of North Carolina age to varying degrees and would differ in their properties. Based on this assumption, it can be stated that the limits obtained for recycled binder based on one single source of RAP would not be applicable directly to all other RAP sources. Therefore, the need exists to investigate the variability in the properties of recycled binder from different sources of RAP and design a framework for accounting for this variability while recommending a set of specifications for designing recycled mixtures.

This research seeks to evaluate the effect of variability in the RAP binders on the recycled binder limits. Extracted RAP binders from different RAP stockpiles across the state of North Carolina were studied for their rheological properties and the variability in these properties was evaluated. In addition to the variability from stockpile to stockpile, variability within a stockpile was also evaluated by taking multiple samples from different locations within the same stockpile to determine tolerances that can be applied to the binder limits.

CHAPTER 2 : - LITERATURE REVIEW

This chapter will discuss literature pertinent to the practices on using reclaimed asphalt pavement in new pavements. This will help in gaining a broader knowledge of the methods and the effects of higher levels of RAP in HMA mixtures. Additionally, it will also help in laying out guidelines for designing this research project with the anticipation to obtain best possible results from the available material and resources.

Researchers have worked on a number of projects aimed at studying asphalt pavements incorporating RAP. Different methodologies have been used to determine the limiting criteria for the amount of RAP that could be used in a HMA without being detrimental to the performance of the asphalt pavement. Although, there have been a number of studies that have focused on the effects of RAP in HMA on pavement performance, limited work has been done on studying the variability in RAP sampled from different geographical regions.

Research projects aimed at studying the effects of aging on asphalt binder characteristics have concluded that aging is a complex phenomenon that depends on a number of factors. Studies have found that there are different types of aging, distinguished by their mechanisms, which can be classified as physical and chemical [1]. Physical aging is a process that corresponds to increase in viscosity of the binder without a change in the chemical composition. Chemical aging on the other hand corresponds to oxidation, cyclization and aromatization reactions. This change leads to hardening of asphalt binder making it brittle. Aging rate has been found to be influenced by temperature, ultraviolet radiation and accessibility to oxygen. Accessibility to oxygen is governed by the layer thickness, type of asphalt used, percentage of voids and the kind of aggregates used [1]. The aforementioned factors leading to aging are highly dependent on the geographic location of the pavement and the design structure of the pavement. Therefore, it is plausible to question, whether, RAP from different geographic regions are different in their properties since they might have aged differently than the others.

RAP is obtained from a variety of sources. The most common of these sources is from milling of existing pavements. The other sources include a full-depth pavement demolition and wasted asphalt plant mix. The wasted asphalt plant mix is the material waste generated during the process of plant start-up, transition between mixes, and clean-out. This material has not been subjected to environmental aging from years of service and the asphalt binder in these cases will be softer than binder in other RAP sources [2]. Depending on the decision of how to handle RAP from different sources, stockpiles could differ in properties to varying degrees. Additionally, the variability would also depend on how RAP has been processed before accumulating in stockpiles and how it is handled for use in future pavements. Studies have focused on stockpile management practices that would help in containing the variability that can be worsened by poor practices [2]. The guidelines in these studies help the contractors to manage RAP stockpiles with the goal to improve performance of mixtures with RAP by improving quality control. A number of these studies have focused on minimizing the variability with regard to aggregate gradation and binder content in RAP and not much emphasis is laid on the RAP binder properties. This research, therefore, will focus mainly on the variability in RAP stockpiles with regard to the RAP binder properties.

A good amount of research has been conducted on the design of recycled mixtures and their performance. Researchers have studied the effects of RAP in HMA and their benefits both economically and functionally. Designing a recycled HMA mixture in laboratory, however, is very different from designing a mix for a large scale project. Higher degree of quality control can be achieved in a laboratory design as researchers need to work with a small sample of RAP. For a design to be accurately representative of a field mix, it has to be ensured that all the components - aggregates, binders and RAP are representative of the component materials in a field mix. Therefore, it is of great importance to study and document the properties of each of the component materials that would be used for a project. As has been discussed earlier, RAP can exhibit a high degree of variability compared to virgin aggregates and binders depending on: the source, how it was handled, and how it was processed. RAP, therefore, in many ways could be the determining factor for the quality and consistency of the HMA mixture produced incorporating RAP.

The National Cooperative Highway Research Program (NCHRP) provided recommendations for the use of recycled materials in asphalt concrete construction and guidelines for determination of RAP limits as part of the project NCHRP 9-12, “Incorporation of Reclaimed Asphalt Pavement in the Superpave System” [3]. This study strongly recommends the investigation of variability among different RAP stockpiles to place limits on the amount of RAP, which is the primary objective of this proposal. Guidelines on the use of blending charts to determine the maximum amount of RAP that can be blended with a known virgin binder grade are also provided for different scenarios. This study also attributed the variability in RAP stockpiles to the differences in the original pavement material, patches, chip seals, in addition to other maintenance treatments. Mixed stockpiles may contain RAP materials from several projects or materials from base, intermediate and surface courses. Use of material from such stockpiles makes it harder to meet the specifications required for the final mixture properties.

Variability in the recycled binder properties obtained from different sources in the state of Virginia was studied under Project VTRC 08-R22, "Evaluation of Using Higher Percentages of Recycled Asphalt Pavement in Asphalt Mixes in Virginia" [4]. Several high RAP sections (typically consisting of 25-30% RAP) were identified and binder characterization was performed on blends prepared using recycled binder from RAP used in each project, and PG 64-22 and PG 70 - 22 virgin binders. The continuous high temperature PG grade was determined for the recycled binders as well as the blended binders containing the corresponding amount of recycled binder, as shown below in Table 2-1. The blended binders tested were prepared in two ways:

a) Prepared in the laboratory by blending the extracted recycled binder from RAP with the virgin binder.
b) Blended binder as recovered from the asphalt concrete mix from the field.

The binder characterization data from the table shows that the recycled binders from different RAP sources exhibit a high degree of variability with the high temperature grades varying from 83 to 96. The blended binder PG grade accordingly varied from 70 to 75, which represents an increase in one high temperature grade. Therefore, it is important to determine the effect of variability in recycled binder properties on selection of the amount of RAP to be used in a mix.

Table 2-1: Continuous High PG Grade of RAP & Blended Binders [4]

Mix Type	% RAP in Blend	PG Grade of 100% RAP	Blended Binder	
			Lab Blend(a)	Field Recovery(b)
S 12.5D	25	PG 94 - 17	PG 72 - 22	PG 69 - 25
S 9.5D	25	PG 90 - 18	PG 72 - 22	PG 71 - 22
S 9.5D	25	PG 96 - 13	PG 74 - 21	PG 71 - 23
S 9.5D	21	PG 95 - 14	PG 74 - 22	PG 72 - 23
I 19.0D	30	PG 93 - 16	PG 75 - 22	PG 73 - 23
S 9.5D	30	PG 83 - 18	PG 70 - 22	PG 76 - 16
S 12.5D	25	PG 88 - 13	PG 72 - 21	PG 76 - 22
S 12.5D	30	PG 93 - 17	PG 75 - 23	PG 76 - 25
S 12.5D*	15	PG 85 - 27	PG 73 - 24	PG 73 - 23
S 12.5D*	20	PG 94 - 16	PG 76 - 22	PG 79 - 16

** Virgin binder PG 70-22 used in asphalt concrete mix*

The binder characterization data from the table shows that the recycled binders from different RAP sources exhibit a high degree of variability with the high temperature grades varying from 83 to 96. The blended binder PG grade accordingly varied from 70 to 75, which represents an increase in one high temperature grade. Therefore, it is important to determine the effect of variability in recycled binder properties on selection of the amount of RAP to be used in a mix.

The study conducted by Shin-Che Huang et. al "Aging Characteristics of RAP Binders – What type of RAP Binders Suitable for Multiple Recycling?" [5] studied how addition of

RAP binders influences the PG grade system of fresh asphalts. They studied blended binders with varying proportions of RAP binder in the blends and concluded that the high temperature grade of the blended binder was linearly dependent on the percent proportion of RAP binder in the blend. They studied blends where, the same RAP binder was blended with different base binders and found that, although the relationship was still linear between the proportion of RAP binder and high temperature grade of the blended binder, the two relationships were different indicating that RAP binders blend differently with different virgin binders.

The research work conducted by Beth Visintine "An Investigation of Various Percentages of Reclaimed Asphalt Pavement on the Performance of Asphalt Pavements" [6] studied recycled asphalt mixtures with two different sources of RAP. As part of the selection process of the two sources of RAP, eight RAP sources were studied for their PG grade characteristics and six of the sources were dropped from the study later. From the Superpave PG grading of the RAP binders from these eight sources, it was found that the high temperature PG grade varied from 82 to 88. The intermediate temperature PG grade of the RAP binders varied between 34 and 46 indicating a high variability in fatigue performance.

As part of the study, virgin asphalt binders were blended with various percentages of binder extracted from the selected sources of RAP and linear blending charts were developed using the rheological properties of complex modulus ($|G^*|$) and phase angle (δ). The blending charts were in turn used to determine the maximum and minimum limits for the proportion of RAP binder that can be safely blended with virgin binder such that the blended binder meets the Superpave rutting, fatigue and thermal cracking criteria. The study found that the minimum limits calculated for the two RAP binders with a virgin binder grade of PG 52-28 to meet the Superpave high temperature requirements of a PG 64 binder varied from 20% to 30%. Similarly, the maximum proportions of RAP binder that could be blended with a virgin binder and still meet the Superpave specifications for a PG 64 binder were determined to be different by 1-3% for RAP binders from two different sources. This study also found that for the state of North Carolina, the determining criteria for RAP binder limits are the Superpave high temperature rutting criterion and the Superpave intermediate temperature fatigue criterion. The limits determined from low temperature criterion resulted in maximum RAP binder limits much higher than the limits determined from the fatigue criterion. Therefore, the current research will focus on the Superpave intermediate and high temperature criteria to derive the limits for RAP binders from various stockpiles in North Carolina.

The research project “Determining Recycled Asphalt Binder Limits Contributed by Waste Materials” [7] by Srikanth Sree Ramoju et. al. studied the effect of RAP on the performance of HMA. As part of the study two virgin binders that were widely used in the state of North Carolina were used: PG 58-28 and PG 64-22. Both the virgin binders were blended with varying proportions of binder extracted from RAP and blending charts were constructed. It was found that the blending charts did follow a linear relationship between percentage recycled binder in the total blended binder and the high temperature PG grade of the blended binder. These blending charts were in turn used to determine the maximum and minimum limits for the amount of binder extracted from RAP that could be safely blended with the selected virgin binders and still the Superpave rutting and fatigue criteria. From the blending charts it was determined that the maximum limits for the single RAP source based on

Superpave binder criteria were 45% for PG 58-28 and 20% for PG 64-22. It was also concluded that the limits determined from binder testing warrant the performance of the S9.5B HMA mixtures for North Carolina that were designed based on these binder limits. Therefore, limiting the amount of RAP in an HMA by limiting the percent binder replaced by binder from waste materials was a viable option.

As an extension to the above project, Haritha Musty worked on the project titled "Impact of Binders from Waste Materials on Performance of Surface Mixtures" [8]. As part of this project, the method of limiting the use of recyclable waste materials by limiting the percentage of binder contributed by waste materials in the total binder was extended to North Carolina's S9.5C and S9.5D mixtures. After conducting dynamic modulus tests on the mixtures designed based on binder limits and performing pavement performance analysis and economic analysis, it was found that limiting the amount of waste materials in HMA by limiting the amount of binder from waste materials was a viable alternative to designing mixtures based on limiting the waste materials by weight of total mixture.

The significance of limiting the use of waste materials based on the limits determined from binder testing does indicate that the higher the variability in the properties of binder from recyclable materials, the higher the variability in the minimum and maximum limits of waste materials in an HMA mixture. Therefore, focusing on the variability in the binder properties of recyclable materials will help in defining specifications that allow accounting for variability within RAP stockpiles without having any detrimental effects on pavement performance.

CHAPTER 3 : - RESEARCH APPROACH AND METHODOLOGY

The research objectives and the methodology used for this study will be discussed in this chapter.

3.1. Specific Research Objectives

The goal of this research was to determine the variability in RAP binder properties observable from stockpile to stockpile and within stockpile, which in turn would be used to recommend RAP binder limits to be incorporated into the NCDOT specifications for recycled materials. The specific research objectives for this study are described below:

- Select nine RAP stockpiles from three different geographical locations (Coastal Plains, Piedmont and Mountains) across North Carolina in order to capture the highest possible variability in RAP material properties. Select three different locations in each stockpile for RAP sampling, binder extraction and further testing to estimate the variability within each stockpile.

- Conduct Superpave performance grade testing of the extracted binders from all the nine RAP stockpiles to identify the differences between the recycled binders and determine if within stockpile variability exists.

- Based on the differences identified between RAP stockpiles, select three stockpiles such that the recycled binders extracted from them exhibit the highest variability from each other in relevant properties to formulate a statistical basis for comparison.

- Extract binder from the above three RAP stockpiles to prepare binder blends containing varying percentages of extracted binders with selected virgin binders. Conduct Superpave performance grading on the blended binders. Select virgin binders PG 58-22 and PG 64-22 as specified by NCDOT for surface mixtures for preparing the blends.
- Develop blending charts to determine the maximum allowable recycled binder based on the blended binder properties for different extracted and virgin binder grade combinations.
- Develop a draft specification for utilizing recycled binder limits for different RAP materials, including sampling and testing protocol for use by NCDOT to determine variability within a RAP stockpile.

3.2. Research Methodology

To realize the aforementioned objectives, the study was partitioned and organized into the following five tasks.

Task 1. Material Acquisition

This research task describes the selection and procurement of recycled materials from the selected stockpiles and the virgin materials. Binders from the selected materials were extracted for further testing and characterization.

Task 1.1. RAP Stockpile Site Selection and Sample Procurement

For this research subtask, nine different stockpiles from three geographical locations across the state of North Carolina - Coastal, Piedmont and Mountains - were selected. RAP was sampled from these nine stockpiles for binder extraction and rheological testing. Owing to the fact that RAP stockpiles are a collection of material from various locations and pavements that have been aged to varying degrees, RAP was sampled from three different locations within each stockpile to factor in the within stockpile variability.

The task of screening the RAP stockpiles and obtaining samples was accomplished in consultation with the NCDOT Materials and Tests Unit. Representative samples of RAP were procured by NCDOT and the task of extraction of the recycled binder from these samples was performed by NCDOT.

Task 1.2. Virgin Material Selection and Procurement

The scope of this research is limited to the roads and highways in North Carolina, and thus, the NCDOT specifications for binders were consulted when choosing the virgin binders. The specifications for NCDOT specifies PG 64-22 graded binder for A and B-level surface mixtures, PG 70-22 graded binder for C-level surface mixtures, and PG 76-22 graded binder for D-level surface mixtures. The most commonly used virgin binder grades in North Carolina are PG 64-22 and PG 70-22. Since, recycled binder is an aged binder that has stiffened during its service life, blended binder obtained by combining a portion of recycled binder with a virgin binder is typically stiffer than the base virgin binder. Therefore, it would be necessary to blend the recycled binder with a softer virgin grade in order for the blended binder to have the desired grade for the project requirements. Consequently, this research included binder grades of PG 58-28 and PG 64-22.

Task 2. Asphalt Binder Testing & Characterization

This task comprised of two stages of asphalt binder testing. The details of the two stages are explained in the following subtasks.

Task 2.1. Rheological Testing of Extracted RAP Binders

In the first stage of testing, the extracted RAP binders were tested on the Dynamic Shear Rheometer (DSR) for their rheological properties which would be required to determine the PG binder grade of the binders. RAP binders were tested on the DSR in accordance with AASHTO T315 "Test Method for Determining the Rheological Properties of Asphalt Binder Using a Dynamic Shear Rheometer" at both high and intermediate test temperatures. Requisite quantities of the RAP binders were aged in a Rolling Thin Film Oven (RTFO) to simulate short term aging of asphalt binders induced during the processes of hauling mixture from production plant to construction site, laying and, finally compacting. The RTFO aged binders were subsequently aged in a Pressure Aging Vessel (PAV) to simulate long term aging of asphalt binders induced during its life cycle in a pavement. These RAP binders were tested in both unaged and RTFO aged conditions at multiple high test temperatures and in PAV aged conditions at multiple intermediate test temperatures. For each of the recycled binders in unaged and RTFO aged conditions, three samples were tested on the DSR at high temperatures and the mean and coefficient of variation were calculated for $|G^*|/\sin\delta$ and phase angle. For the recycled binders in the PAV aged conditions, mean and coefficient of variation were calculated for |G*|sinδ and phase angle. These values were used to determine the high and intermediate temperature PG grades of all the extracted RAP binders.

The data from the DSR testing of the various RAP binders was analyzed for statistical inferences on the variability from stockpile to stockpile. “R” software was used for the statistical analysis of the data. Since, the rheological properties of RAP binders were studied at three different aging conditions (unaged, RTFO, and PAV aged), statistical analysis could be performed on data from the three aged conditions. Linear models can be used with stockpile as the categorical independent variable, |G*|/sinδ values for the RAP binders as the dependent variable and, temperature as the covariate in the case of unaged and RTFO aged RAP binders. This regression was, however, not performed for this study for reasons that are explained in later chapters. In the case of PAV aged RAP binders, regression was performed with stockpile as the independent categorical variable, |G*|sinδ values for the RAP binders as the dependent variable, and temperature as the covariate. The above regression lines for RAP binders from different stockpiles were compared using ANCOVA. The models for the analysis of the RAP binders are as given below:

MODEL 1: Log (|G*|/sinδ) ~ Temperature + Stockpile + Temperature*Stockpile

Temperature levels: 70, 76, 82, 88, 94, 100

Stockpile levels: Stockpile X_i *for* $(i \, \varepsilon \, 1{:}9)$*.*

MODEL 2: Log (|G*|sinδ) ~ Temperature + Stockpile + Temperature*Stockpile

Temperature levels: 16, 19, 22, 25, 28, 31, 34, 37, 40

Stockpile levels: Stockpile X_i for ($i \varepsilon 1{:}9$).

Model 1 can be used for the unaged and RTFO aged RAP binders and Model 2 was used for the PAV aged RAP binders.

Task 2.2. Rheological Study of Blended Binders Obtained by Blending RAP Binders and Virgin Binders of Known PG Grade.

The PG grades of all the nine RAP stockpiles were compared and the three most distinct RAP stockpiles were selected for blending with virgin binders of known grades. For this research study, as discussed earlier, PG 58-28 and PG 64-22 were used for blending and further testing and analysis. RAP binder from three locations within each of the selected stockpiles was blended with both PG 58-28 and PG 64-22 virgin binders at a known proportion on a laboratory hot plate using mechanical means. These blended binders were tested on the DSR in their unaged, RTFO aged and PAV aged conditions at high and intermediate test temperatures.

Blending charts were developed for each of the virgin binders with relevant rheological property plotted against the percentage of recycled binder in the blended binder. Limits for the recycled binders were calculated based on the blending charts in order for the blended binders to meet the Superpave criteria at specified high and intermediate temperatures. Recycled binder limits were estimated for RAP binders from each of the three locations for all the three selected stockpiles. The variation in the limits obtained from the three different locations within a stockpile were used to recommend tolerance levels for the three selected stockpiles.

CHAPTER 4 : - RAP BINDER CHARACTERISTICS

This chapter will discuss the results of the tests on the selected RAP binders that have been used in this research.

As mentioned earlier, three RAP stockpiles were selected from each of the three different geographical regions of the state of North Carolina, namely: Coastal Region, Piedmont Region & Mountain Region. The names of the nine stockpiles are listed in Table 4-1 below. The portion of the names in bold text are used to refer to the corresponding stockpile in the rest of the document.

Table 4-1: List of Selected Stockpiles

Sl. No.	**RAP Stockpile**
1	St Wooten - **Wilmington**
2	**Pineville**
3	**Maymead** - Lenoir
4	**Sunrock**
5	**Sims**
6	Harrison Construction - **Weaverville**
7	**Highland** - Fayetville
8	**Harrison** - Hayesville
9	APAC Thomson Arthur - **Burlington**

RAP was sampled from three randomly selected locations within each stockpile for a total of 27 RAP samples. The task of screening the RAP stockpiles and obtaining samples was accomplished in consultation with the NCDOT Materials and Tests Unit. The NCDOT procured the representative RAP samples and extracted the recycled binders from these samples. These recycled binders were subjected to Superpave Performance Grade testing on a DSR in various aged conditions and the results are discussed in the following sections.

4.1. RAP Binders in Unaged Conditions

The extracted RAP binders from the 27 samples were tested on the DSR in accordance with AASHTO T315 "Test Method for Determining the Rheological Properties of Asphalt Binder Using a Dynamic Shear Rheometer" to determine the rheological properties of Complex Modulus (G*) and Phase Angle (delta, δ) of each binder at different temperatures. These values together with the results of tests on RTFO aged binders were used to determine the high temperature PG grade of the RAP binders.

4.1.1. Source of RAP – Wilmington

RAP was sampled from three randomly selected locations within the Wilmington stockpile and the binder was extracted by the NCDOT personnel. These three RAP binders were tested on the DSR in their unaged conditions. Table 4-2, Table 4-3 and Table 4-4, and Figure 4-1 show the results of the DSR testing on the three binders. The mean values of $|G^*|/\sin\delta$ and standard deviations are shown in the tables.

Table 4-2: DSR Results of Unaged RAP Binder (Wilmington – 1)

Temperature	$\|G^*\|/\sin\delta$ (kPa)		δ^o(Phase Angle)	
ºC	Mean	Std. Deviation	Mean	Std. Deviation
70	20.43	0.49	72.36	0.09
76	9.61	0.17	75.43	0.03
82	4.60	0.08	78.34	0.04
88	2.27	0.04	80.92	0.02
94	1.15	0.02	83.19	0.01
100	0.60	0.01	85.12	0.01

Table 4-3: DSR Results of Unaged RAP Binder (Wilmington – 2)

Temperature	$\|G^*\|/\sin\delta$ (kPa)		δ^o(Phase Angle)	
ºC	Mean	Std. Deviation	Mean	Std. Deviation
70	28.29	0.84	70.59	0.13
76	13.18	0.24	73.70	0.18
82	6.30	0.13	76.79	0.14
88	3.08	0.08	79.55	0.14
94	1.54	0.04	81.98	0.12
100	0.80	0.02	84.10	0.09

Table 4-4: DSR Results of Unaged RAP Binder (Wilmington – 3)

Temperature	|G*|/sinδ (kPa)		δ°(Phase Angle)	
°C	Mean	Std. Deviation	Mean	Std. Deviation
64	59.77	1.04	67.57	0.04
70	27.32	0.26	70.61	0.10
76	12.71	0.18	73.84	0.04
82	6.07	0.09	76.96	0.01
88	2.96	0.03	79.72	0.03
94	1.49	0.01	82.13	0.01
100	0.77	0.01	84.22	0.01

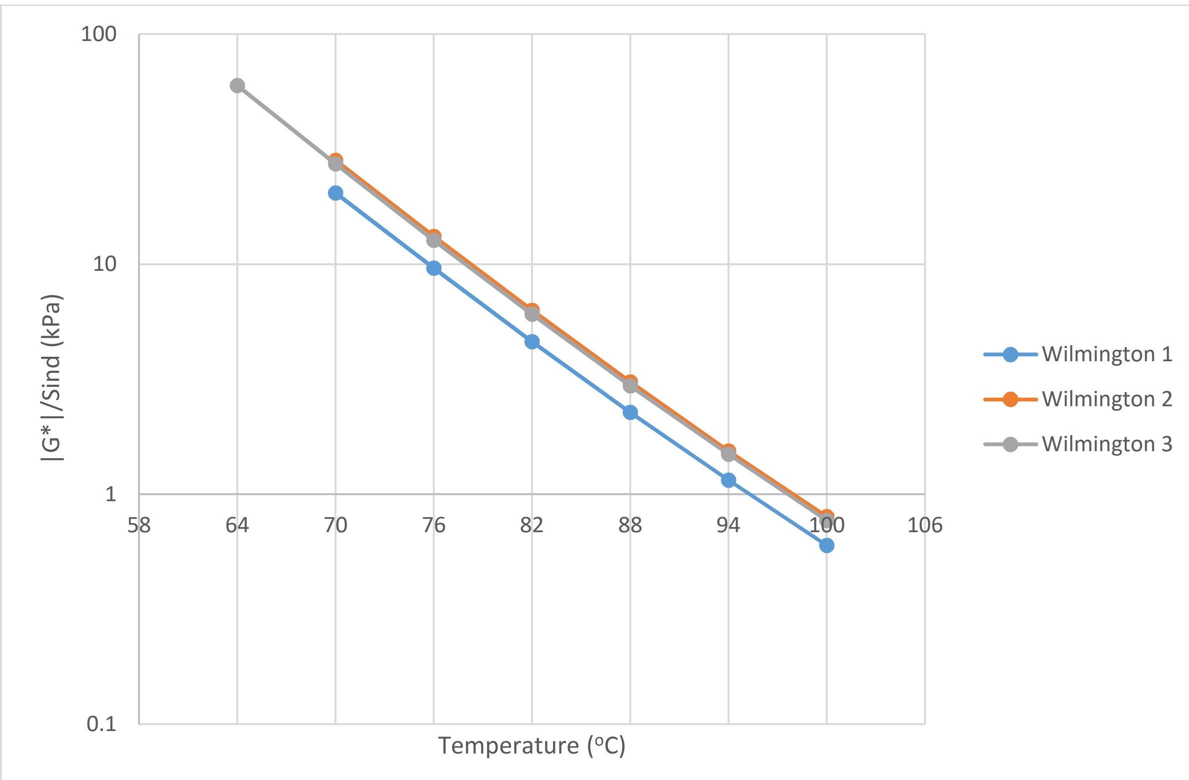

Figure 4-1: DSR Results for the Wilmington RAP Binders (Unaged) at Various Temperatures

It can be observed from the above tables and the figure that the |G*|/sinδ values decreased as temperature increased and the condition of |G*|/sinδ < 1.0kPa was met at a temperature of 100°C for Wilmington 1, Wilmington 2 and Wilmington 3 RAP binders. All the Wilmington RAP binders qualified for a high temperature PG grade of 94 based on DSR tests on unaged binders. The continuous high temperature PG grades were calculated as 95.3, 97.7 and 97.3 for Wilmington 1, Wilmington 2 and Wilmington 3 RAP binders, respectively, in their unaged condition. The |G*|/sinδ values for Wilmington 1 RAP binder were lower than that of Wilmington 2 and Wilmington 3 RAP binders over the entire range of test temperatures.

4.1.2. Source of RAP – Pineville

Extracted RAP binders from three randomly selected locations within Pineville stockpile were tested on the DSR in their unaged conditions. Table 4-5, Table 4-6 and Table 4-7, and Figure 4-2 show the results of the DSR testing on these three binders. The mean values of |G*|/sinδ and standard deviations are shown in the tables.

Table 4-5: DSR Results of Unaged RAP Binder (Pineville – 1)

Temperature	|G*|/sinδ (kPa)		δ° (Phase Angle)	
°C	Mean	Std. Deviation	Mean	Std. Deviation
64	47.41	0.80	70.06	0.08
70	21.45	0.45	73.34	0.07
76	10.00	0.18	76.26	0.04
82	4.77	0.08	78.94	0.08
88	2.35	0.03	81.42	0.07
94	1.19	0.02	83.54	0.05
100	0.63	0.01	85.33	0.03

Table 4-6: DSR Results of Unaged RAP Binder (Pineville – 2)

Temperature	$\lvert G^*\rvert/\sin\delta$ (kPa)		δ^o (Phase Angle)	
^oC	Mean	Std. Deviation	Mean	Std. Deviation
64	49.87	0.80	70.05	0.03
70	22.56	0.41	73.24	0.23
76	10.38	0.10	76.27	0.03
82	4.94	0.03	79.01	0.03
88	2.43	0.02	81.46	0.03
94	1.23	0.01	83.55	0.03
100	0.64	0.01	85.30	0.03

Table 4-7: DSR Results of Unaged RAP Binder (Pineville – 3)

Temperature	$\lvert G^*\rvert/\sin\delta$ (kPa)		δ^o (Phase Angle)	
^oC	Mean	Std. Deviation	Mean	Std. Deviation
64	26.09	0.22	72.55	0.02
70	11.75	0.14	75.54	0.08
76	5.47	0.07	78.43	0.03
82	2.64	0.04	80.95	0.01
88	1.32	0.02	83.01	0.02
94	0.68	0.01	84.75	0.01

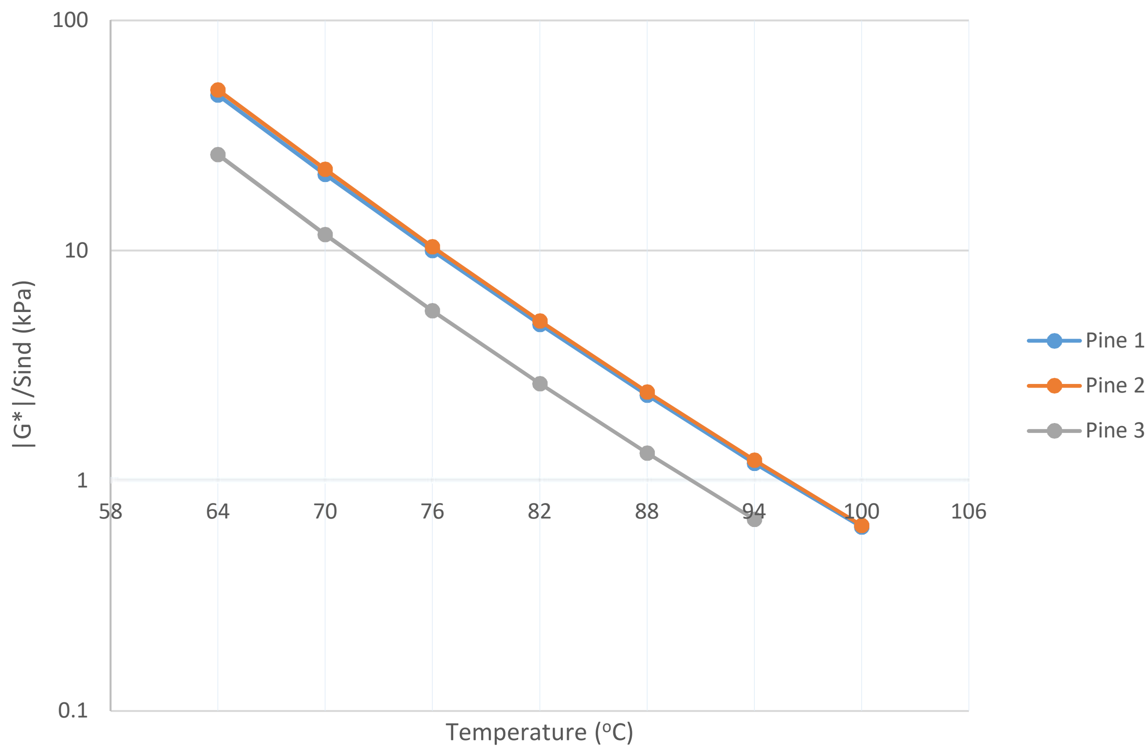

Figure 4-2: DSR Results for the Pineville RAP Binders (Unaged) at Various Temperatures

As expected, the |G*|/sinδ values decreased as temperature increased and the condition of |G*|/sinδ < 1.0kPa was met at a temperature of 100ºC for Pineville 1 and Pineville 2 RAP binders, and at a temperature of 94ºC for Pineville 3 RAP binder. Pineville 1 and Pineville 2 RAP binders qualified for a high temperature PG grade of 94; Pineville 3 RAP binder qualified for a high temperature PG grade of 88ºC based on DSR tests on unaged binders. The Pineville 1, 2 and 3 RAP binders' continuous high temperature grades were calculated as 95.5, 95.7 and 90.4, respectively, in their unaged condition. Pineville 3 RAP binder showed lower values of |G*|/sinδ for the entire range of test temperatures compared to that of Pineville 1 and Pineville

2 RAP binders. Pineville 1 and Pineville 2 RAP binders showed comparable values of |G*|/sinδ, and Pineville 3 RAP binder showed the least stiffness values.

4.1.3. Source of RAP – Maymead

The Maymead stockpile was randomly sampled in three locations, and the extracted binders were tested in their unaged conditions. Table 4-8, Table 4-9 and Table 4-10, and Figure 4-3 show the results of the DSR testing on these three binders. The mean values of |G*|/sinδ and standard deviations are shown in the tables.

Table 4-8: DSR Results of Unaged RAP Binder (Maymead – 1)

Temperature	|G*|/sinδ (kPa)		δ° (Phase Angle)	
°C	Mean	Std. Deviation	Mean	Std. Deviation
64	178.05	2.31	61.75	0.16
70	83.97	2.33	64.56	0.36
76	38.72	0.78	68.27	0.22
82	18.15	0.40	71.64	0.07
88	8.68	0.30	75.01	0.19
94	4.26	0.14	78.00	0.29
100	2.15	0.07	80.71	0.18
106	1.11	0.03	82.99	0.16
112	0.60	0.01	84.92	0.12

Table 4-9: DSR Results of Unaged RAP Binder (Maymead – 2)

Temperature	$\|G^*\|/\sin\delta$ (kPa)		δ^o (Phase Angle)	
^oC	Mean	Std. Deviation	Mean	Std. Deviation
64	123.22	1.40	64.65	0.07
70	56.18	0.76	68.01	0.21
76	24.95	0.44	71.88	0.27
82	11.32	0.16	75.56	0.17
88	5.34	0.10	78.81	0.09
94	2.59	0.05	81.49	0.06
100	1.29	0.02	83.81	0.09
106	0.66	0.01	85.71	0.08

Table 4-10: DSR Results of Unaged RAP Binder (Maymead – 3)

Temperature	$\|G^*\|/\sin\delta$ (kPa)		δ^o (Phase Angle)	
^oC	Mean	Std. Deviation	Mean	Std. Deviation
64	99.73	2.59	65.67	0.15
70	44.75	1.51	68.79	0.27
76	20.35	0.35	72.61	0.18
82	9.60	0.22	75.96	0.02
88	4.64	0.11	79.16	0.16
94	2.30	0.05	81.79	0.12
100	1.17	0.02	83.93	0.13
106	0.61	0.01	85.72	0.14

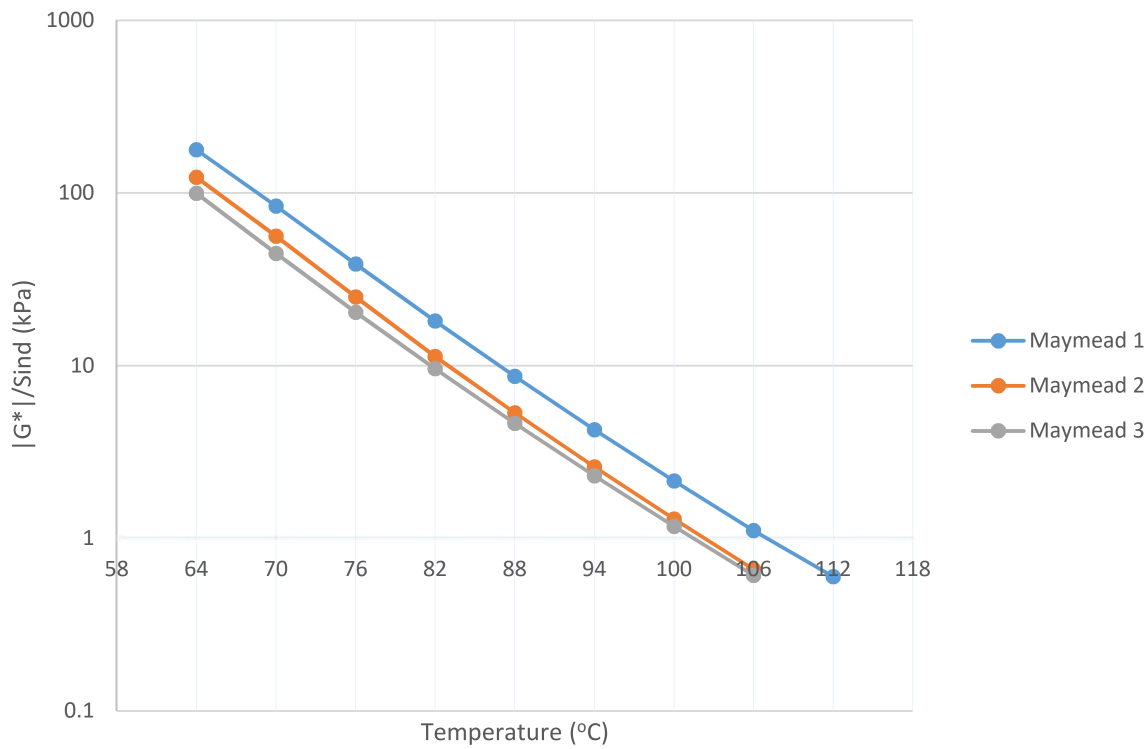

Figure 4-3: DSR Results for the Maymead RAP Binders (Unaged) at Various Temperatures

As shown in the above tables and figure, the condition of |G*|/sinδ < 1.0kPa was met at a temperature of 112^{o}C for Maymead 1 RAP binder, and at a temperature of 106^{o}C for Maymead 2 and Maymead 3 RAP binders. Maymead 1 RAP binder qualified for a high temperature PG grade of 106, while Maymead 2 and Maymead 3 RAP binders both qualified for a high temperature PG grade of 100^{o}C. The continuous high temperature PG grades for Maymead binders were calculated as follows: Maymead 1, 106.7; Maymead 2, 102; and Maymead 3, 101.2.

4.1.4. Source of RAP – Sunrock

Within the Sunrock stockpile, three samples of RAP were randomly taken and the extracted binders were tested on the DSR. Table 4-11, Table 4-12 and Table 4-13, and Figure 4-4 show the results of the DSR testing on these three RAP binders. The mean values of |G*|/sinδ and standard deviations are shown in the tables.

Table 4-11: DSR Results of Unaged RAP Binder (Sunrock – 1)

Temperature	|G*|/sinδ (kPa)		δº(Phase Angle)	
ºC	Mean	Std. Deviation	Mean	Std. Deviation
64	50.07	0.15	68.72	0.06
70	23.07	0.34	71.82	0.04
76	10.63	0.09	75.30	0.08
82	5.05	0.05	78.41	0.05
88	2.48	0.02	81.06	0.04
94	1.25	0.01	83.29	0.03
100	0.66	0.01	85.10	0.03

Table 4-12: DSR Results of Unaged RAP Binder (Sunrock – 2)

Temperature	|G*|/sinδ (kPa)		δº(Phase Angle)	
ºC	Mean	Std. Deviation	Mean	Std. Deviation
64	59.73	0.79	67.11	0.15
70	27.65	0.42	70.01	0.27
76	12.93	0.14	73.75	0.31
82	6.17	0.08	76.82	0.06
88	3.04	0.03	79.69	0.05
94	1.54	0.02	82.15	0.07
100	0.80	0.010	84.26	0.06

Table 4-13: DSR Results of Unaged RAP Binder (Sunrock – 3)

Temperature °C	|G*|/sinδ (kPa)		δ°(Phase Angle)	
	Mean	Std. Deviation	Mean	Std. Deviation
64	72.26	1.10	65.75	0.06
70	33.22	0.94	68.85	0.27
76	15.47	0.26	72.49	0.24
82	7.30	0.11	75.89	0.14
88	3.54	0.06	78.90	0.11
94	1.77	0.03	81.52	0.09
100	0.91	0.02	83.74	0.06

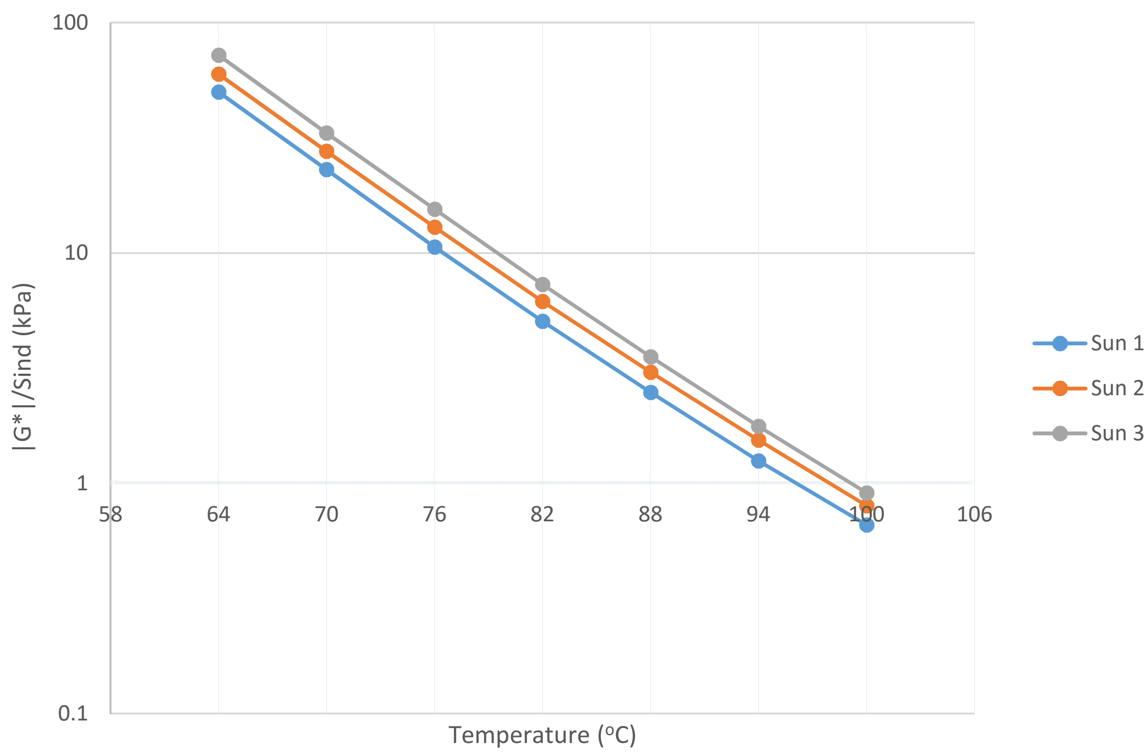

Figure 4-4: DSR Results for the Sunrock RAP Binders (Unaged) at Various Temperatures

The tables and the figure above indicate that the three binders were different in their stiffness values at the tested temperatures, and the |G*|/sinδ values decreased as temperature increased. The condition of |G*|/sinδ < 1.0kPa was met at a temperature of 100ºC for Sunrock 1, Sunrock 2 and Sunrock 3 RAP binders. All of the Sunrock RAP binders qualified for a high temperature PG grade of 94 based on DSR tests on unaged binders.

4.1.5. Source of RAP – Sims

RAP was also randomly sampled from three different locations in the Sims stockpile and the binder was extracted from these three samples. These binders were tested on the DSR in their unaged condition for their high temperature rheological properties. Table 4-14, Table 4-15 and Table 4-16, and Figure 4-5 show the results of the DSR testing on the three Sims RAP binders. The mean values of |G*|/sinδ and standard deviations are shown in the tables.

Table 4-14: DSR Results of Unaged RAP Binder (Sims – 1)

Temperature ºC	|G*|/sinδ (kPa)		δº (Phase Angle)	
	Mean	**Std. Deviation**	**Mean**	**Std. Deviation**
64	209.46	3.52	59.51	0.49
70	104.77	1.18	61.13	0.18
76	51.82	0.46	63.50	0.13
82	26.00	0.05	66.18	0.09
88	13.24	0.10	68.78	0.06
94	6.92	0.10	71.80	0.10
100	3.71	0.05	74.53	0.06
106	2.03	0.03	77.05	0.06
112	1.13	0.02	79.44	0.04
118	0.65	0.01	81.67	0.07

Table 4-15: DSR Results of Unaged RAP Binder (Sims – 2)

Temperature °C	$\|G^*\|/\sin\delta$ (kPa)		δ^o (Phase Angle)	
	Mean	Std. Deviation	Mean	Std. Deviation
64	321.57	10.07	61.34	0.17
70	193.54	3.76	60.31	0.19
76	93.80	1.38	62.84	0.25
82	46.31	0.54	65.48	0.22
88	23.32	0.28	68.31	0.15
94	11.93	0.20	71.09	0.20
100	6.28	0.13	73.71	0.18
106	3.38	0.06	76.33	0.18
112	1.86	0.04	78.74	0.14
118	1.05	0.02	81.00	0.13
124	0.61	0.01	83.02	0.11

Table 4-16: DSR Results of Unaged RAP Binder (Sims – 3)

Temperature °C	$\|G^*\|/\sin\delta$ (kPa)		δ^o (Phase Angle)	
	Mean	Std. Deviation	Mean	Std. Deviation
64	209.40	0.53	59.70	0.53
70	106.58	1.94	62.02	0.06
76	51.83	0.71	65.03	0.40
82	24.83	0.41	67.77	0.35
88	12.35	0.07	70.76	0.08
94	6.37	0.09	73.69	0.11
100	3.38	0.05	76.32	0.08
106	1.83	0.03	78.83	0.10
112	1.02	0.01	81.12	0.08
118	0.58	0.01	83.14	0.09

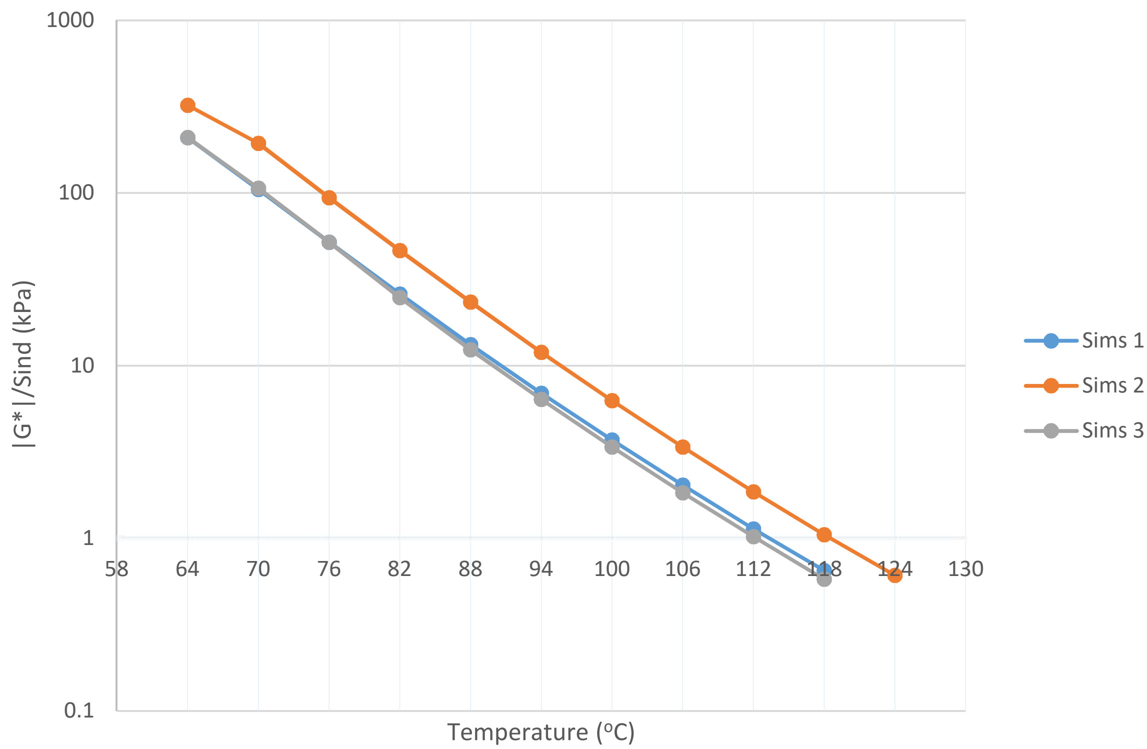

Figure 4-5: DSR Results for the Sims RAP Binders (Unaged) at Various Temperatures

The Sims 1 and Sims 3 RAP binders met the condition of |G*|/sinδ < 1.0kPa at a temperature of 118ºC; the Sims 2 RAP binder met the condition at 124ºC. Sims 1 and Sims 3 RAP binders qualified for a high temperature PG grade of 112. Sims 2 RAP binder qualified for a high temperature PG grade of 118ºC based on DSR tests on unaged binders. Sims 1 and 3 RAP binders showed similar stiffness values, whereas, Sims 2 RAP binder showed highest stiffness values.

4.1.6. Source of RAP – Weaverville

Three locations were randomly selected and RAP sampled from the Weaverville stockpile. Table 4-17, Table 4-18and Table 4-19, and Figure 4-6 show the results of the DSR testing on the three extracted RAP binders. The mean values of |G*|/sinδ and standard deviations are shown in the tables.

Table 4-17: DSR Results of Unaged RAP Binder (Weaverville – 1)

Temperature	|G*|/sinδ (kPa)		δ° (Phase Angle)	
°C	Mean	Std. Deviation	Mean	Std. Deviation
64	34.68	1.51	71.06	0.13
70	16.06	0.53	74.40	0.16
76	7.43	0.18	77.68	0.18
82	3.50	0.07	80.65	0.12
88	1.65	0.03	83.19	0.12
94	0.85	0.01	85.14	0.11

Table 4-18: DSR Results of Unaged RAP Binder (Weaverville – 2)

Temperature	|G*|/sinδ (kPa)		δ° (Phase Angle)	
°C	Mean	Std. Deviation	Mean	Std. Deviation
64	38.31	0.85	70.35	0.11
70	17.41	0.38	73.64	0.28
76	8.00	0.23	77.06	0.11
82	3.72	0.06	80.09	0.15
88	1.76	0.02	82.57	0.09
94	0.90	0.01	84.56	0.08

Table 4-19: DSR Results of Unaged RAP Binder (Weaverville – 3)

Temperature °C	|G*|/sinδ (kPa)		δ°(Phase Angle)	
	Mean	Std. Deviation	Mean	Std. Deviation
64	42.39	0.59	70.19	0.10
70	19.31	0.35	73.47	0.17
76	8.78	0.13	76.70	0.09
82	4.15	0.06	79.59	0.14
88	2.03	0.03	82.08	0.08
94	1.03	0.01	84.21	0.07
100	0.52	0.01	86.02	0.05

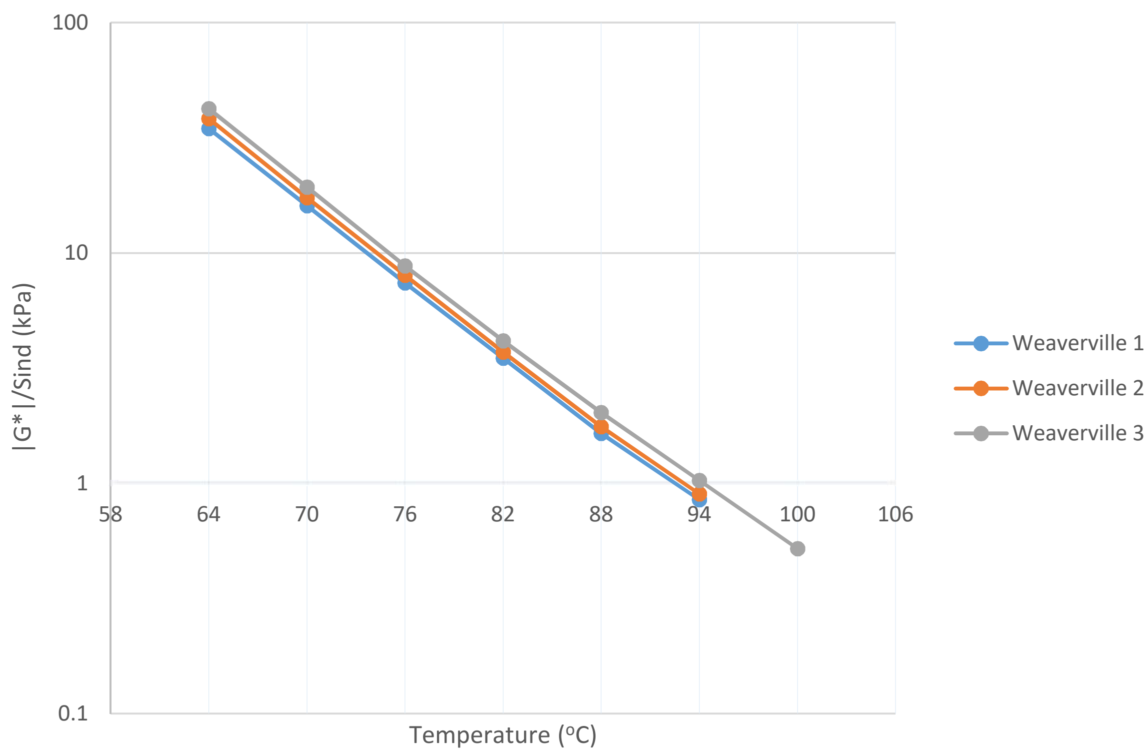

Figure 4-6: DSR Results for the Weaverville RAP Binders (Unaged) at Various Temperatures

In the case of unaged RAP binders from the Weaverville stockpile, the condition of |G*|/sinδ < 1.0kPa was met at a temperature of 94°C for Weaverville 1 and Weaverville 2 RAP binders, whereas, the condition was met at a temperature of 100°C for Weaverville RAP 3 binder. Weaverville 1 and 2 RAP binders qualified for a PG 88 high temperature grade, whereas, Weaverville 3 RAP binder qualified for a PG 94 high temperature grade. The variation between the three samples from Weaverville stockpile was relatively low compared to the other stockpiles.

4.1.7. Source of RAP – Highland

Three randomly-selected locations were sampled within the Highland stockpile, and the binder extracted from these samples. These three binders were tested on the DSR in unaged condition for their high temperature rheological properties. Table 4-20, Table 4-21 and Table 4-22, and Figure 4-7 show the results of the DSR testing on the three Highland RAP binders. The mean values of |G*|/sinδ and standard deviations are shown in the tables.

Table 4-20: DSR Results of Unaged RAP Binder (Highland – 1)

Temperature °C	|G*|/sinδ (kPa)		δ° (Phase Angle)	
	Mean	Std. Deviation	Mean	Std. Deviation
64	49.46	0.40	68.85	0.03
70	22.82	0.48	72.39	0.24
76	10.49	0.05	75.53	0.06
82	4.74	0.03	78.83	0.04
88	2.32	0.02	81.43	0.05
94	1.18	0.01	83.68	0.04
100	0.62	0.01	85.49	0.05

Table 4-21: DSR Results of Unaged RAP Binder (Highland – 2)

Temperature ^{o}C	$\|G^*\|/\sin\delta$ (kPa)		δ^{o} (Phase Angle)	
	Mean	**Std. Deviation**	**Mean**	**Std. Deviation**
64	38.39	0.81	70.33	0.30
70	17.79	0.27	73.54	0.29
76	8.24	0.22	76.83	0.32
82	3.80	0.14	79.90	0.25
88	1.85	0.04	82.39	0.20
94	0.94	0.02	84.45	0.20

Table 4-22: DSR Results of Unaged RAP Binder (Highland – 3)

Temperature ^{o}C	$\|G^*\|/\sin\delta$ (kPa)		δ^{o} (Phase Angle)	
	Mean	**Std. Deviation**	**Mean**	**Std. Deviation**
64	40.03	0.40	69.83	0.09
70	18.34	0.20	73.10	0.09
76	8.53	0.11	76.53	0.04
82	3.88	0.06	79.75	0.04
88	1.89	0.03	82.30	0.02
94	0.96	0.01	84.40	0.01

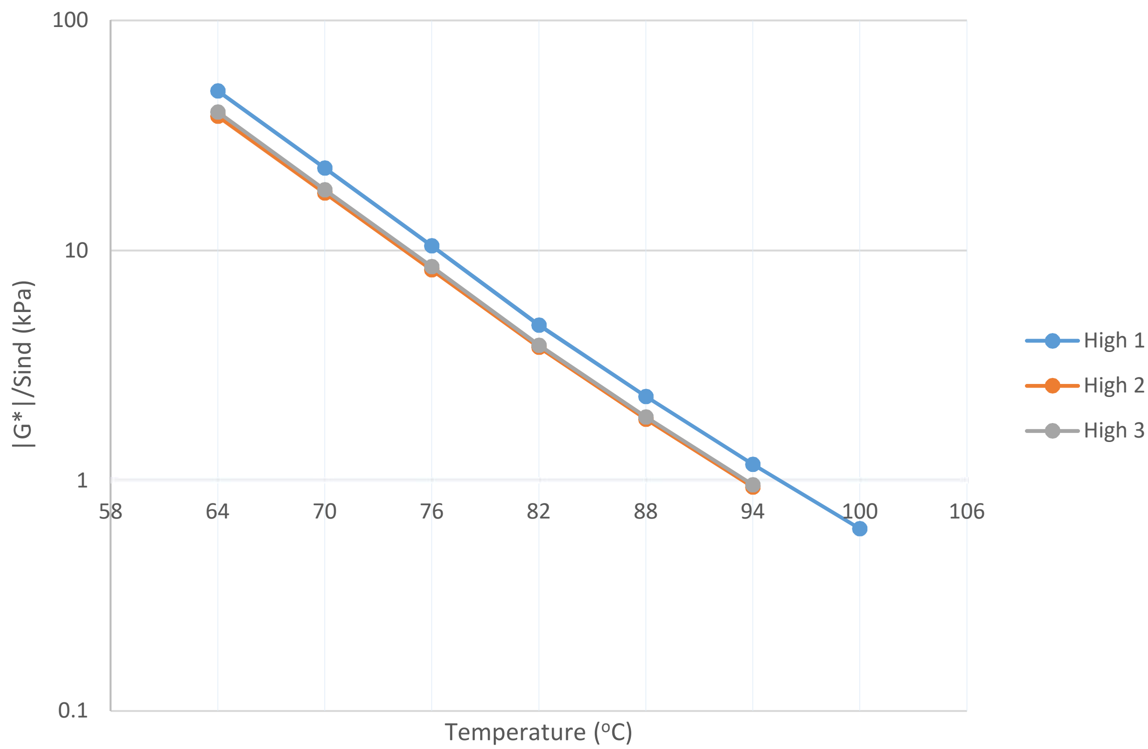

Figure 4-7: DSR Results for the Highland RAP Binders (Unaged) at Various Temperatures

The condition of |G*|/sinδ < 1.0kPa was met at a temperature of 100°C for Highland 1 RAP binder and at a temperature of 94°C for Highland 2 and Highland 3 RAP binders. Highland 1 RAP binder qualified for a high temperature PG grade of 94. Highland 2 and Highland 3 RAP binders qualified for a high temperature PG grade of 88°C. The variability in the stiffness values among the three RAP binders from this stockpile was also lower compared to the other stockpiles.

4.1.8. Source of RAP – Harrison

The Harrison stockpile was also randomly sampled in three different locations and the binders extracted. Table 4-23, Table 4-24 and Table 4-25, and Figure 4-8 show the results of DSR testing on the three Harrison RAP binders. The mean values of |G*|/sinδ and standard deviations are shown in the tables.

Table 4-23: DSR Results of Unaged RAP Binder (Harrison – 1)

Temperature	|G*|/sinδ (kPa)		δ° (Phase Angle)	
°C	Mean	Std. Deviation	Mean	Std. Deviation
64	39.92	0.49	71.25	0.05
70	17.49	0.11	74.81	0.07
76	7.74	0.12	78.37	0.11
82	3.52	0.03	81.39	0.06
88	1.67	0.02	83.80	0.06
94	0.82	0.01	85.69	0.04

Table 4-24: DSR Results of Unaged RAP Binder (Harrison – 2)

Temperature	|G*|/sinδ (kPa)		δ° (Phase Angle)	
°C	Mean	Std. Deviation	Mean	Std. Deviation
64	26.41	0.63	75.63	0.04
70	11.47	0.24	78.98	0.11
76	5.07	0.11	81.77	0.09
82	2.34	0.04	84.14	0.06
88	1.13	0.02	85.98	0.04
94	0.57	0.01	87.36	0.04

Table 4-25: DSR Results of Unaged RAP Binder (Harrison – 3)

Temperature	$\lvert G^* \rvert / \sin\delta$ (kPa)		δ^o (Phase Angle)	
^oC	Mean	Std. Deviation	Mean	Std. Deviation
64	16.62	0.23	77.37	0.03
70	7.20	0.10	80.53	0.13
76	3.23	0.04	83.11	0.07
82	1.51	0.02	85.23	0.05
88	0.74	0.01	86.80	0.02

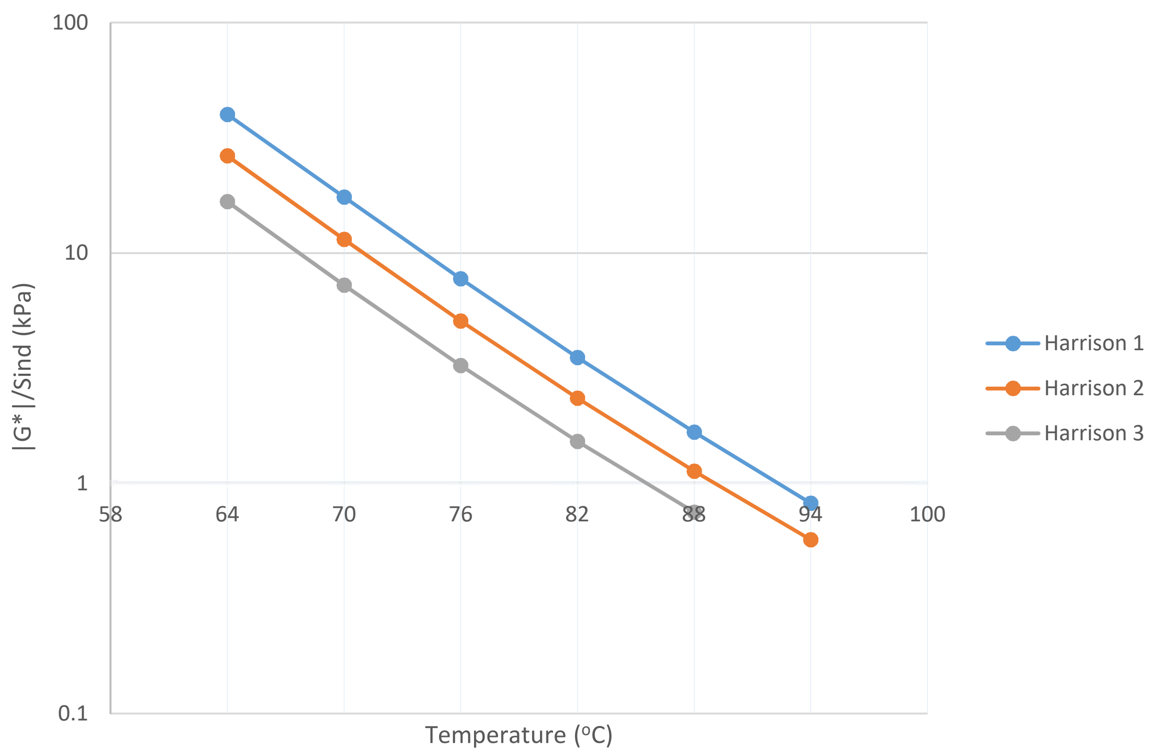

Figure 4-8: DSR Results for the Harrison RAP Binders (Unaged) at Various Temperatures

For the Harrison 1 and Harrison 2 RAP binders, the condition of $\lvert G^* \rvert / \sin\delta < 1.0$kPa was met at a temperature of 94ºC. The same condition was, however, met at a temperature of

88^{o}C for Harrison 3 RAP binder. Harrison 1 and Harrison 2 RAP binders qualified for a high temperature PG grade of 88. Harrison 3 RAP binder qualified for a high temperature PG grade of 82^{o}C based on DSR tests on unaged binders. All the three sampled RAP binders from Harrison stockpile showed strikingly different stiffness values indicating a high variability within stockpile.

4.1.9. Source of RAP – Burlington

The last source of RAP was Burlington. RAP was randomly sampled from three different locations from this stockpile and the binders extracted. Table 4-26, Table 4-27 and Table 4-28, and Figure 4-9 show the results of DSR testing on the three Burlington RAP binders. The mean values of |G*|/sinδ and standard deviations are shown in the tables.

Table 4-26: DSR Results of Unaged RAP Binder (Burlington – 1)

Temperature	|G*|/sinδ (kPa)		δ^{o} (Phase Angle)	
^{o}C	Mean	Std. Deviation	Mean	Std. Deviation
64	41.99	0.30	71.51	0.08
70	18.79	0.24	74.89	0.12
76	8.47	0.05	78.13	0.05
82	3.96	0.02	80.85	0.04
88	1.92	0.01	83.21	0.08
94	0.96	0.01	85.20	0.04

Table 4-27: DSR Results of Unaged RAP Binder (Burlington – 2)

Temperature	|G*|/sinδ (kPa)		δ° (Phase Angle)	
°C	Mean	Std. Deviation	Mean	Std. Deviation
64	46.29	0.59	71.33	0.09
70	20.56	0.06	74.56	0.14
76	9.26	0.14	77.98	0.18
82	4.29	0.05	80.84	0.09
88	2.07	0.02	83.23	0.07
94	1.03	0.01	85.23	0.01
100	0.54	0.01	86.79	0.01

Table 4-28: DSR Results of Unaged RAP Binder (Burlington – 3)

Temperature	|G*|/sinδ (kPa)		δ° (Phase Angle)	
°C	Mean	Std. Deviation	Mean	Std. Deviation
64	44.62	0.62	72.09	0.09
70	19.81	0.05	75.32	0.07
76	8.83	0.18	78.48	0.26
82	4.10	0.06	81.25	0.06
88	1.98	0.03	83.55	0.05
94	0.99	0.01	85.38	0.04

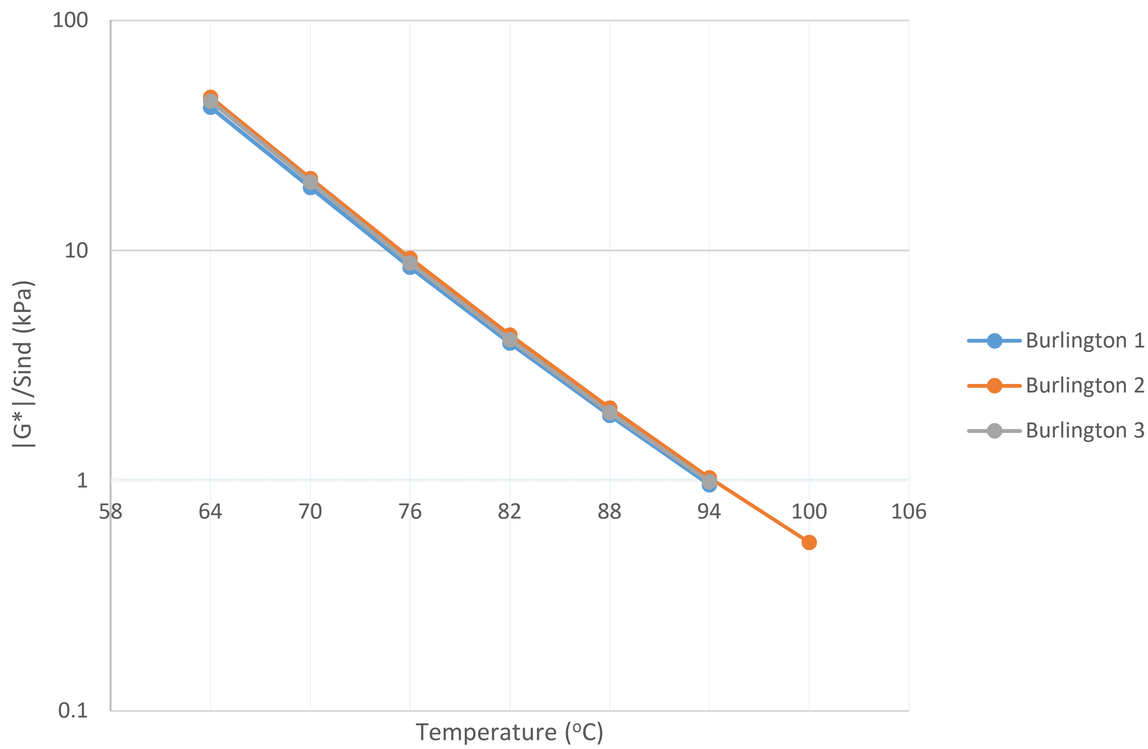

Figure 4-9: DSR Results for the Burlington RAP Binders (Unaged) at Various Temperatures

It can be observed from the above tables and the figure that the |G*|/sinδ values decreased as temperature increased. The condition of |G*|/sinδ < 1.0kPa was met at a temperature of 100^{o}C for Burlington 2 RAP binder, and at a temperature of 94^{o}C for Burlington 1 and Burlington 3 RAP binders. Burlington 2 RAP binder qualified for a high temperature PG grade of 94. Burlington 1 and Burlington 3 RAP binders qualified for a high temperature PG grade of 88^{o}C. All the three RAP binders showed similar stiffness values indicating a low variability within stockpile.

4.2. RAP Binders in RTFO Aged Conditions

All the aforementioned 27 RAP binders were aged in a Rolling Thin Film Oven (RTFO) in accordance with AASHTO T240 “Standard Method of Test for Effect of Heat and Air on Moving Film of Asphalt Binder (Rolling Thin-Film Oven Test)”. These RTFO aged RAP binders were later tested on the DSR to determine if the same trend of variability translated into aged binders from the unaged binders. The results from the DSR testing on the RTFO aged binders are discussed in this section.

4.2.1. Source of RAP – Wilmington

Table 4-29, Table 4-30 and Table 4-31, and Figure 4-10 show the results of the DSR testing on the three RTFO aged Wilmington RAP binders. The mean values of |G*|/sinδ and standard deviations are shown in the tables.

Table 4-29: DSR Results of RTFO Aged RAP Binder (Wilmington – 1)

Temperature	|G*|/sinδ (kPa)		δ°(Phase Angle)	
°C	Mean	Std. Deviation	Mean	Std. Deviation
64	110.13	1.74	63.74	0.12
70	50.90	1.17	66.46	0.11
76	24.33	0.31	69.69	0.46
82	11.89	0.15	72.85	0.09
88	5.92	0.12	75.79	0.01
94	3.00	0.04	78.63	0.02
100	1.57	0.02	81.10	0.05

Table 4-30: DSR Results of RTFO Aged RAP Binder (Wilmington – 2)

Temperature °C	|G*|/sinδ (kPa)		δ°(Phase Angle)	
	Mean	Std. Deviation	Mean	Std. Deviation
64	132.08	1.43	62.47	0.13
70	63.02	1.56	65.04	0.02
76	29.97	0.56	68.21	0.16
82	14.60	0.17	71.38	0.20
88	7.24	0.11	74.48	0.13
94	3.65	0.05	77.34	0.05
100	1.89	0.02	80.03	0.06

Table 4-31: DSR Results of RTFO Aged RAP Binder (Wilmington – 3)

Temperature °C	|G*|/sinδ (kPa)		δ°(Phase Angle)	
	Mean	Std. Deviation	Mean	Std. Deviation
64	140.57	1.68	61.84	0.19
70	67.94	1.70	64.36	0.03
76	32.22	0.68	67.50	0.23
82	15.53	0.25	70.71	0.19
88	7.66	0.11	73.86	0.20
94	3.90	0.03	76.82	0.04
100	2.04	0.02	79.44	0.03

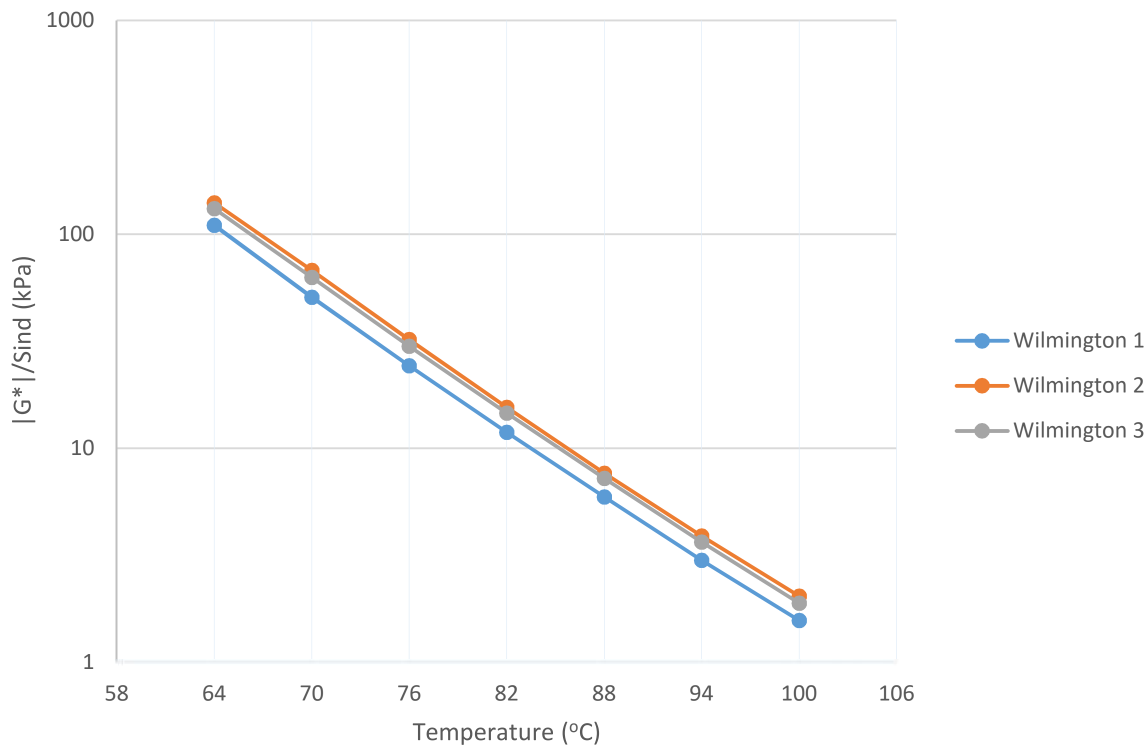

Figure 4-10: DSR Results for the Wilmington RAP Binders (RTFO Aged) at Various Temperatures

The Wilmington RAP binders in their RTFO aged state showed lesser variability in their high temperature PG grade and the Superpave condition of |G*|/sinδ < 2.2kPa was met at a temperature of 100ºC for all the three Wilmington RAP binders. These three RAP binders qualified for a high temperature PG grade of 94.

4.2.2. Source of RAP – Pineville

The extracted RAP binders from three randomly selected locations within Pineville stockpile were tested on the DSR in their RTFO aged conditions. Table 4-32, Table 4-33 and Table 4-34, and Figure 4-11 show the results of the DSR testing on these three binders. The mean values of |G*|/sinδ and standard deviations are shown in the tables.

Table 4-32: DSR Results of RTFO Aged RAP Binder (Pineville – 1)

Temperature	|G*|/sinδ (kPa)		δº(Phase Angle)	
ºC	Mean	Std. Deviation	Mean	Std. Deviation
64	95.63	0.59	65.28	0.06
70	42.27	1.15	68.40	0.25
76	20.20	0.24	71.53	0.30
82	9.81	0.02	74.73	0.07
88	4.79	0.02	77.75	0.04
94	2.39	0.01	80.38	0.04
100	1.23	0.01	82.64	0.04

Table 4-33: DSR Results of RTFO Aged RAP Binder (Pineville – 2)

Temperature	|G*|/sinδ (kPa)		δº(Phase Angle)	
ºC	Mean	Std. Deviation	Mean	Std. Deviation
64	115.77	0.13	64.35	0.09
70	54.00	1.29	67.36	0.31
76	24.90	0.10	70.76	0.14
82	11.90	0.01	73.69	0.07
88	5.77	0.02	76.64	0.01
94	2.88	0.02	79.42	0.02
100	1.48	0.01	81.79	0.07

Table 4-34: DSR Results of RTFO Aged RAP Binder (Pineville – 3)

Temperature °C	|G*|/sinδ (kPa)		δ°(Phase Angle)	
	Mean	Std. Deviation	Mean	Std. Deviation
64	70.82	1.77	66.07	0.06
70	32.96	1.95	68.99	0.29
76	15.13	0.38	72.52	0.21
82	7.17	0.03	75.64	0.05
88	3.53	0.02	78.54	0.10
94	1.78	0.01	81.02	0.02

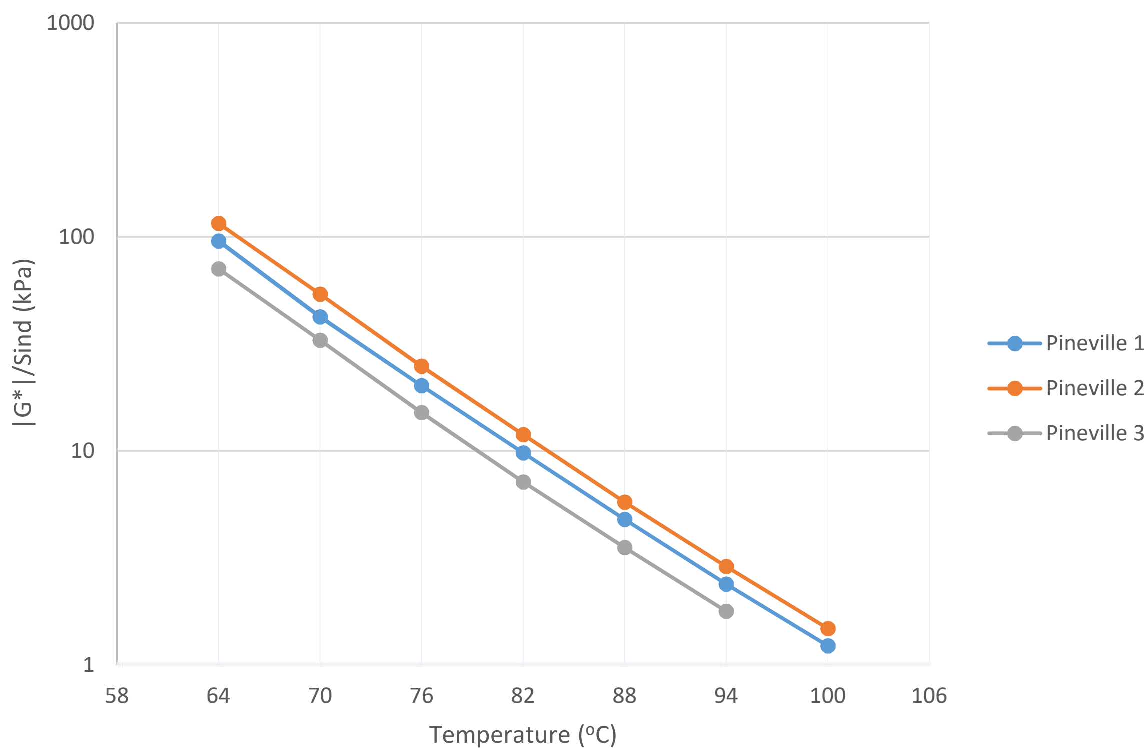

Figure 4-11: DSR Results for the Pineville RAP Binders (RTFO Aged) at Various Temperatures

For the RTFO aged Pineville RAP binders, the condition of |G*|/sinδ < 2.2kPa was met at a temperature of 100°C for Pineville 1 and Pineville 2 RAP binders, and at a temperature of

94^{o}C for Pineville 3 RAP binders. Pineville 1 and Pineville 2 RAP binders qualified for a high temperature PG grade of 94 and Pineville 3 RAP binder qualified for a high temperature PG grade of 88.

4.2.3. Source of RAP – Maymead

The three RAP binders from the Maymead stockpile were also tested in their RTFO aged conditions. Table 4-35, Table 4-36 and Table 4-37, and Figure 4-12 show the results of the DSR testing on these three binders. The mean values of |G*|/sinδ and standard deviations are shown in the tables.

Table 4-35: DSR Results of RTFO Aged RAP Binder (Maymead – 1)

Temperature	|G*|/sinδ (kPa)		δ^{o}(Phase Angle)	
^{o}C	Mean	Std. Deviation	Mean	Std. Deviation
64	315.38	24.06	58.33	1.10
70	165.60	4.95	59.55	0.34
76	77.77	2.15	62.70	0.11
82	37.03	0.74	66.23	0.15
88	18.04	0.22	69.69	0.08
94	8.89	0.05	73.12	0.08
100	4.48	0.03	76.30	0.06
106	2.31	0.02	79.11	0.05
112	1.22	0.01	81.62	0.05

Table 4-36: DSR Results of RTFO Aged RAP Binder (Maymead – 2)

Temperature °C	$\|G^*\|/\sin\delta$ (kPa)		δ° (Phase Angle)	
	Mean	**Std. Deviation**	**Mean**	**Std. Deviation**
64	261.07	4.41	59.60	0.03
70	125.49	2.45	62.27	0.05
76	56.97	1.31	66.06	0.16
82	26.44	0.69	69.79	0.19
88	12.39	0.31	73.41	0.20
94	5.97	0.15	76.87	0.08
100	2.97	0.07	79.86	0.06
106	1.51	0.04	82.36	0.08

Table 4-37: DSR Results of RTFO Aged RAP Binder (Maymead – 3)

Temperature °C	$\|G^*\|/\sin\delta$ (kPa)		δ° (Phase Angle)	
	Mean	**Std. Deviation**	**Mean**	**Std. Deviation**
64	205.27	1.26	60.56	0.02
70	98.18	4.04	63.49	0.13
76	45.34	1.91	67.02	0.06
82	21.20	0.52	70.64	0.27
88	9.98	0.07	74.07	0.10
94	4.89	0.03	77.23	0.12
100	2.46	0.01	80.08	0.08
106	1.27	0.01	82.54	0.07

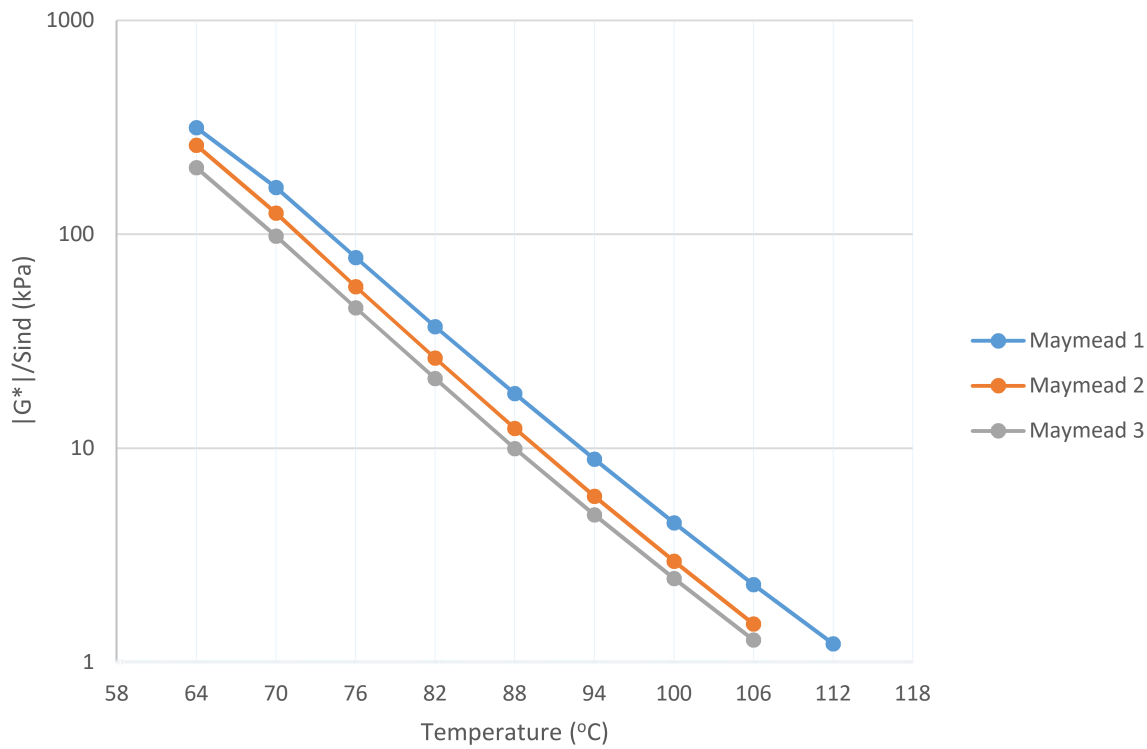

Figure 4-12: DSR Results for the Maymead RAP Binders (RTFO Aged) at Various Temperatures

In the case of the three RAP binders from Maymead stockpile, the condition of $|G^*|/\sin\delta < 2.2$kPa was met at a temperature of 112ºC for Maymead 1 RAP binder, and at a temperature of 106ºC for Maymead 2 and Maymead 3 RAP binders. Maymead 1 RAP binder qualified for a high temperature PG grade of 106, and Maymead 2 and Maymead 3 RAP binders qualified for a high temperature PG grade of 100 based on the DSR tests on RTFO binders.

4.2.4. Source of RAP – Sunrock

Table 4-38, Table 4-39 and Table 4-40, and Figure 4-13 show the results of the DSR testing on the three RTFO aged Sunrock binders. The mean values of |G*|/sinδ and standard deviations are shown in the tables.

Table 4-38: DSR Results of RTFO Aged RAP Binder (Sunrock – 1)

Temperature °C	|G*|/sinδ (kPa)		δ°(Phase Angle)	
	Mean	Std. Deviation	Mean	Std. Deviation
64	122.9	1.58	62.55	0.20
70	57.61	1.72	65.48	0.09
76	26.64	0.48	69.03	0.12
82	12.49	0.17	72.55	0.22
88	6.01	0.05	75.89	0.13
94	2.96	0.02	78.85	0.10
100	1.51	0.01	81.40	0.03

Table 4-39: DSR Results of RTFO Aged RAP Binder (Sunrock – 2)

Temperature °C	|G*|/sinδ (kPa)		δ°(Phase Angle)	
	Mean	Std. Deviation	Mean	Std. Deviation
64	127.07	1.37	61.9	0.06
70	59.31	0.78	64.77	0.09
76	27.76	0.26	68.08	0.08
82	13.28	0.14	71.67	0.05
88	6.47	0.07	74.84	0.04
94	3.21	0.04	77.81	0.11
100	1.63	0.02	80.49	0.03

Table 4-40: DSR Results of RTFO Aged RAP Binder (Sunrock – 3)

Temperature °C	|G*|/sinδ (kPa)		δ°(Phase Angle)	
	Mean	Std. Deviation	Mean	Std. Deviation
64	137.52	1.58	60.70	0.07
70	64.52	2.79	63.30	0.19
76	30.30	0.59	67.00	0.22
82	14.41	0.18	70.62	0.21
88	6.99	0.12	73.97	0.04
94	3.45	0.05	77.13	0.04
100	1.74	0.02	79.94	0.03

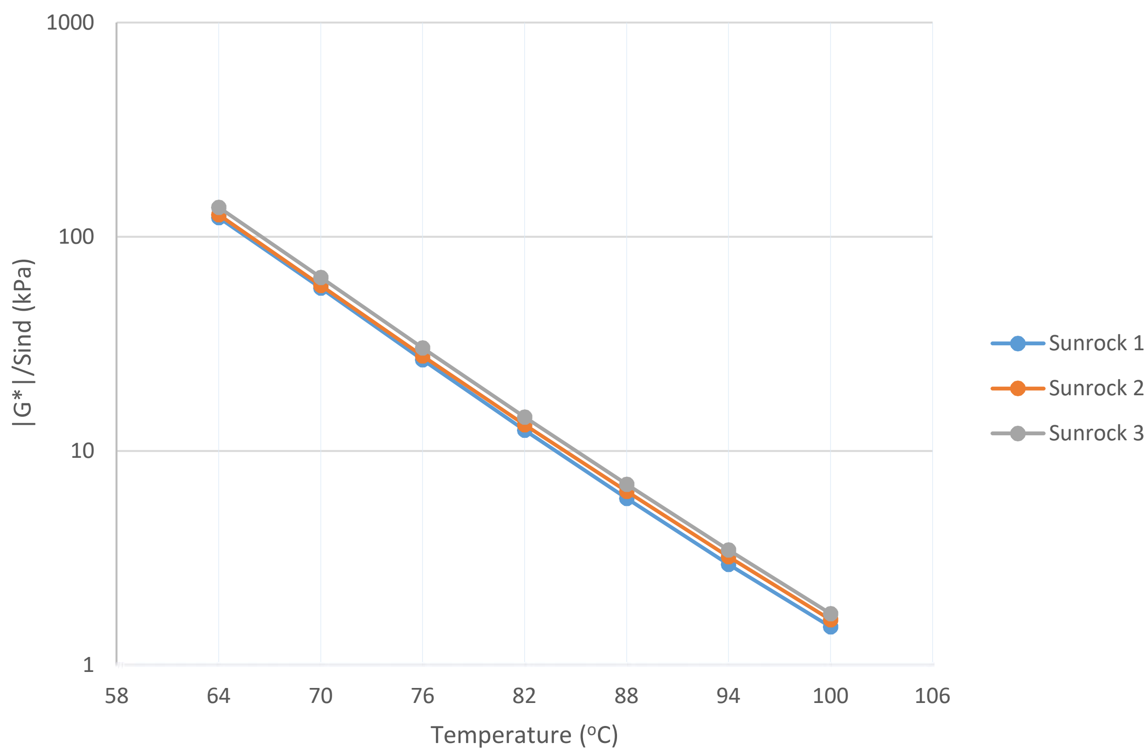

Figure 4-13: DSR Results for the Sunrock RAP Binders (RTFO Aged) at Various Temperatures

The $|G^*|/\sin\delta$ values decreased as temperature increased and the condition of $|G^*|/\sin\delta < 2.2$kPa was met at a temperature of 100°C for all the three Sunrock RAP binders. All the Sunrock RAP binders qualified for a high temperature PG grade of 94 based on DSR tests on RTFO aged binders. Again, the RAP binders from Sunrock stockpile showed relatively lesser variability in their high temperature PG grades in their RTFO aged state.

4.2.5. Source of RAP – Sims

Table 4-41, Table 4-42 and Table 4-43, and Figure 4-14 show the results of the DSR testing on the three Sims RAP binders. The mean values of $|G^*|/\sin\delta$ and standard deviations are shown in the tables.

Table 4-41: DSR Results of RTFO Aged RAP Binder (Sims – 1)

Temperature	$\|G^*\|/\sin\delta$ (kPa)		δ^o (Phase Angle)	
°C	Mean	Std. Deviation	Mean	Std. Deviation
64	426.60	8.65	54.02	0.18
70	210.63	5.52	54.89	0.13
76	106.62	2.48	56.78	0.36
82	55.51	1.23	59.29	0.29
88	29.59	0.66	61.96	0.16
94	16.04	0.32	64.67	0.06
100	8.79	0.17	67.33	0.20
106	4.84	0.09	70.10	0.15
112	2.70	0.06	72.80	0.15
118	1.54	0.03	75.41	0.15

Table 4-42: DSR Results of RTFO Aged RAP Binder (Sims – 2)

Temperature	$\|G^*\|/\sin\delta$ (kPa)		δ^o (Phase Angle)	
^oC	Mean	Std. Deviation	Mean	Std. Deviation
64	669.31	15.80	54.70	0.11
70	350.10	7.47	55.82	0.37
76	171.09	3.50	58.16	0.08
82	85.31	1.52	60.53	0.11
88	43.39	0.84	63.09	0.06
94	22.40	0.51	65.75	0.27
100	11.75	0.30	68.53	0.17
106	6.32	0.16	71.25	0.07
112	3.47	0.08	73.92	0.08
118	1.94	0.04	76.49	0.10

Table 4-43: DSR Results of RTFO Aged RAP Binder (Sims – 3)

Temperature	$\|G^*\|/\sin\delta$ (kPa)		δ^o (Phase Angle)	
^oC	Mean	Std. Deviation	Mean	Std. Deviation
64	355.88	0.70	55.66	0.08
70	184.86	2.28	57.06	0.02
76	92.23	0.51	59.35	0.05
82	46.84	0.11	62.01	0.10
88	24.07	0.29	64.74	0.04
94	12.54	0.04	67.57	0.06
100	6.68	0.01	70.44	0.13
106	3.64	0.01	73.31	0.09
112	2.02	0.01	75.98	0.10

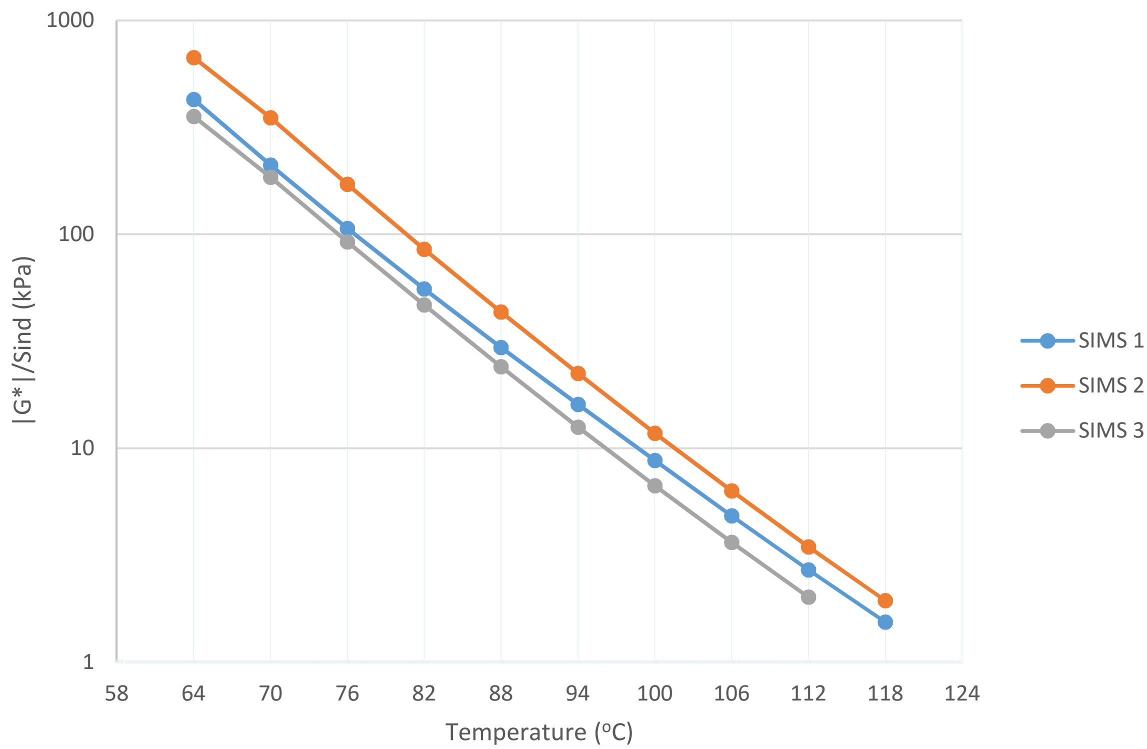

Figure 4-14: DSR Results for the Sims RAP Binders (RTFO Aged) at Various Temperatures

It can be observed that RAP binders from the Sims stockpile were stiffer than the binders from all other stockpiles. The condition of |G*|/sinδ < 2.2kPa was met at a relatively higher temperature of 118°C for Sims 1 and Sims 2 RAP binders, and at a temperature of 112°C for Sims 3 RAP binder. Sims 1 and Sims 2 RAP binders qualified for a high temperature PG grade of 112. Sims 3 RAP binder qualified for a high temperature PG grade of 106°C based on DSR tests on RTFO aged binders.

4.2.6. Source of RAP – Weaverville

The three binders extracted from RAP sampled randomly within the Weaverville stockpile were also aged in an RTFO under standard conditions and were tested on the DSR at various temperatures. Table 4-44, Table 4-45 and Table 4-46, and Figure 4-15 show the results of the DSR testing on the three extracted RAP binders. The mean values of |G*|/sinδ and standard deviations are shown in the tables.

Table 4-44: DSR Results of RTFO Aged RAP Binder (Weaverville – 1)

Temperature	|G*|/sinδ (kPa)		δ° (Phase Angle)	
°C	Mean	Std. Deviation	Mean	Std. Deviation
64	103.99	1.18	63.83	0.14
70	47.64	1.35	66.84	0.59
76	21.75	0.29	70.62	0.08
82	10.12	0.12	74.24	0.08
88	4.81	0.03	77.60	0.05
94	2.35	0.02	80.45	0.07
100	1.18	0.01	82.85	0.06

Table 4-45: DSR Results of RTFO Aged RAP Binder (Weaverville – 2)

Temperature	|G*|/sinδ (kPa)		δ° (Phase Angle)	
°C	Mean	Std. Deviation	Mean	Std. Deviation
64	103.08	1.23	63.63	0.04
70	48.55	0.81	66.69	0.04
76	21.92	0.08	70.46	0.05
82	10.09	0.16	74.14	0.12
88	4.79	0.07	77.35	0.04
94	2.34	0.03	80.20	0.08
100	1.18	0.01	82.60	0.07

Table 4-46: DSR Results of RTFO Aged RAP Binder (Weaverville – 3)

Temperature	|G*|/sinδ (kPa)		δº(Phase Angle)	
ºC	Mean	Std. Deviation	Mean	Std. Deviation
64	141.37	0.36	61.66	0.09
70	66.43	0.96	64.41	0.20
76	30.60	0.12	67.88	0.10
82	14.32	0.11	71.46	0.03
88	6.87	0.06	74.74	0.04
94	3.37	0.02	77.83	0.15
100	1.70	0.02	80.58	0.06

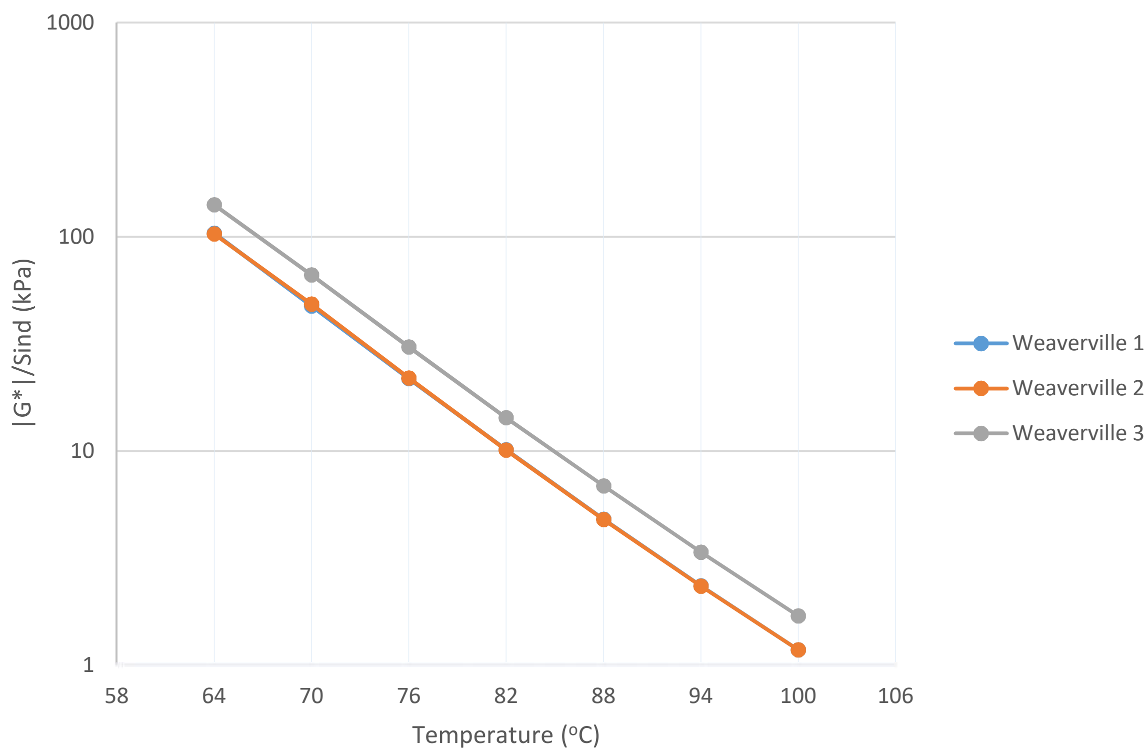

Figure 4-15: DSR Results for the Weaverville RAP Binders (RTFO Aged) at Various Temperatures

It can be observed from the above tables and the figure that the |G*|/sinδ values decreased as temperature increased and the condition of |G*|/sinδ < 2.2kPa was met at a temperature of 100°C for the three Weaverville RAP binders. The three Weaverville RAP binders qualified for a high temperature PG grade of 94 based on the DSR tests on RTFO aged binders.

4.2.7. Source of RAP – Highland

The three extracted binders from three different locations in Highland stockpile were also aged in an RTFO under standard conditions and tested on the DSR at various temperatures. Table 4-47, Table 4-48 and

Table 4-49, and Figure 4-16 show the results of the DSR testing on the three Highland RAP binders. The mean values of |G*|/sinδ and standard deviations are shown in the tables.

Table 4-47: DSR Results of RTFO Aged RAP Binder (Highland – 1)

Temperature	|G*|/sinδ (kPa)		δ° (Phase Angle)	
°C	Mean	Std. Deviation	Mean	Std. Deviation
64	110.11	1.52	63.10	0.11
70	50.83	1.23	66.17	0.10
76	23.62	0.42	69.74	0.13
82	11.16	0.12	73.28	0.14
88	5.39	0.06	76.58	0.09
94	2.65	0.03	79.50	0.04
100	1.34	0.01	82.00	0.05

Table 4-48: DSR Results of RTFO Aged RAP Binder (Highland – 2)

Temperature	$\|G^*\|/\sin\delta$ (kPa)		δ^o (Phase Angle)	
^oC	Mean	Std. Deviation	Mean	Std. Deviation
64	99.84	1.67	64.12	0.16
70	45.84	0.45	67.26	0.19
76	21.09	0.25	70.86	0.10
82	9.87	0.12	74.44	0.30
88	4.71	0.05	77.70	0.02
94	2.32	0.01	80.45	0.05
100	1.18	0.01	82.84	0.02

Table 4-49: DSR Results of RTFO Aged RAP Binder (Highland – 3)

Temperature	$\|G^*\|/\sin\delta$ (kPa)		δ^o (Phase Angle)	
^oC	Mean	Std. Deviation	Mean	Std. Deviation
64	102.94	0.93	63.40	0.15
70	48.13	0.80	66.39	0.21
76	21.90	0.17	70.00	0.27
82	10.20	0.13	73.78	0.05
88	4.86	0.05	77.13	0.11
94	2.40	0.01	80.05	0.05
100	1.21	0.01	82.51	0.04

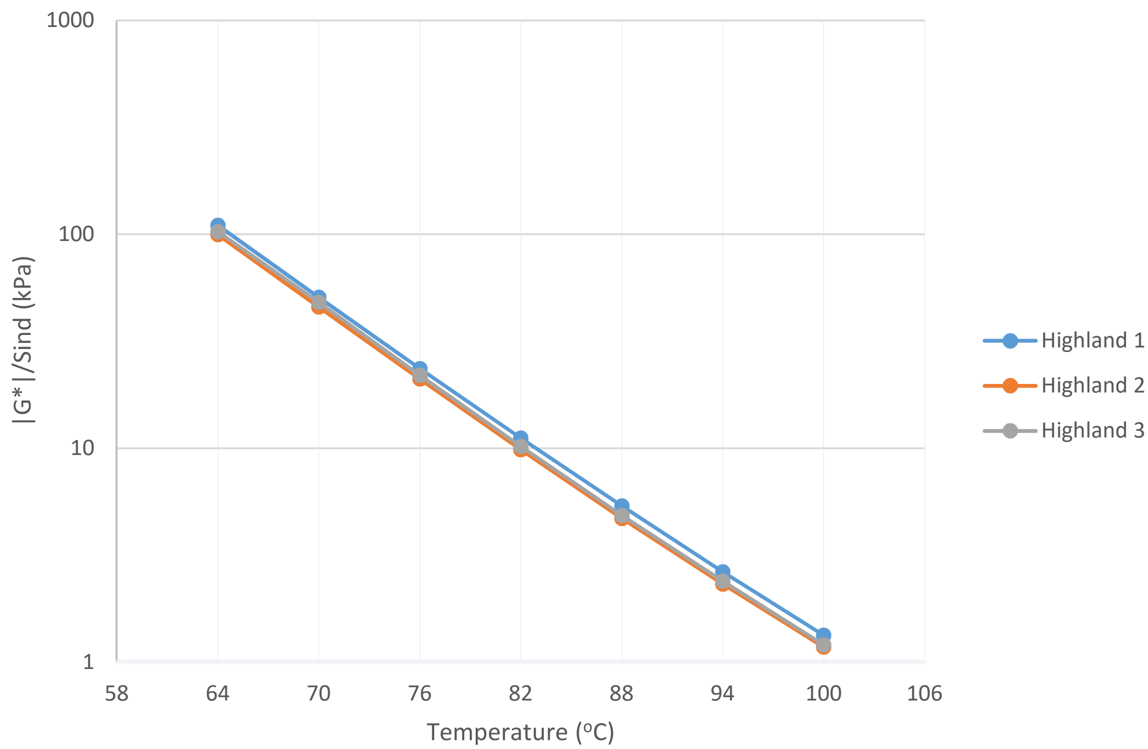

Figure 4-16: DSR Results for the Highland RAP Binders (RTFO Aged) at Various Temperatures

In the case of RAP binders from the Highland stockpile, the |G*|/sinδ values decreased as temperature increased and the condition of |G*|/sinδ < 2.2kPa was met at a temperature of 100°C for all the three Highland RAP binders. Therefore, all the three Highland RAP binders qualified for a high temperature PG grade of 94 based on the DSR tests on RTFO aged binders.

4.2.8. Source of RAP – Harrison

The RTFO aged binders from the three locations of Harrison stockpile were also tested on the DSR at various high temperatures. Table 4-50, Table 4-51 and Table 4-52, and Figure 4-17 show the results of DSR testing on the three Harrison RAP binders. The mean values of $|G^*|/\sin\delta$ and standard deviations are shown in the tables.

Table 4-50: DSR Results of RTFO Aged RAP Binder (Harrison – 1)

Temperature	$\|G^*\|/\sin\delta$ (kPa)		δ^o (Phase Angle)	
^oC	Mean	Std. Deviation	Mean	Std. Deviation
64	106.15	2.12	64.26	0.16
70	47.50	0.18	67.47	0.49
76	21.12	0.34	71.48	0.21
82	9.49	0.19	75.45	0.13
88	4.40	0.09	78.96	0.16
94	2.08	0.04	81.74	0.14

Table 4-51: DSR Results of RTFO Aged RAP Binder (Harrison – 2)

Temperature	$\|G^*\|/\sin\delta$ (kPa)		δ^o (Phase Angle)	
^oC	Mean	Std. Deviation	Mean	Std. Deviation
64	76.56	0.62	68.70	0.11
70	33.33	0.58	72.20	0.18
76	14.53	0.19	76.10	0.19
82	6.51	0.09	79.39	0.10
88	3.02	0.02	82.16	0.06
94	1.45	0.02	84.42	0.07

Table 4-52: DSR Results of RTFO Aged RAP Binder (Harrison – 3)

Temperature °C	$\|G^*\|/\sin\delta$ (kPa)		δ° (Phase Angle)	
	Mean	Std. Deviation	Mean	Std. Deviation
64	45.91	0.31	70.92	0.06
70	20.12	0.08	74.67	0.24
76	8.65	0.08	78.14	0.11
82	3.91	0.01	81.19	0.08
88	1.84	0.01	83.66	0.06

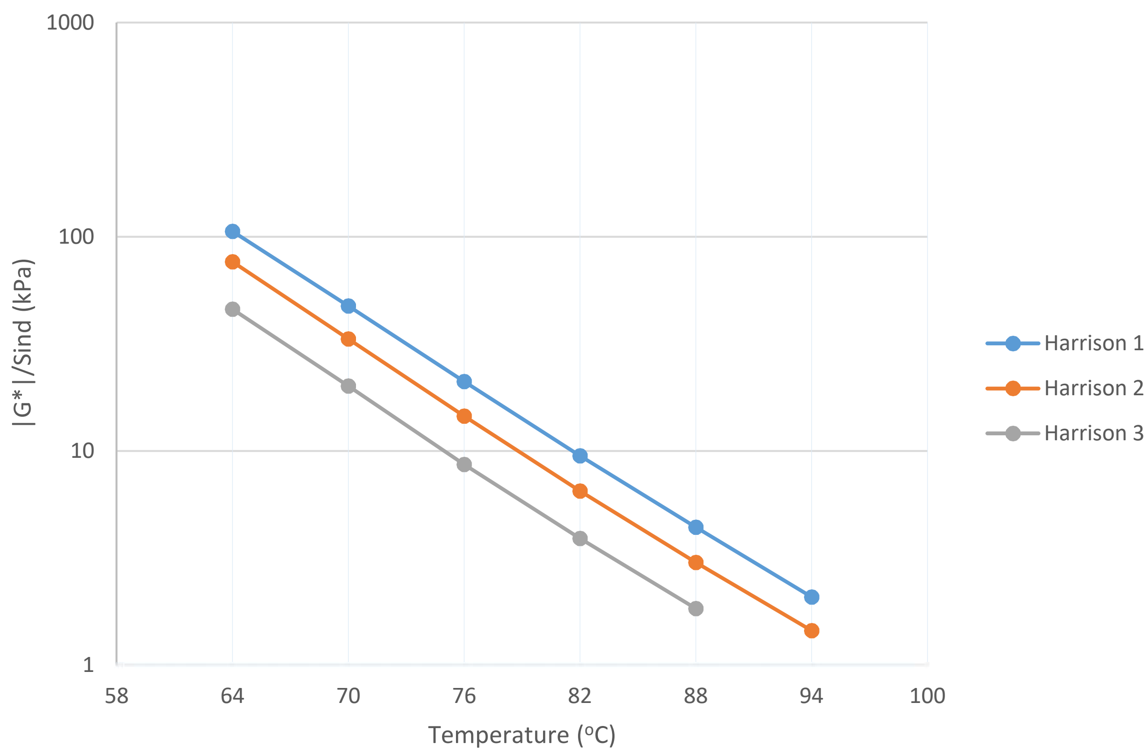

Figure 4-17: DSR Results for the Harrison RAP Binders (RTFO Aged) at Various Temperatures

From the above tables and figure, it can be observed that the condition of $|G^*|/\sin\delta <$ 2.2kPa was met at a temperature of 94°C for Harrison 1 and Harrison 2 RAP binders, and at a temperature of 88^{o}C for Harrison 3 RAP binder. Harrison 1 and Harrison 2 RAP binders qualified for a high temperature PG grade of 88. Harrison 3 RAP binder qualified for a high temperature PG grade of 82^{o}C based on DSR tests on RTFO aged binders.

4.2.9. Source of RAP – Burlington

The extracted binders from the three locations of the Burlington stockpile were also aged in an RTFO under standard conditions and tested on the DSR. Table 4-53, Table 4-54and Table 4-55, and Figure 4-18 show the results of DSR testing on the three RTFO aged Burlington RAP binders. The mean values of |G*|/sinδ and standard deviations are shown in the tables.

Table 4-53: DSR Results of RTFO Aged RAP Binder (Burlington – 1)

Temperature	|G*|/sinδ (kPa)		δ^{o} (Phase Angle)	
^{o}C	Mean	Std. Deviation	Mean	Std. Deviation
64	99.12	1.75	65.25	0.18
70	44.40	0.43	68.12	0.45
76	20.21	0.24	71.83	0.31
82	9.52	0.20	75.23	0.28
88	4.53	0.09	78.47	0.07
94	2.21	0.03	81.15	0.08
100	1.12	0.01	83.37	0.00

Table 4-54: DSR Results of RTFO Aged RAP Binder (Burlington – 2)

Temperature	|G*|/sinδ (kPa)		δº (Phase Angle)	
ºC	Mean	Std. Deviation	Mean	Std. Deviation
64	113.37	0.72	65.28	0.05
70	51.00	1.50	68.36	0.10
76	22.81	0.49	72.01	0.22
82	10.56	0.06	75.48	0.13
88	4.98	0.03	78.56	0.05
94	2.42	0.01	81.26	0.07
100	1.22	0.01	83.61	0.01

Table 4-55: DSR Results of RTFO Aged RAP Binder (Burlington – 3)

Temperature	|G*|/sinδ (kPa)		δº (Phase Angle)	
ºC	Mean	Std. Deviation	Mean	Std. Deviation
64	104.20	1.30	66.39	0.04
70	45.70	1.82	69.72	0.28
76	20.61	0.52	73.11	0.05
82	9.58	0.10	76.43	0.09
88	4.51	0.06	79.51	0.06
94	2.18	0.04	82.02	0.01

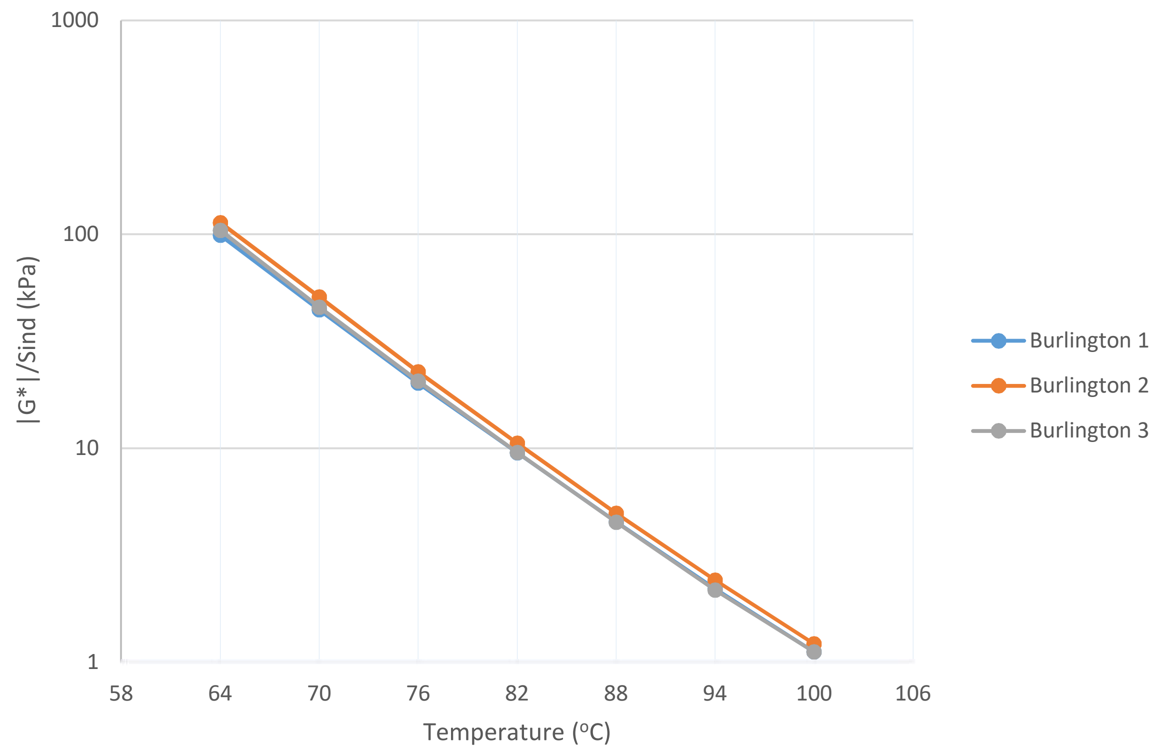

Figure 4-18: DSR Results for the Burlington RAP Binders (RTFO Aged) at Various Temperatures

The condition of |G*|/sinδ < 2.2kPa was met at a temperature of 100^{o}C for Burlington 1 and Burlington 2 RAP binders and, at a temperature of 94^{o}C for Burlington 3 RAP binder. Burlington 1 and Burlington 2 RAP binders qualified for a high temperature PG grade of 94. Burlington 3 RAP binder qualified for a high temperature PG grade of 88^{o}C.

4.3. RAP Binders in PAV Aged Conditions

All the RTFO aged RAP binders were further aged in a Pressure Aging Vessel (PAV) in accordance with AASHTO PP1 "Standard Practice for Accelerated Aging of Asphalt Binder Using a Pressurized Aging Vessel (PAV)". The PAV aged binders were tested on the DSR at intermediate test temperatures and standard conditions. The results from the DSR testing on the PAV aged binders are discussed in this section.

4.3.1. Source of RAP – Wilmington

The three PAV aged RAP binders from Wilmington stockpile were tested using the DSR at intermediate temperatures.

Table 4-56, Table 4-57 and Table 4-58, and Figure 4-19 show the results of the DSR testing on the three binders. The mean values of |G*|sinδ and standard deviations are shown in the tables.

Table 4-56: DSR Results of PAV Aged RAP Binder (Wilmington – 1)

Temperature °C	|G*|sinδ (kPa)		δ°(Phase Angle)	
	Mean	Std. Deviation	Mean	Std. Deviation
16	27717.77	273.72	27.61	0.13
19	21973.27	414.11	28.96	0.20
22	17416.80	298.03	31.03	0.20
25	13594.97	198.56	33.12	0.21
28	10453.67	114.93	35.32	0.08
31	7911.71	58.77	37.40	0.12
34	5909.27	54.67	39.54	0.07
37	4355.32	45.22	41.64	0.09

Table 4-57: DSR Results of PAV Aged RAP Binder (Wilmington – 2)

Temperature	|G*|sinδ (kPa)		δº(Phase Angle)	
ºC	Mean	Std. Deviation	Mean	Std. Deviation
16	30550.83	543.38	26.31	0.26
19	24411.1	764.08	27.74	0.14
22	19612.43	470.89	29.74	0.26
25	15503.03	359.52	31.81	0.26
28	12050.7	304.99	33.89	0.23
31	9260.1	252.21	36.07	0.24
34	7022.17	233.14	38.18	0.3
37	5250	189.07	40.27	0.33
40	3885.04	140.92	42.3	0.38

Table 4-58: DSR Results of PAV Aged RAP Binder (Wilmington – 3)

Temperature	|G*|sinδ (kPa)		δº(Phase Angle)	
ºC	Mean	Std. Deviation	Mean	Std. Deviation
16	29797.37	668.66	26.55	0.16
19	24423.63	873.36	27.97	0.2
22	19579.13	817.05	29.98	0.25
25	15357.27	654.34	31.92	0.22
28	11975.67	551.17	34.08	0.37
31	9150.94	431.55	36.04	0.35
34	6967.47	377.00	38.21	0.64
37	5187.99	306.43	40.04	0.61
40	3812.83	169.12	42.12	0.26

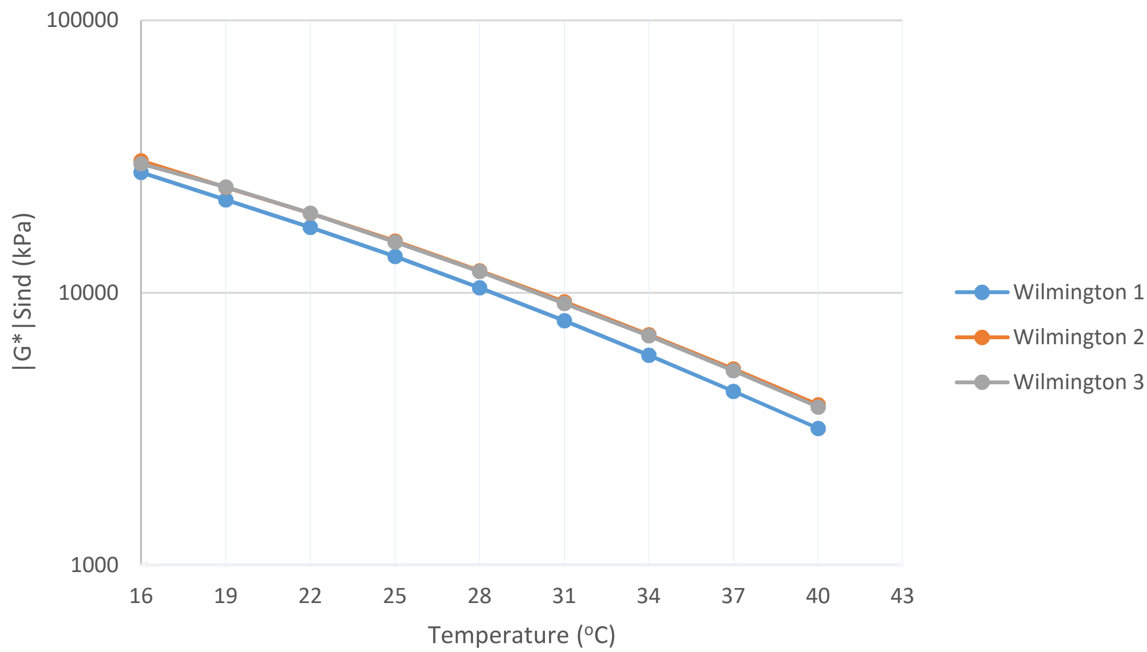

Figure 4-19: DSR Results for the Wilmington RAP Binders (PAV Aged) at Various Temperatures

It can be observed from the above tables and the figure that the |G*|sinδ values decreased as test temperatures increased. The condition of |G*|sinδ < 5000kPa was met at a temperature of 37ºC for Wilmington 1 RAP binder, and at a test temperature of 40ºC for Wilmington 2 and Wilmington 3 RAP binders. The PAV aged Wilmington 1 RAP binder was softer than the Wilmington 2 and Wilmington 3 RAP binders in their PAV aged conditions and Wilmington 3 RAP binder was softer than the Wilmington 2 RAP binder in the PAV aged state.

4.3.2. Source of RAP – Pineville

The results of testing the PAV aged RAP binders from Pineville stockpile are discussed in this section. Table 4-59, Table 4-60 and Table 4-61, and Figure 4-20 show the results of the DSR testing on these three binders. The mean values of |G*|sinδ and standard deviations are shown in the tables.

Table 4-59: DSR Results of PAV Aged RAP Binder (Pineville – 1)

Temperature	|G*|sinδ (kPa)		δº (Phase Angle)	
ºC	Mean	Std. Deviation	Mean	Std. Deviation
16	24731.93	855.53	28.45	0.18
19	19960.8	450.69	29.83	0.11
22	15864.8	272.38	31.94	0.12
25	12408.7	156.62	34.15	0.07
28	9507.17	70.64	36.3	0.15
31	7207.47	72.69	38.61	0.24
34	5366.17	84.71	40.89	0.19
37	3956.85	67.38	43.1	0.33

Table 4-60: DSR Results of PAV Aged RAP Binder (Pineville – 2)

Temperature	|G*|sinδ (kPa)		δº (Phase Angle)	
ºC	Mean	Std. Deviation	Mean	Std. Deviation
16	26453.5	1348.88	26.59	0.24
19	21607.57	975.27	28.15	0.07
22	17225.63	738.27	30.05	0.19
25	13699.87	599.17	32.25	0.18
28	10589.33	474.16	34.4	0.17
31	8123.57	345.73	36.65	0.27
34	6118.55	252.66	38.83	0.33
37	4545.44	207.66	41.1	0.24

Table 4-61: DSR Results of PAV Aged RAP Binder (Pineville – 3)

Temperature	|G*|sinδ (kPa)		δ° (Phase Angle)	
°C	Mean	Std. Deviation	Mean	Std. Deviation
16	18906.23	409.10	30.42	0.07
19	15280.57	298.73	31.78	0.09
22	11867.27	216.70	33.86	0.14
25	9095.35	169.41	36.01	0.07
28	6861.62	141.24	38.16	0.05
31	5086.05	94.68	40.29	0.09
34	3715.38	66.73	42.37	0.06
37	2679.17	46.05	44.42	0.07

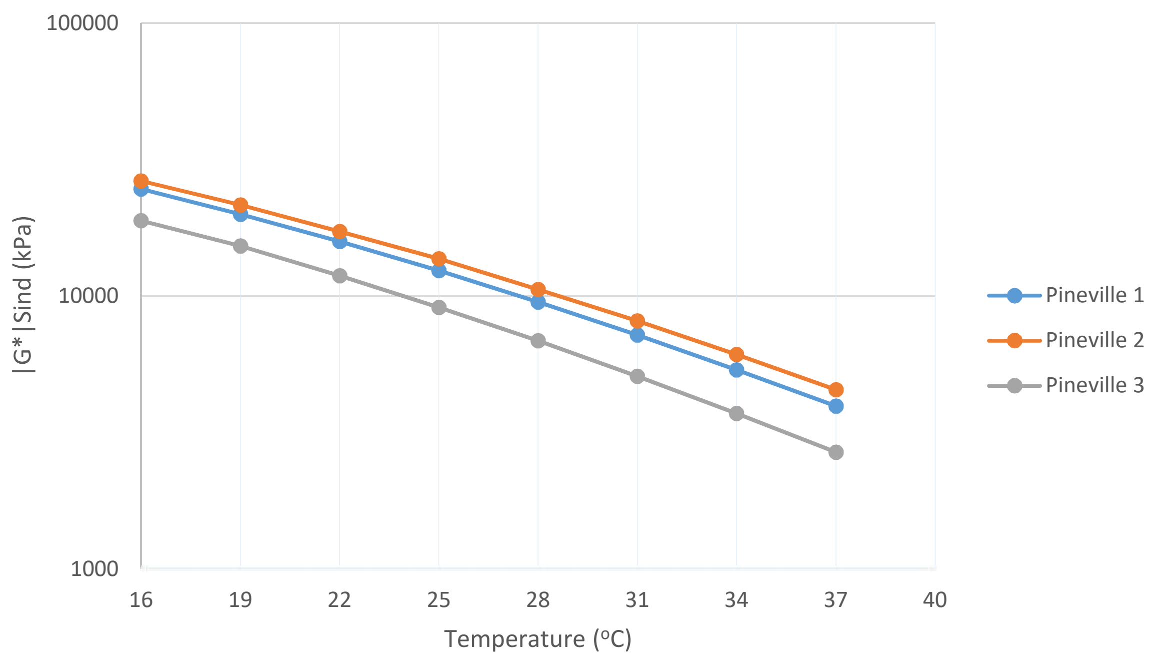

Figure 4-20: DSR Results for the Pineville RAP Binders (PAV Aged) at Various Temperatures

The condition of |G*|/sinδ < 5000kPa was met at a temperature of 37°C for Pineville 1 and Pineville 2 RAP binders, and at a temperature of 34°C for Pineville 3 RAP binder. Pineville

2 RAP binder was the stiffest among the three Pineville RAP binders followed by Pineville 1 and Pineville 3 RAP binders, respectively in their PAV aged conditions.

4.3.3. Source of RAP – Maymead

The PAV aged RAP binders from Maymead stockpile were also tested on the DSR at intermediate testing temperatures. Table 4-62, Table 4-63 and Table 4-64, and Figure 4-21 show the results of the DSR testing on these three binders. The mean values of |G*|/sinδ and standard deviations are shown in the tables.

Table 4-62: DSR Results of PAV Aged RAP Binder (Maymead – 1)

Temperature	|G*|sinδ (kPa)		δ° (Phase Angle)	
°C	Mean	Std. Deviation	Mean	Std. Deviation
16	30320.93	1567.62	21.48	0.25
19	25704.17	816.11	22.41	0.06
22	21764.27	690.45	23.97	0.11
25	18166.53	534.86	25.59	0.11
28	14984.13	450.77	27.35	0.18
31	12203.83	362.65	29.19	0.20
34	9810.21	278.52	31.07	0.23
37	7811.53	214.78	33.09	0.33
40	6130.97	147.29	35.09	0.38

Table 4-63: DSR Results of PAV Aged RAP Binder (Maymead – 2)

Temperature	|G*|sinδ (kPa)		δº (Phase Angle)	
ºC	Mean	Std. Deviation	Mean	Std. Deviation
16	22809.90	2144.27	22.53	0.70
19	19145.60	1102.49	23.68	0.58
22	16036.87	812.86	25.24	0.62
25	13282.70	584.57	26.88	0.70
28	10882.73	346.31	28.76	0.69
31	8786.62	220.63	30.61	0.82
34	7011.76	121.92	32.60	0.86
37	5522.44	45.92	34.66	0.97
40	4287.62	49.40	36.71	1.01

Table 4-64: DSR Results of PAV Aged RAP Binder (Maymead – 3)

Temperature	|G*|sinδ (kPa)		δº (Phase Angle)	
ºC	Mean	Std. Deviation	Mean	Std. Deviation
16	22210.93	335.46	25.19	0.25
19	18221.90	577.06	26.37	0.39
22	14968.40	469.22	28.24	0.46
25	12095.27	343.85	30.18	0.51
28	9612.39	297.19	32.11	0.66
31	7542.63	258.19	34.12	0.68
34	5827.79	204.02	36.24	0.83
37	4445.24	164.7	38.32	0.95

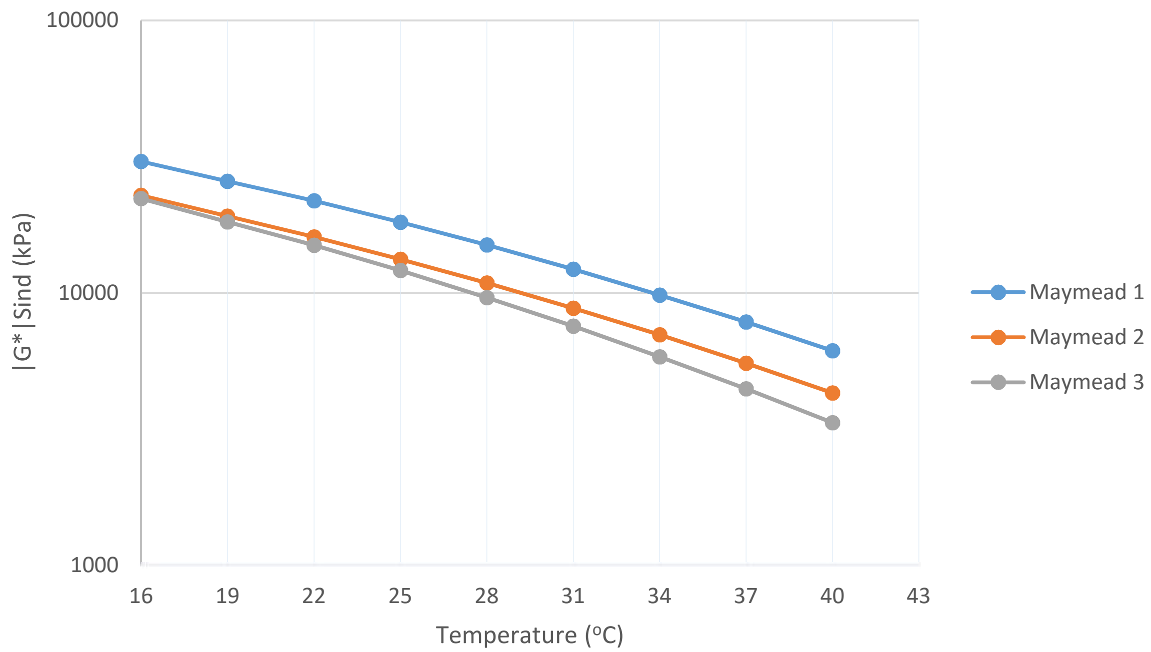

Figure 4-21: DSR Results for the Maymead RAP Binders (PAV Aged) at Various Temperatures

For the PAV aged binders from Maymead stockpile, the condition of |G*|sinδ < 5000kPa was met at a temperature of 43°C for Maymead 1 RAP binder, at a temperature of 40°C for Maymead 2 RAP binder, and at a temperature of 37°C for Maymead 3 RAP binder. Maymead 1 RAP binder showed the highest stiffness values for the intermediate test temperatures, followed by Maymead 2 RAP binder and, finally, Maymead 3 RAP binder in PAV aged conditions.

4.3.4. Source of RAP – Sunrock

The PAV aged RAP binders from the Sunrock stockpile were also tested on the DSR at intermediate test temperatures and the results are discussed in this section. Table 4-65, Table

4-66 and Table 4-67, and Figure 4-22 show the results of the DSR testing on these three RAP binders. The mean values of |G*|sinδ and standard deviations are shown in the tables.

Table 4-65: DSR Results of PAV Aged RAP Binder (Sunrock – 1)

Temperature	|G*|sinδ (kPa)		δº(Phase Angle)	
ºC	Mean	Std. Deviation	Mean	Std. Deviation
16	22995.77	262.92	27.7	0.18
19	18058.93	183.06	28.7	0.28
22	14597.07	169.59	30.39	0.18
25	11458.63	148.32	32.32	0.22
28	8896.35	123.71	34.15	0.25
31	6742.99	126.99	36.15	0.27
34	5092.26	72.47	38.04	0.43
37	3784.40	68.63	40.11	0.61

Table 4-66: DSR Results of PAV Aged RAP Binder (Sunrock – 2)

Temperature	|G*|sinδ (kPa)		δº(Phase Angle)	
ºC	Mean	Std. Deviation	Mean	Std. Deviation
16	23799.77	1424.39	27.88	0.32
19	20384.2	371.62	28.72	0.26
22	16503.27	357.18	30.66	0.06
25	13030.37	169.56	32.28	0.59
28	10007.65	82.71	34.21	0.62
31	7646.5	77.26	36.30	0.70
34	5726.52	60.86	38.12	0.95
37	4251.02	127.88	40.66	0.53

Table 4-67: DSR Results of PAV Aged RAP Binder (Sunrock – 3)

Temperature	|G*|sinδ (kPa)		δº(Phase Angle)	
ºC	Mean	Std. Deviation	Mean	Std. Deviation
16	21798.37	126.74	26.98	0.29
19	18388.5	649.59	28.13	0.51
22	15117.1	502.58	29.69	0.47
25	12144.53	425.89	31.48	0.58
28	9486.28	358.28	33.45	0.68
31	7230.91	334.12	35.45	0.88
34	5468.14	297.75	37.25	1.17
37	4090.84	87.99	39.38	0.30

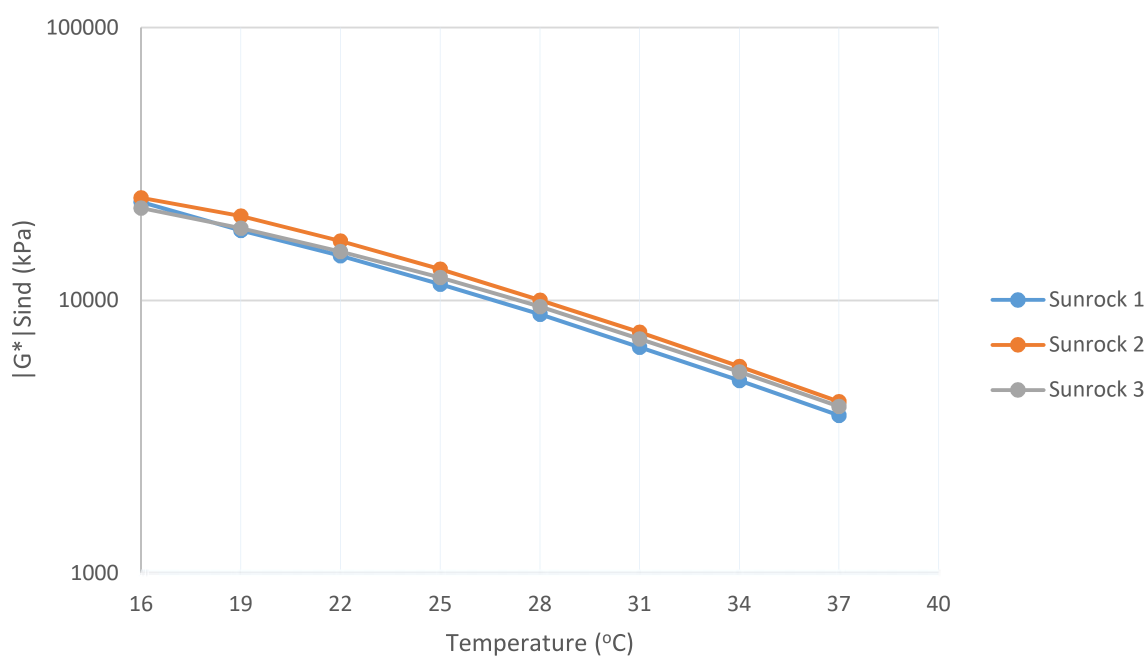

Figure 4-22: DSR Results for the Sunrock RAP Binders (PAV Aged) at Various Temperatures

The Superpave condition of |G*|sinδ < 5000kPa was met at a temperature of 37ºC for the three Sunrock RAP binders in their PAV aged state. PAV aged Sunrock 2 binder showed the highest stiffness in the range of intermediate test temperatures used. Sunrock 3 binder showed higher stiffness than Sunrock 1 binder for all temperatures except at 16°C.

4.3.5. Source of RAP – Sims

The three PAV aged RAP binders from the Sims stockpile were also tested on the DSR at intermediate testing temperatures under standard test conditions. Table 4-68, Table 4-69 and Table 4-70, and Figure 4-23 show the results of the DSR testing on the three Sims RAP binders. The mean values of |G*|sinδ and standard deviations are shown in the tables.

Table 4-68: DSR Results of PAV Aged RAP Binder (Sims – 1)

Temperature	|G*|sinδ (kPa)		δ° (Phase Angle)	
°C	Mean	Std. Deviation	Mean	Std. Deviation
16	45658.73	524.72	24.05	0.19
19	38483.73	1240.9	25.38	0.3
22	31319.9	800.38	27.15	0.35
25	25494.73	940.23	29.22	0.37
28	20102.53	892.42	31.31	0.36
31	15610.37	512.89	33.32	0.33
34	12006.43	394.25	35.25	0.34
37	9146.29	267.58	37.21	0.39
40	6871.58	208.78	38.99	0.38
43	5144.15	127.09	40.58	0.45

Table 4-69: DSR Results of PAV Aged RAP Binder (Sims – 2)

Temperature	|G*|sinδ (kPa)		δº (Phase Angle)	
ºC	Mean	Std. Deviation	Mean	Std. Deviation
16	57525.20	4218.58	22.59	1.52
19	51451.83	1501.60	23.06	0.17
22	43916.53	1831.49	24.79	0.06
25	36641.40	1393.20	26.79	0.27
28	29732.07	1258.69	28.78	0.19
31	23783.80	966.48	30.88	0.23
34	18669.77	679.25	32.92	0.32
37	14393.60	480.36	34.83	0.46
40	10961.60	401.91	36.82	0.51
43	8284.65	281.76	38.63	0.42
46	6293.87	196.84	40.42	0.57
49	4674.41	186.94	42.16	0.82

Table 4-70: DSR Results of PAV Aged RAP Binder (Sims – 3)

Temperature	|G*|sinδ (kPa)		δº (Phase Angle)	
ºC	Mean	Std. Deviation	Mean	Std. Deviation
16	43968.90	1420.19	25.03	0.25
19	39477.27	1819.73	26.30	0.23
22	32423.07	1131.00	28.15	0.34
25	26078.87	917.11	30.03	0.29
28	20376.27	708.26	31.81	0.42
31	15783.90	513.85	33.78	0.59
34	12090.70	464.44	35.63	0.62
37	9164.03	381.50	37.46	0.57
40	6846.94	295.53	39.25	0.52
43	5047.03	180.21	40.82	0.47
46	3757.85	136.56	41.74	0.42

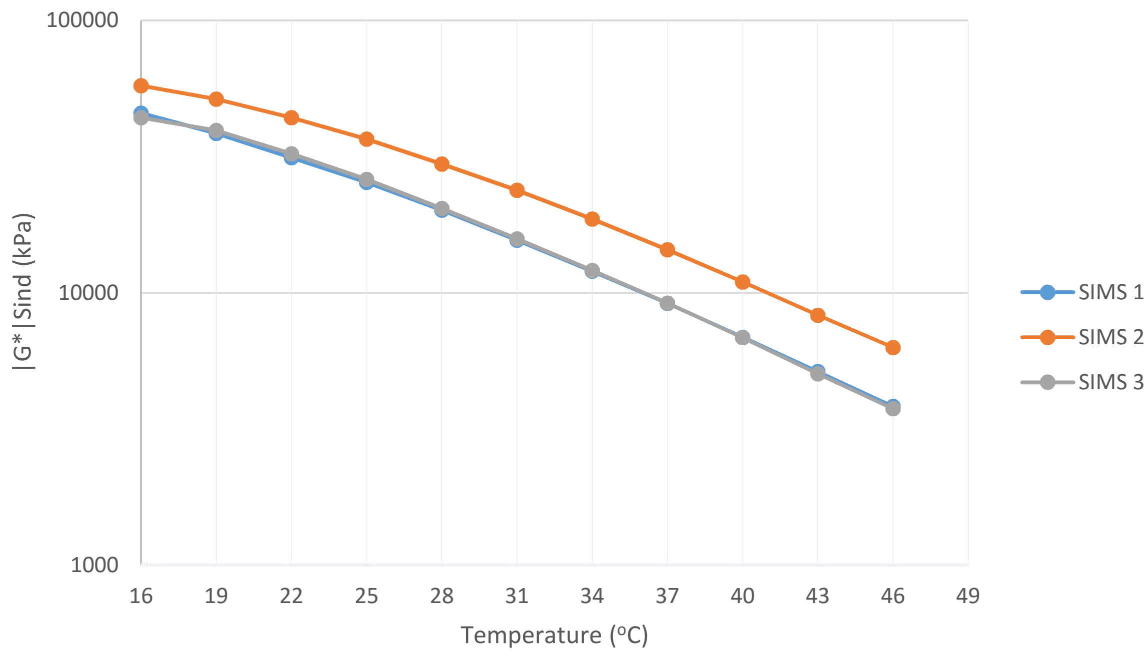

Figure 4-23: DSR Results for the Sims RAP Binders (PAV Aged) at Various Temperatures

As expected, the |G*|sinδ values decreased as the testing temperature increased. The condition of |G*|sinδ < 5000kPa was met at a temperature of 46°C for Sims 1 and Sims 3 RAP binders, and at a temperature of 49°C for Sims 3 RAP binder. Sims 2 RAP binder showed the highest stiffness values among the three Sims binders, followed by the Sims 1 RAP binder and, finally, Sims 3 RAP binder in their PAV aged conditions and the intermediate temperature range.

4.3.6. Source of RAP – Weaverville

The three Weaverville RAP binders were aged in the PAV and tested on the DSR at intermediate testing temperatures. Table 4-71, Table 4-72 and Table 4-73, and Figure 4-24 show the results of the DSR testing on the three extracted Weaverville RAP binders. The mean values of |G*|sinδ and standard deviations are shown in the tables below.

Table 4-71: DSR Results of PAV Aged RAP Binder (Weaverville – 1)

Temperature	|G*|sinδ (kPa)		δ° (Phase Angle)	
°C	Mean	Std. Deviation	Mean	Std. Deviation
16	20667.87	796.47	27.57	0.21
19	16735.40	713.35	28.73	0.44
22	13512.30	632.99	30.35	0.69
25	10657.70	460.46	32.32	0.82
28	8295.98	353.27	34.26	0.85
31	6407.61	273.39	36.35	0.77
34	4786.98	150.64	38.19	0.96

Table 4-72: DSR Results of PAV Aged RAP Binder (Weaverville – 2)

Temperature	|G*|sinδ (kPa)		δ° (Phase Angle)	
°C	Mean	Std. Deviation	Mean	Std. Deviation
16	18132.80	700.04	27.21	0.49
19	15018.73	911.21	28.05	0.44
22	12478.10	523.39	29.63	0.52
25	9901.52	422.62	31.47	0.58
28	7713.24	324.11	33.46	0.64
31	5934.49	215.22	35.34	0.84
34	4522.72	150.45	37.74	1.19

Table 4-73: DSR Results of PAV Aged RAP Binder (Weaverville – 3)

Temperature	|G*|sinδ (kPa)		δº(Phase Angle)	
ºC	Mean	Std. Deviation	Mean	Std. Deviation
16	22416.07	386.51	25.98	0.02
19	19332.67	909.94	27.22	0.28
22	16003.60	516.46	28.80	0.18
25	12996.00	335.11	30.56	0.06
28	10320.47	343.11	32.54	0.35
31	8081.95	185.76	34.73	0.27
34	6211.28	207.47	36.77	0.09
37	4706.34	125.35	38.9	0.07

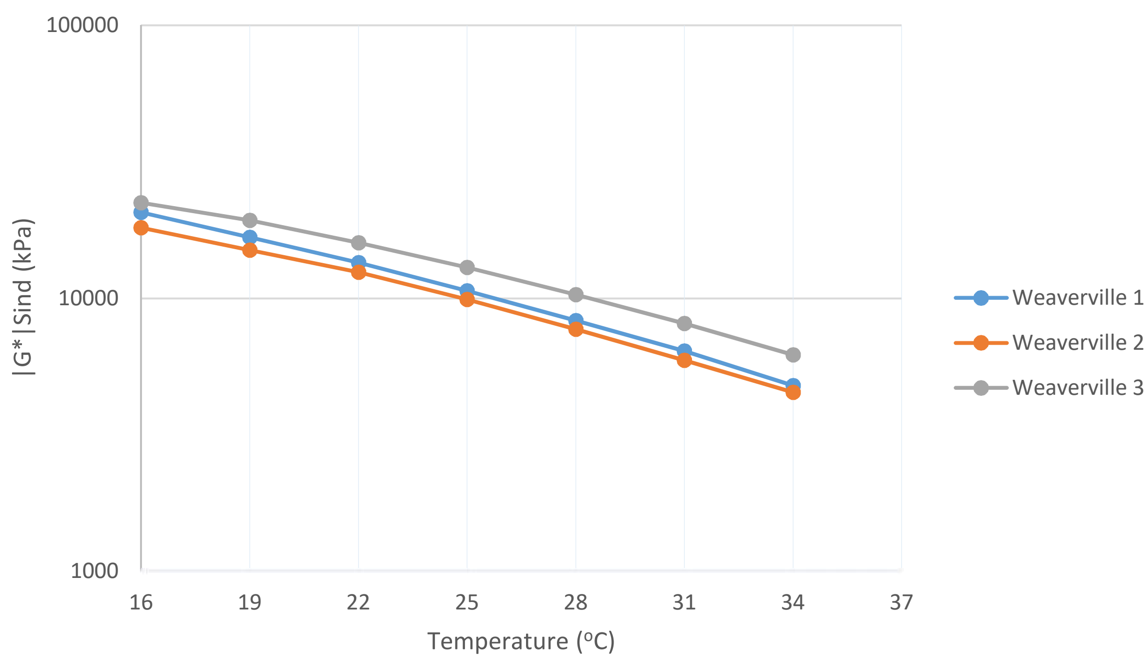

Figure 4-24: DSR Results for the Weaverville RAP Binders (PAV Aged) at Various Temperatures

The condition of |G*|/sinδ < 5000kPa was met at a temperature of 34ºC for Weaverville 1 and Weaverville 2 RAP binders, whereas the condition was met at a temperature of 37ºC for

Weaverville RAP 3 binder. Weaverville 3 RAP binder showed the highest stiffness followed by Weaverville 1 RAP binder and finally, Weaverville 2 RAP binder in their PAV aged state at the intermediate testing temperature range.

4.3.7. Source of RAP – Highland

The results of the DSR tests on the three PAV aged RAP binders from Highland stockpile are discussed in this section. Table 4-74, Table 4-75 and Table 4-76, and Figure 4-25 show the results of the DSR testing on the three Highland RAP binders. The mean values of |G*|sinδ and standard deviations are shown in the tables.

Table 4-74: DSR Results of PAV Aged RAP Binder (Highland – 1)

Temperature	|G*|sinδ (kPa)		δ° (Phase Angle)	
°C	Mean	Std. Deviation	Mean	Std. Deviation
16	24452.17	848.47	27.98	0.43
19	21131.77	1151.78	29.18	0.28
22	16941.60	907.28	31.11	0.32
25	13295.90	646.64	33.18	0.26
28	10227.90	528.58	35.29	0.27
31	7762.35	398.05	37.49	0.28
34	5827.80	343.91	39.64	0.24
37	4308.05	236.95	41.74	0.26

Table 4-75: DSR Results of PAV Aged RAP Binder (Highland – 2)

Temperature	|G*|sinδ (kPa)		δ° (Phase Angle)	
°C	Mean	Std. Deviation	Mean	Std. Deviation
16	25123.63	460.77	28.12	0.45
19	21248.63	621.81	29.41	0.53
22	17086.30	579.29	31.26	0.56
25	13525.90	238.74	33.26	0.55
28	10382.53	194.43	35.41	0.65
31	7859.84	150.02	37.57	0.78
34	5846.73	133.97	39.83	0.92
37	4286.11	111.87	41.91	1.04

Table 4-76: DSR Results of PAV Aged RAP Binder (Highland – 3)

Temperature	|G*|sinδ (kPa)		δ° (Phase Angle)	
°C	Mean	Std. Deviation	Mean	Std. Deviation
16	24031.05	246.71	27.67	0.02
19	18200.90	197.42	28.57	0.06
22	14796.90	141.85	30.27	0.04
25	11799.35	108.68	32.13	0.07
28	9144.76	86.34	34.41	0.07
31	6988.27	96.94	36.39	0.28
34	5260.67	69.46	38.53	0.35
37	3929.81	37.16	40.71	0.25

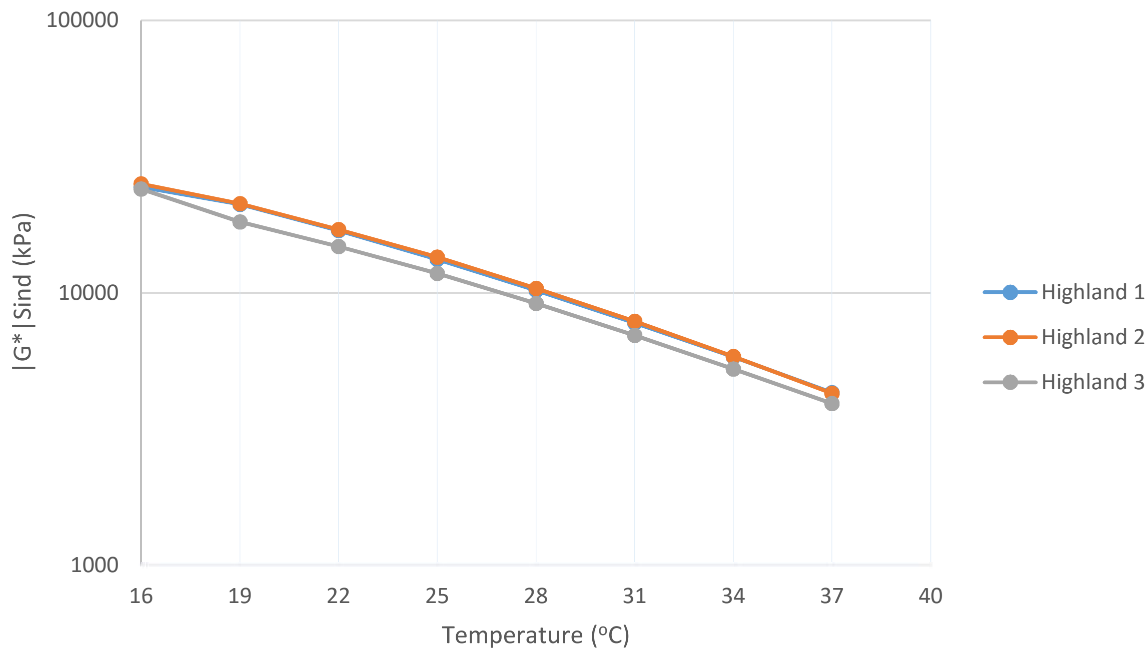

Figure 4-25: DSR Results for the Highland RAP Binders (PAV Aged) at Various Temperatures

The condition of |G*|sinδ < 5000kPa was met at a temperature of 37°C for all three PAV aged Highland RAP binders. Highland 3 RAP binder was the softest among the three Highland RAP binders in their PAV aged state. Highland 2 RAP binder showed higher stiffness than Highland 1 RAP binder for all the intermediate test temperatures except at 37°C. This could be due to experimental error.

4.3.8. Source of RAP – Harrison

The three PAV aged RAP binders from Harrison stockpile were tested on the DSR at intermediate test temperatures. Table 4-77, Table 4-78 and Table 4-79, and Figure 4-26 show the results of DSR testing on the three PAV aged Harrison RAP binders. The mean values of |G*|/sinδ and standard deviations are shown in the tables.

Table 4-77: DSR Results of PAV Aged RAP Binder (Harrison – 1)

Temperature	|G*|sinδ (kPa)		δ° (Phase Angle)	
°C	Mean	Std. Deviation	Mean	Std. Deviation
16	18690.67	153.65	26.42	0.05
19	15044.9	221.03	27.23	0.14
22	12258.3	190.48	28.90	0.25
25	9850.15	181.59	30.61	0.23
28	7711.13	211.33	32.64	0.27
31	6001.26	162.94	34.56	0.44
34	4569.61	159.60	36.82	0.25

Table 4-78: DSR Results of PAV Aged RAP Binder (Harrison – 2)

Temperature	|G*|sinδ (kPa)		δ° (Phase Angle)	
°C	Mean	Std. Deviation	Mean	Std. Deviation
16	21668.57	129.09	27.70	0.07
19	17705.13	603.25	28.19	0.11
22	14489.9	674.41	30.08	0.07
25	11571.43	494.65	32.04	0.13
28	8932.25	391.25	34.38	0.31
31	6821.74	313.33	36.68	0.52
34	5142.06	238.41	39.12	0.51
37	3931.49	150.68	41.95	0.28

Table 4-79: DSR Results of PAV Aged RAP Binder (Harrison – 3)

Temperature °C	$\|G^*\|\sin\delta$ (kPa)		δ° (Phase Angle)	
	Mean	Std. Deviation	Mean	Std. Deviation
16	15807.07	22.54	29.70	0.40
19	12361.90	485.29	30.68	0.23
22	9947.13	381.23	32.35	0.32
25	7887.74	335.62	34.24	0.38
28	5989.74	210.31	36.44	0.44
31	4464.47	165.27	38.53	0.72

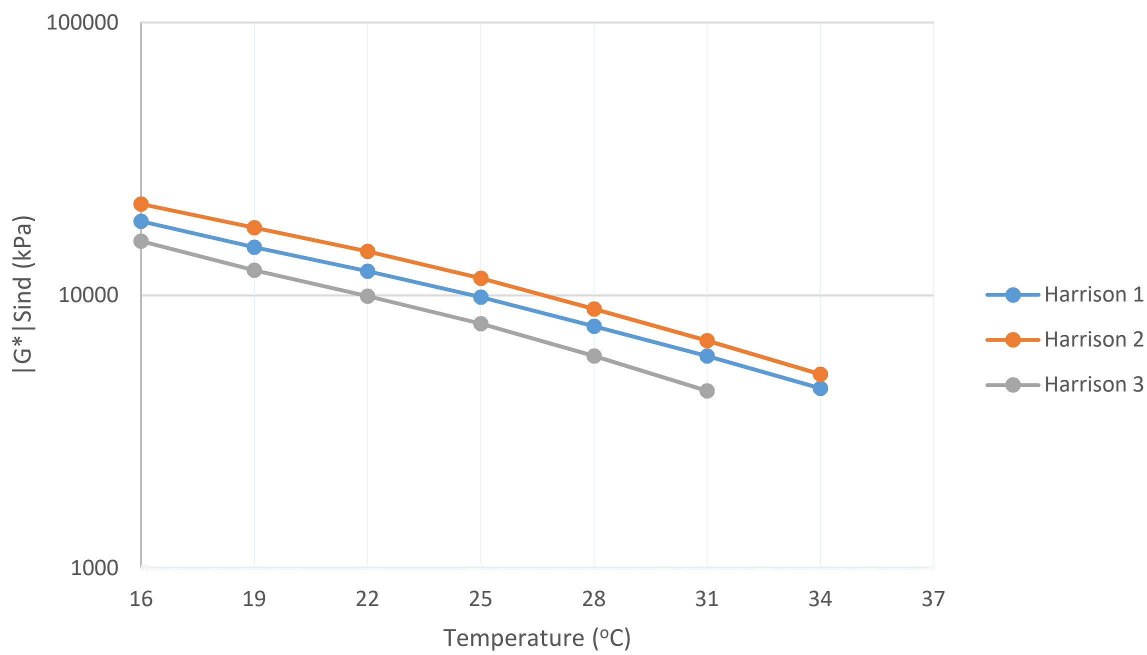

Figure 4-26: DSR Results for the Harrison RAP Binders (PAV Aged) at Various Temperatures

As expected, the $|G^*|\sin\delta$ values decreased as temperature increased and the condition of $|G^*|\sin\delta < 5000$kPa was met at a temperature of 34°C for Harrison 1, at a temperature of 37°C for Harrison 2, and at a temperature of 31°C for Harrison 3 RAP binders. Clearly, Harrison 2 RAP binder showed the highest stiffness among the three PAV aged Harrison RAP binders in the intermediate testing temperature range, followed by Harrison 1 and, finally, Harrison 3 RAP binder.

4.3.9. Source of RAP – Burlington

The last source of RAP was Burlington. The three PAV aged RAP binders from Burlington were tested on the DSR at intermediate test temperatures. Table 4-80, Table 4-81and Table 4-82, and Figure 4-27 show the results of DSR testing on the three Burlington RAP binders. The mean values of |G*|sinδ and standard deviations are shown in the tables.

Table 4-80: DSR Results of PAV Aged RAP Binder (Burlington – 1)

Temperature	|G*|sinδ (kPa)		δ° (Phase Angle)	
°C	Mean	Std. Deviation	Mean	Std. Deviation
16	26142.00	826.12	28.24	0.13
19	21577.57	283.64	29.13	0.36
22	17330.27	334.37	31.11	0.44
25	13871.57	276.47	32.94	0.51
28	10778.70	219.13	35.18	0.35
31	8162.50	225.34	37.40	0.61
34	6097.12	198.26	39.58	0.81
37	4512.69	128.73	41.81	1.03

Table 4-81: DSR Results of PAV Aged RAP Binder (Burlington – 2)

Temperature	|G*|sinδ (kPa)		δº (Phase Angle)	
ºC	Mean	Std. Deviation	Mean	Std. Deviation
16	28133.07	80.86	27.94	0.25
19	21465.57	639.71	29.06	0.21
22	17228.20	444.53	30.99	0.06
25	13454.70	286.66	33.07	0.11
28	10357.43	220.64	35.25	0.08
31	7820.22	254.92	37.37	0.19
34	5774.88	210.46	39.37	0.12
37	4245.11	143.76	41.57	0.25

Table 4-82: DSR Results of PAV Aged RAP Binder (Burlington – 3)

Temperature	|G*|sinδ (kPa)		δº (Phase Angle)	
ºC	Mean	Std. Deviation	Mean	Std. Deviation
16	30723.40	1244.93	27.30	0.46
19	27911.25	163.41	28.74	0.40
22	22493.30	387.07	30.59	0.35
25	17703.45	294.79	32.83	0.37
28	13626.40	259.51	35.17	0.43
31	10323.85	216.73	37.49	0.60
34	7816.72	142.56	39.49	0.65
37	5754.21	43.08	42.07	1.04
40	4146.23	123.99	44.02	0.88

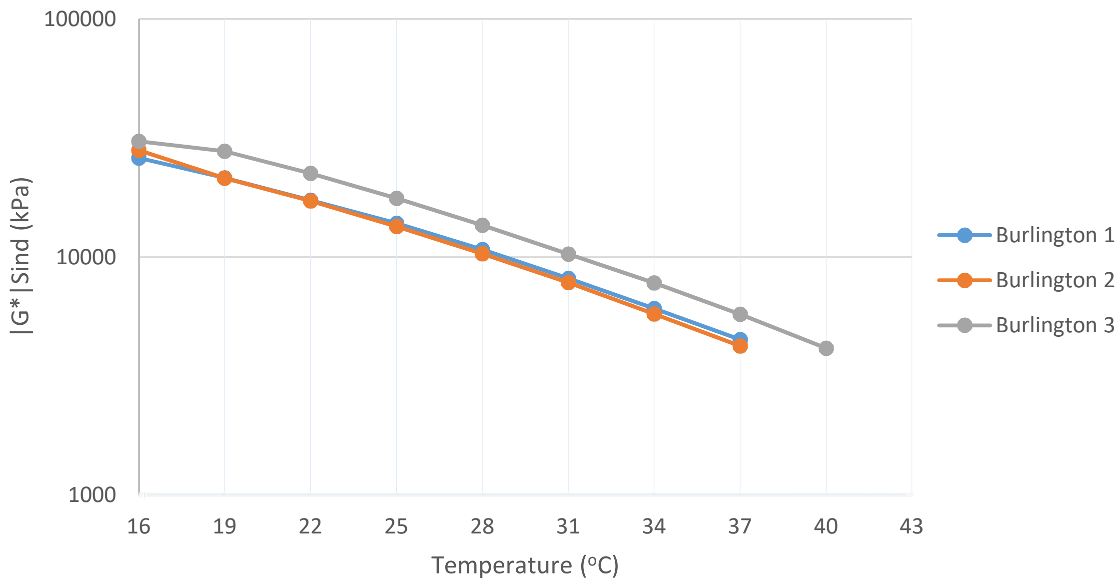

Figure 4-27: DSR Results for the Burlington RAP Binders (PAV Aged) at Various Temperatures

The condition of |G*|sinδ < 5000kPa was met at a temperature of 37°C for Burlington 1 and Burlington 2 RAP binders and at a temperature of 40°C for Burlington 3 RAP binders. Burlington 3 RAP binder showed the highest stiffness among the three PAV aged RAP binders from Burlington stockpile. Within the intermediate test temperature range, PAV aged Burlington 1 RAP binder showed greater stiffness than PAV aged Burlington 2 RAP binder for all temperatures except 16°C. Again, this could be due to experimental error.

4.4. Summary

The 27 RAP binders from nine stockpiles selected from three geographic locations in North Carolina were tested on the DSR for their relevant rheological properties in their unaged, RTFO aged and PAV aged conditions. These properties in turn were used to derive the high and intermediate temperature PG grades of the RAP binders. Table 4-83 below shows the highest temperature at which the $|G^*|/\sin\delta > 1.0$kPa for unaged binders, the highest temperature at which $|G^*|/\sin\delta > 2.2$kPa for RTFO aged binders and the lowest intermediate temperature at which $|G^*|\sin\delta < 5000$kPa for PAV aged binders. For every RAP binder, the lower of the two temperatures in the 'Unaged' and 'RTFO' columns of Table 4-83 is carried over to reflect the high temperature PG grade of that RAP binder which is shown in the 'High PG' column. From the table, it can be noted that the high temperature PG grade for the selected RAP binders varied from 88 to 112 with median for the values at 94. Similarly, the intermediate test temperatures at which $|G^*|\sin\delta < 5000$kPa for the selected binders varied from 31 to 49 with median values at 37. The high temperature PG grade for the three RAP binders within a stockpile varied for some stockpiles whereas, for some stockpiles there was no difference. It should, however, be noted that similarity in PG grades does not mean similarity in stiffness values of binders.

Figure 4-28, Figure 4-29, and Figure 4-30 show the line plots for the DSR results of the twenty seven RAP binders in their unaged, RTFO aged and PAV aged conditions, respectively. Here, the large variation between different RAP binders can be seen in their different aged conditions.

Table 4-83: Summary of DSR Test Results on RAP Binders

Stockpile	Location	Unaged	RTFO Aged	PAV Aged	High PG
Wilmington	1	94	94	37	94
	2	94	94	40	94
	3	94	94	40	94
Pineville	1	94	94	37	94
	2	94	94	37	94
	3	88	88	34	88
Maymead	1	106	106	43	106
	2	100	100	40	100
	3	100	100	37	100
Sunrock	1	94	94	37	94
	2	94	94	37	94
	3	94	94	37	94
Sims	1	112	112	46	112
	2	118	112	49	112
	3	112	106	46	106
Weaverville	1	88	94	34	88
	2	88	94	34	88
	3	94	94	37	94
Highland	1	94	94	37	94
	2	88	94	37	88
	3	88	94	37	88
Harrison	1	88	88	34	88
	2	88	88	37	88
	3	82	82	31	82
Burlington	1	88	94	37	88
	2	94	94	37	94
	3	88	88	40	88

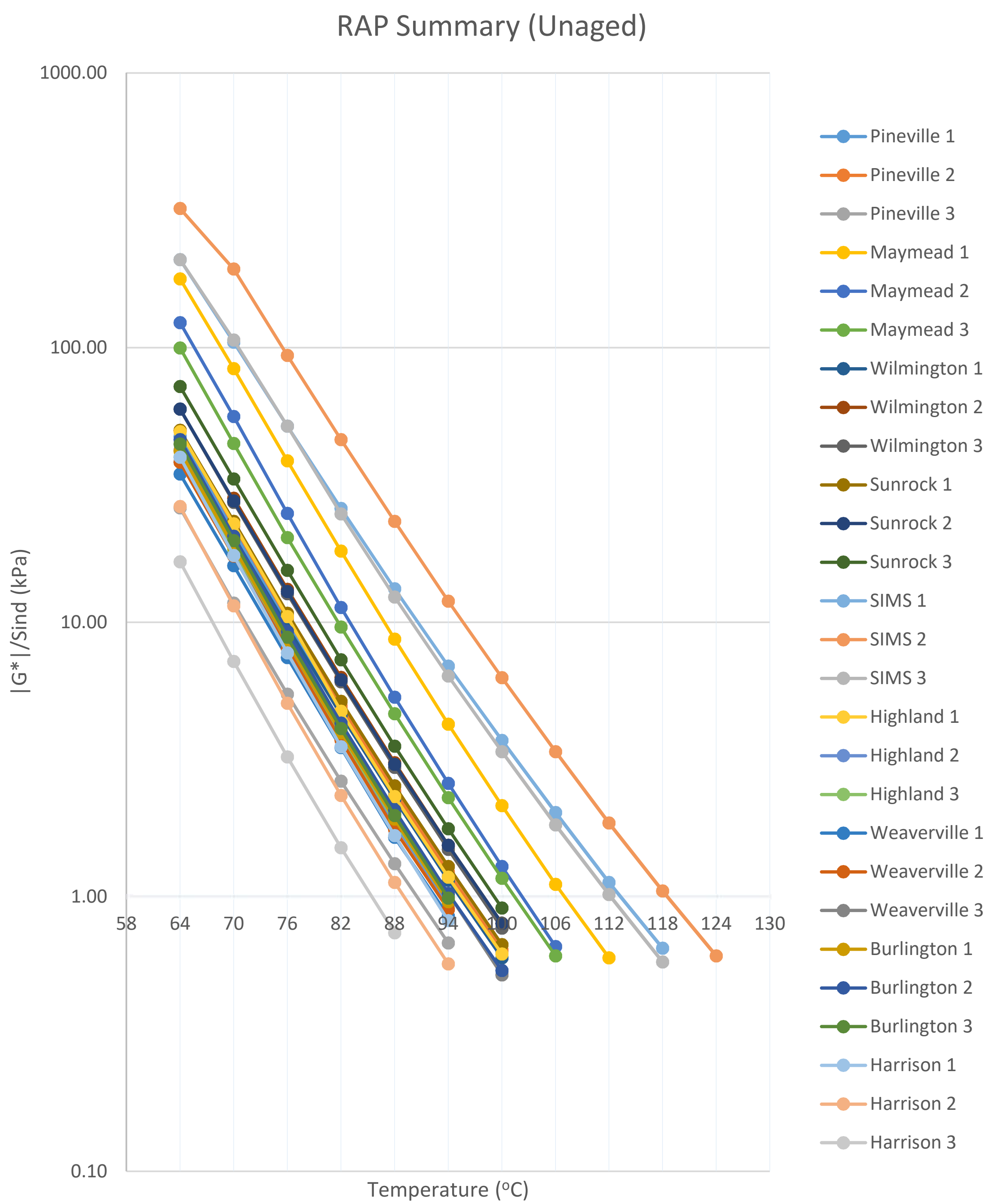

Figure 4-28: DSR Test Results of All RAP Binders in Unaged Conditions

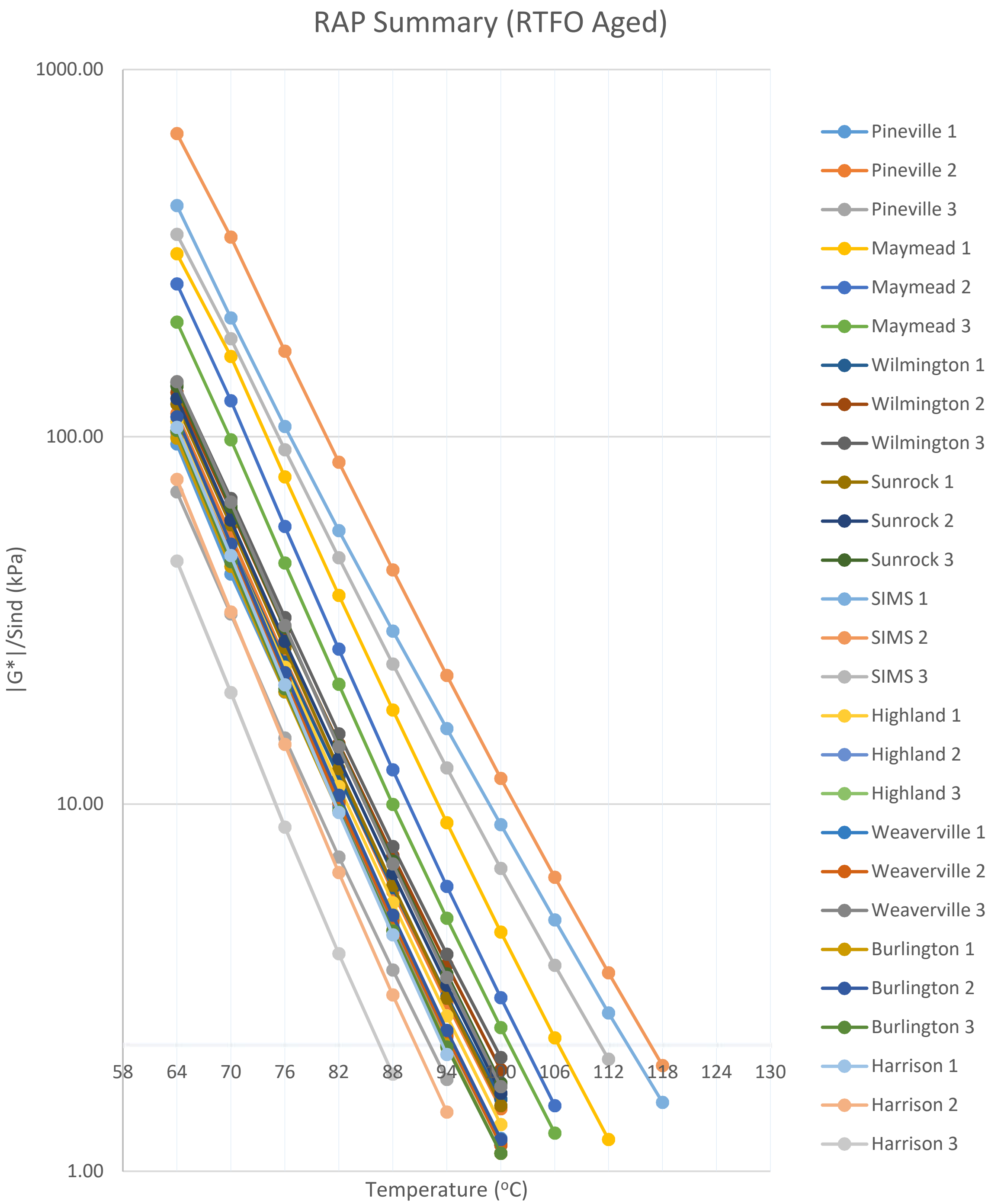

Figure 4-29: DSR Test Results of All RAP Binders in RTFO Aged Conditions

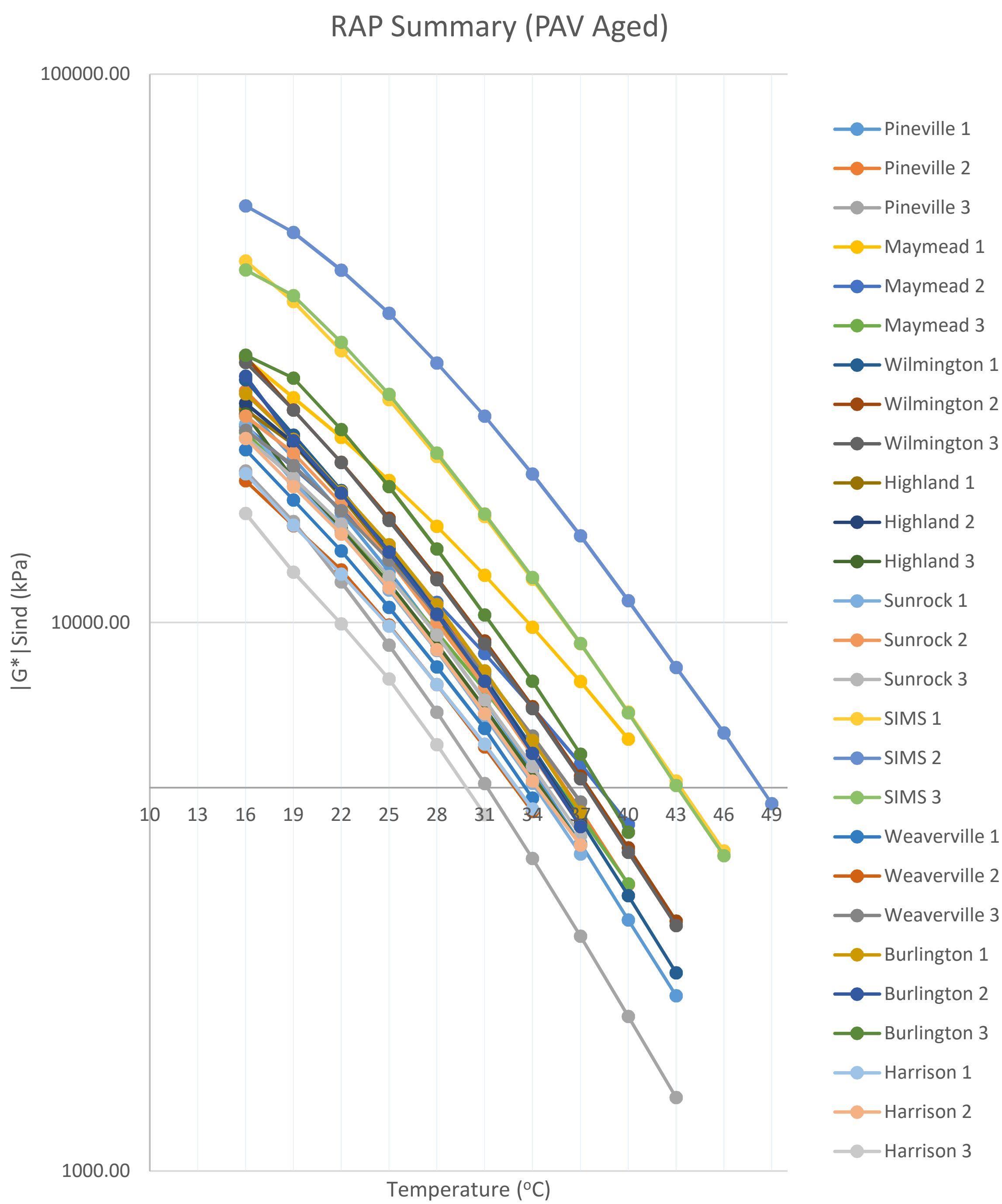

Figure 4-30: DSR Test Results of All RAP Binders in PAV Aged Conditions

From the figures, it can be seen that the RAP binders varied in stiffness within stockpile and also from stockpile to stockpile. Sims 2 RAP binder showed the highest stiffness among all the RAP binders tested and Harrison 3 RAP binder the least stiffness. These results will be used in the next chapter to statistically determine the significance of the variability within RAP binders and select three stockpiles that would potentially capture the maximum variation between stockpiles. The RAP binders from these selected stockpiles will be subsequently blended with known virgin binders to determine how much of the variability translates to blended binders.

CHAPTER 5 : - ANALYSIS OF RAP BINDERS

This chapter will discuss the analysis of the results obtained in the previous chapter from conducting rheological testing on the various RAP binders sampled from the nine stockpiles. The objective of this analysis was to determine if the RAP binders across stockpiles varied significantly. Additionally, data was also used to determine which of the nine stockpiles differed the most and the three most differing stockpiles were selected to perform blending with virgin binders and conduct further testing.

5.1. Statistical Analysis of RAP Binder Data

The rheological data obtained from the testing of the 27 RAP binders from the nine stockpiles was compiled together to be analyzed and determine if there was a statistical difference between RAP binders sampled from the nine stockpiles. The rheological properties of the PAV aged binders will be crucial in determining the maximum limits for each of the stockpile and therefore only test data of the PAV aged binders were used to perform statistical hypothesis testing. The three sample data for each of the 27 PAV aged RAP binders was averaged to get the mean values of $|G^*|\sin\delta$ for the three locations at various test temperatures within each stockpile. These values were used as the response variable and the stockpiles were treated as the treatment factor to determine if the RAP binders sampled from various stockpiles differed in their rheological properties. Table 5-1 below is a partial summary of the rheological data of the stockpiles that was used for the statistical analysis. The table only shows data for three locations within each of the three stockpiles: Wilmington, Pineville and Maymead. This data combined with the data for the other six stockpiles was used for the analysis. The complete data can be found in the appendix (Table A.1)

Table 5-1: Summary of DSR Test Results on PAV Aged RAP Binders for Statistical Analysis

Temp (ºC)	|G*|sinδ (kPa)								
	Wilmington			Pineville			Maymead		
	Wil 1	Wil 2	Wil 3	Pin 1	Pin 2	Pin 3	May 1	May 2	May 3
16	27718	30551	29797	24732	26454	18906	30321	22810	22211
19	21973	24411	24424	19961	21608	15281	25704	19146	18222
22	17417	19612	19579	15865	17225	11867	21765	16037	14968
25	13595	15503	15357	12409	13700	9095	18166	13283	12095
28	10454	12051	11976	9507	10589	6862	14984	10883	9612
31	7912	9260	9151	7207	8123	5086	12204	8787	7543

A linear model was fit with logarithm of mean |G*|sinδ values for each stockpile as the response and stockpile as the predictor and, temperature as the covariate. Equation 5-1 below shows the linear model fit to the data.

Equation 5-1: *log(|G*|sinδ) ~ Stockpile + Temperature + Stockpile*Temperature*

The third term on the right hand side of the equation is the interaction term to determine if the effect of the covariate 'temperature' depended on the stockpile. The null and the alternate hypothesis that was put to test by this model fit was:

H_o : the mean |G*|sinδ values for each of the stockpiles are not statistically different

H_a : the mean |G*|sinδ values for at least one of the stockpiles is different from the others.

Since the objective was to determine if the RAP binder did differ from stockpile to stockpile, only the overall test for treatment effects was performed and no multiple comparisons were performed to identify which of the stockpiles were different.

Table 5-2 below shows the summary of the linear model fit in Equation 5-1. The p-value for the treatment factor 'stockpile' was close to zero suggesting that the null hypothesis H_o can be rejected in favor of the alternate hypothesis H_a. The p-value for the effect of temperature also suggests that the effect of temperature is significant in determining the response. The interaction term between stockpile and temperature did not prove to be significant in the model which could be understood as; the effect of temperature on the response was not dependent on the stockpile that the binder was sampled from. The model diagnostic plots did not show any major deviations from the assumption of normality.

Table 5-2: ANOVA Table of Model Fit for PAV Aged RAP Binders

Treatment	**Df**	**Sum Sq.**	**Mean Sq.**	**F Value**	**P-Value**
Stockpile	8	13.6554	1.1.7069	92.4237	<2e-16
Temperature	1	24.4333	24.4333	1322.9739	<2e-16
Stock*Temp	8	0.1393	0.0174	0.9427	0.4835
Residuals	144	2.6595	0.0185		

The statistical analysis of the rheological properties of the PAV aged RAP binders led to the conclusion that there is a significant variation in the properties of RAP binder from stockpile to stockpile. Additionally, the variation in $|G^*|\sin\delta$ values for RAP binders from a given stockpile indicate that variation does exist within a stockpile.

5.2. Selection of RAP Stockpiles for Blending

In practice, RAP is used by combining with virgin materials and therefore, it was important to study how the variability in the RAP binders from various stockpiles would affect the properties of the blended binders. To be able to conduct this study in the allotted time frame, only three of the nine stockpiles were selected to be blended with virgin binders. The selection process was done in such a way that the variation in the selected RAP binders would be representative of the total variation observed among the entire set of stockpiles. For this, the mean $|G^*|\sin\delta$ values of all the PAV aged RAP binders at 25°C were selected and their quartiles were determined. The temperature 25°C was selected because the blending charts would be plotted at this temperature and the reason would be explained in the following chapter. The stockpile from which the $|G^*|\sin\delta$ of all the three sampled binders fell into the first quartile was selected to represent the stockpile with the softest RAP binders and the stockpile from which the $|G^*|\sin\delta$ of all the three sampled binders fell into the last quartile was selected to represent the stockpile with the stiffest RAP binders. The third stockpile was selected to represent values in the median range.

Table 5-3 is a summary of the quartiles of the $|G^*|\sin\delta$ values at 25°C of the various PAV aged RAP binders and Table 5-4 shows the grouping of the RAP binders into one of these quartiles. The three RAP binders from Harrison stockpile were grouped into 1st quartile; the three RAP binders from Sims stockpile were grouped into the 4th quartile, and the three RAP binders from Highland stockpile were grouped into either 2nd or 3rd quartile based on the $|G^*|\sin\delta$ values at 25°C in their PAV aged state.

Table 5-3: Quartiles for |G*|sinδ Values of RAP Binders at 25ºC

Percentile	Value (kPa)	Quartile
Minimum	7887.74	0
25th Percentile	11685.39	1
50th Percentile	13282.70	2
75th Percentile	14614.42	3
Maximum	36641.40	4

Table 5-4: Grouping of Stockpiles into Quartiles

Stockpile	Location	|G*|sinδ	Quartile
Wilmington	Wilmington 1	13594.67	3
	Wilmington 2	15503	4
	Wilmington 3	15357.33	4
Pineville	Pineville 1	12408.67	2
	Pineville 2	13700	3
	Pineville 3	9095.33	1
Maymead	Maymead 1	18166.33	4
	Maymead 2	13283	3
	Maymead 3	12095.33	2
Sunrock	Sunrock 1	11458.63	1
	Sunrock 2	13030.37	2
	Sunrock 3	12144.53	2
Sims	**Sims 1**	**25494.73**	**4**
	Sims 2	**36641.4**	**4**
	Sims 3	**26078.87**	**4**
Highland	**Highland 1**	**13295.9**	**3**
	Highland 2	**13525.9**	**3**
	Highland 3	**11799.35**	**2**
Weaverville	Weaverville 1	10657.7	1
	Weaverville 2	9901.52	1
	Weaverville 3	12996	2
Burlington	Burlington 1	13871.57	3
	Burlington 2	13454.7	3
	Burlington 3	17703.45	4
Harrison	**Harrison 1**	**9850.15**	**1**
	Harrison 2	**11571.43**	**1**
	Harrison 3	**7887.74**	**1**

Therefore, the three stockpiles (highlighted in Table 5-4) selected for blending with virgin binders were:

Harrison - representative of the softest RAP

Highland - representative of the RAP with median stiffness values

Sims - representative of the RAP with the greatest stiffness values.

The RAP binders from all the other stockpiles were grouped into the remaining quartiles. This grouping was later used in subsequent chapters to determine the probabilities of each of the stockpile which in turn were used to estimate the overall confidence intervals for the maximum limits of RAP binder with the selected virgin binder.

CHAPTER 6 : - VIRGIN AND BLENDED BINDER CHARACTERIZATION

The selected RAP binders showed statistically significant variation in critical rheological properties with change in stockpile as well as variation with change in location within a stockpile. However, the goal of this research is to study and understand how the variability in RAP binder properties translates to variability in binders obtained by blending RAP binders with virgin binders. The most commonly used virgin binder in the state of North Carolina is PG 64-22. Additionally, it is often required to lower the grade of the virgin binder when high proportions of RAP are incorporated in HMA. Therefore, two virgin binders PG 64-22 and PG 58-22 were selected for blending with the binders from the three selected RAP stockpiles. This chapter discusses the properties of the virgin binders and the blended binders obtained by blending the two virgin binders with the selected RAP binders at known proportions.

6.1. Virgin Binders

The rheological properties of |G*| (complex shear modulus) and δ (phase angle) for the virgin binders are important to determine the maximum and minimum amount of recycled binders that can be blended with the virgin binders. Therefore, the two selected virgin binders were tested on the DSR in their unaged, RTFO aged and PAV aged state under standard conditions and, at varying test temperatures.

6.1.1. Virgin Binders in Unaged Conditions

The virgin binders PG 64-22 and PG 58-28 were tested on the DSR in the unaged conditions to determine the rheological properties at high temperatures. Three samples for each of the binder were tested in accordance with AASHTO T315 “Test Method for Determining the Rheological Properties of Asphalt Binder Using a Dynamic Shear Rheometer” to determine the mean values of |G*|/sinδ and standard deviation. Table 6-1, Table 6-2 and Figure 6-1 show the properties for the virgin binders PG 64-22 and PG 58-28, respectively.

Table 6-1: DSR Results of PG 64-22 Binder (Unaged)

Temperature	**|G*|/sinδ (kPa)**		**δ° (Phase Angle)**	
°C	**Mean**	**Std. Deviation**	**Mean**	**Std. Deviation**
64	1.39	0.01	86.95	0.02
70	0.66	0.01	88.09	0.01
76	0.33	0.01	88.88	0.01

Table 6-2: DSR Results of PG 58-28 Binder (Unaged)

Temperature	**|G*|/sinδ (kPa)**		**δ° (Phase Angle)**	
°C	**Mean**	**Std. Deviation**	**Mean**	**Std. Deviation**
58	1.64	0.02	86.89	0.05
64	0.75	0.01	88.12	0.06
70	0.37	0.01	88.96	0.05
76	0.19	0.01	89.44	0.04

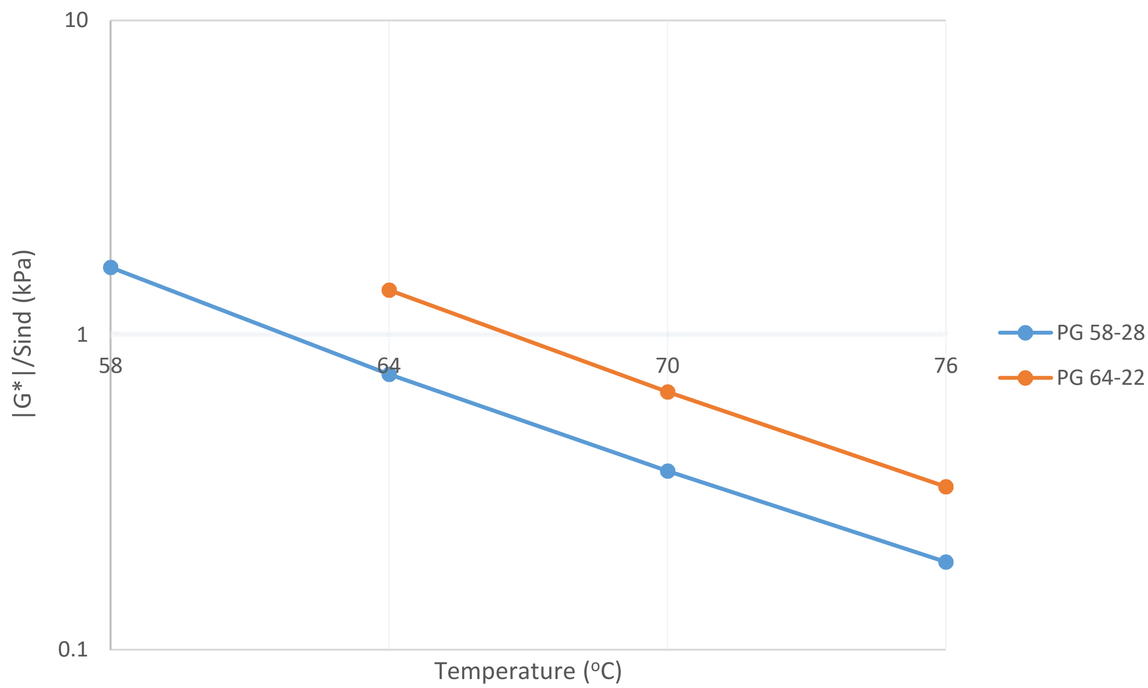

Figure 6-1: DSR Results of Virgin Binders (Unaged)

The virgin binder PG 64-22 clearly showed higher stiffness than the PG 58-28 binder for the entire range of test temperatures. As expected the |G*|/sinδ values for PG 64-22 were less than 1.0kPa for every 6°C jump in test temperatures over 64°C. Similarly, the |G*|/sinδ values for PG 58-28 were less than 1.0kPa for every 6°C jump in test temperatures over 58°C.

6.1.2. Virgin Binders in RTFO Aged Conditions

The two virgin binders PG 58-28 and PG 64-22 were aged in an RTFO in accordance with AASHTO T240 "Standard Method of Test for Effect of Heat and Air on a Moving Film of Asphalt Binder (Rolling Thin-Film Oven Test)" to simulate the short term aging of the binder at the time of mixing and compaction in field construction. The RTFO aged virgin binders were tested on the DSR in accordance with AASHTO T315 "Test Method for Determining the

Rheological Properties of Asphalt Binder Using a Dynamic Shear Rheometer" to determine the mean values of $|G^*|/\sin\delta$ and standard deviation. Table 6-3, Table 6-4 and Figure 6-2 show the results of the DSR tests on the RTFO aged virgin binders.

Table 6-3: DSR Results of PG 64-22 Binder (RTFO Aged)

Temperature	$\|G^*\|/\sin\delta$ (kPa)		δ^o (Phase Angle)	
^oC	Mean	Std. Deviation	Mean	Std. Deviation
64	3.65	0.03	83.26	0.02
70	1.65	0.01	85.29	0.02
76	0.79	0.01	86.85	0.01

Table 6-4: DSR Results of PG 58-28 Binder (RTFO Aged)

Temperature	$\|G^*\|/\sin\delta$ (kPa)		δ^o (Phase Angle)	
^oC	Mean	Std. Deviation	Mean	Std. Deviation
58	3.43	0.05	83.74	0.05
64	1.55	0.02	85.66	0.01
70	0.74	0.01	87.20	0.05
76	0.37	0.01	88.34	0.06

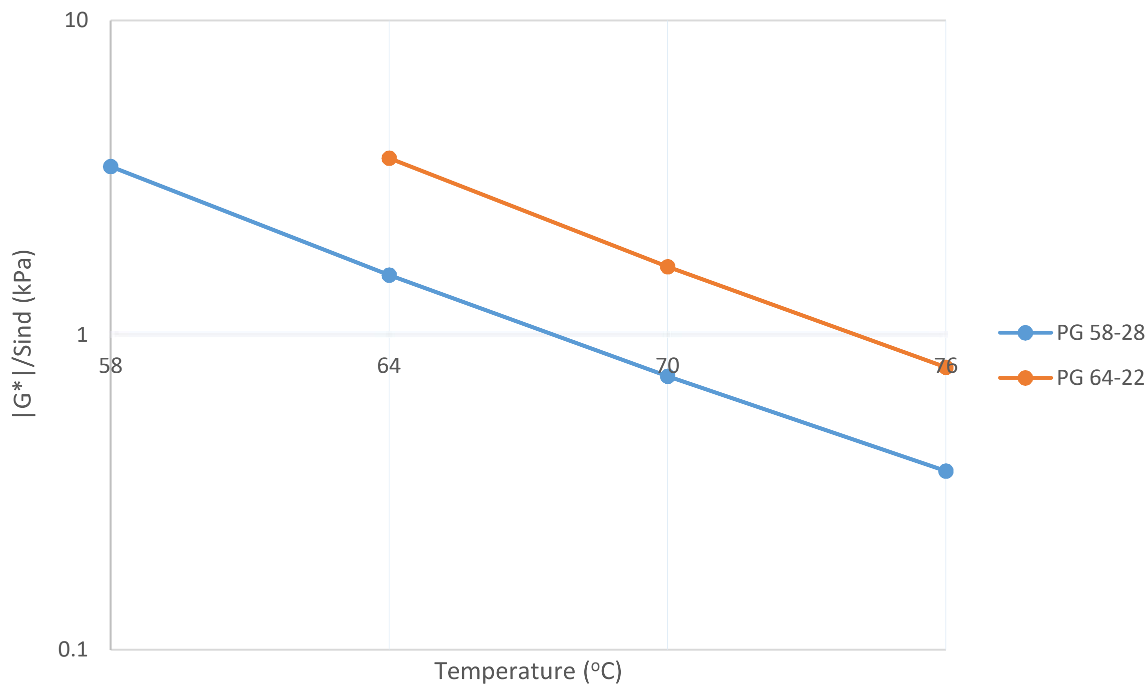

Figure 6-2: DSR Results of Virgin Binders (RTFO Aged)

From the figure it can be observed that the virgin binder PG 64-22 showed |G*|/sinδ values lesser than 2.2kPa for every 6°C jump in test temperatures over 64°C and similarly the virgin binder PG 58-28 showed |G*|/sinδ values lesser than 2.2kPa for every 6°C jump in test temperatures over 58°C. This is expected as the high temperature grades of the virgin binders were 64 and 58.

6.1.3. Virgin Binders in PAV Aged Conditions

The RTFO aged virgin binders were subsequently aged in the PAV in accordance with AASHTO R28 "Standard Practice for Accelerated Aging of Asphalt Binder Using a Pressurized Aging Vessel (PAV)" to simulate the long term aging of asphalt binder during the service life of an asphalt pavement. Three samples for each of the PAV aged virgin binders were later tested on the DSR in accordance with AASHTO T315 “Test Method for Determining the Rheological Properties of Asphalt Binder Using a Dynamic Shear Rheometer” to determine the mean values of |G*|sinδ and standard deviation for intermediate test temperatures. Table 6-5, Table 6-6 and Figure 6-3 show the results of the DSR tests at intermediate test temperatures.

Table 6-5: DSR Results of PG 58-28 Binder (PAV Aged)

Temperature	|G*|sinδ (kPa)		δ° (Phase Angle)	
°C	Mean	Std. Deviation	Mean	Std. Deviation
16	5687.70	64.46	46.73	0.07
19	4009.78	207.25	49.57	0.35
22	2636.46	104.57	52.16	0.33
25	1766.40	56.47	54.31	0.07
28	1165.26	16.51	56.48	0.04

Table 6-6: DSR Results of PG 64-22 Binder (PAV Aged)

Temperature	|G*|sinδ (kPa)		δ° (Phase Angle)	
°C	Mean	Std. Deviation	Mean	Std. Deviation
16	9960.67	104.24	38.77	0.14
19	8007.41	24.02	41.13	0.89
22	5728.08	88.77	43.64	1.17
25	4024.25	59.37	46.26	0.05
28	2761.96	21.52	48.85	0.14

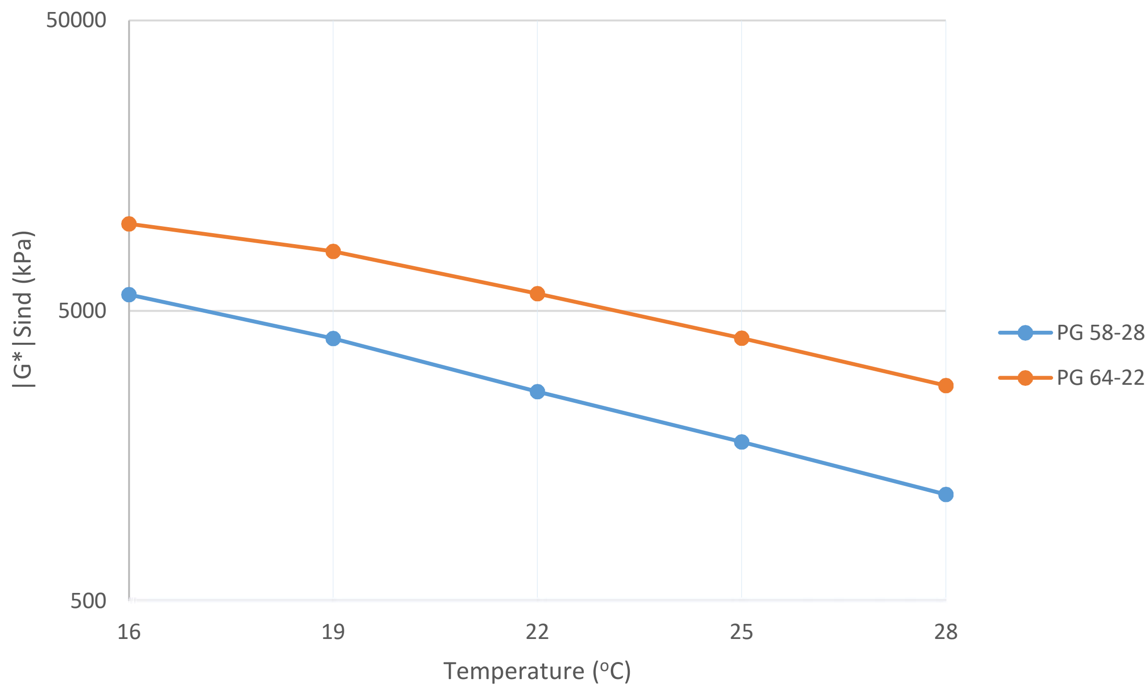

Figure 6-3: DSR Results of Virgin Binders (PAV Aged)

The PAV aged virgin binder PG 64-22 showed higher stiffness values than PG 58-28 over the entire range of intermediate test temperatures. The |G*|sinδ values for PG 64-22 were lesser than 5000kPa for every jump in test temperature by 3°C over 22°C. Similarly, the |G*|sinδ values for PG 58-28 were lesser than 5000kPa for every jump in test temperature by 3°C over 16°C.

6.2. Blended Binders

In order for determining the maximum amount of recycled binder that can be blended with the two virgin binders (PG 64-22 and PG 58-28) and still meet the Superpave specifications, it was required to blend the recycled binders with the virgin binders and develop blending charts. Therefore, the two virgin binders PG 64-22 and PG 58-28 were blended with the RAP binders from the three selected stockpiles using a mechanical mixer and a hot plate in 70:30 (70% virgin & 30% RAP binder) proportions and the blended binders were again tested on the DSR for their rheological properties of |G*| and δ in their various aged conditions. The results of the tests on these binders in various aged conditions are discussed in the following section.

6.2.1. Blended Binders in Unaged Conditions

The blended binders obtained by blending the two virgin binders with the selected RAP binders in fixed proportions were tested on the DSR in the unaged conditions to determine the rheological properties at high temperatures. Three samples for each of the binders were tested in accordance with AASHTO T315 "Test Method for Determining the Rheological Properties of Asphalt Binder Using a Dynamic Shear Rheometer" to determine the mean values of |G*|/sinδ and standard deviation.

Table 6-7 through Table 6-15 and Figure 6-4 through Figure 6-6 show the properties for the blended binders at high temperatures with PG 58-28 as the base virgin binder blended with the selected nine RAP binders from the three stockpiles.

Table 6-7: DSR Results of PG 58-28 + 30% Harrison 1 RAP (Unaged)

Temperature	|G*|/sinδ (kPa)		δ° (Phase Angle)	
°C	Mean	Std. Deviation	Mean	Std. Deviation
64	2.31	0.04	84.89	0.09
70	1.06	0.01	86.58	0.02
76	0.52	0.01	87.86	0.01

Table 6-8: DSR Results of PG 58-28 + 30% Harrison 2 RAP (Unaged)

Temperature	|G*|/sinδ (kPa)		δº (Phase Angle)	
ºC	Mean	Std. Deviation	Mean	Std. Deviation
64	2.23	0.02	85.45	0.07
70	1.03	0.01	87.01	0.05
76	0.51	0.01	88.17	0.07

Table 6-9: DSR Results of PG 58-28 + 30% Harrison 3 RAP (Unaged)

Temperature	|G*|/sinδ (kPa)		δº (Phase Angle)	
ºC	Mean	Std. Deviation	Mean	Std. Deviation
64	1.88	0.03	85.82	0.11
70	0.87	0.01	87.38	0.04

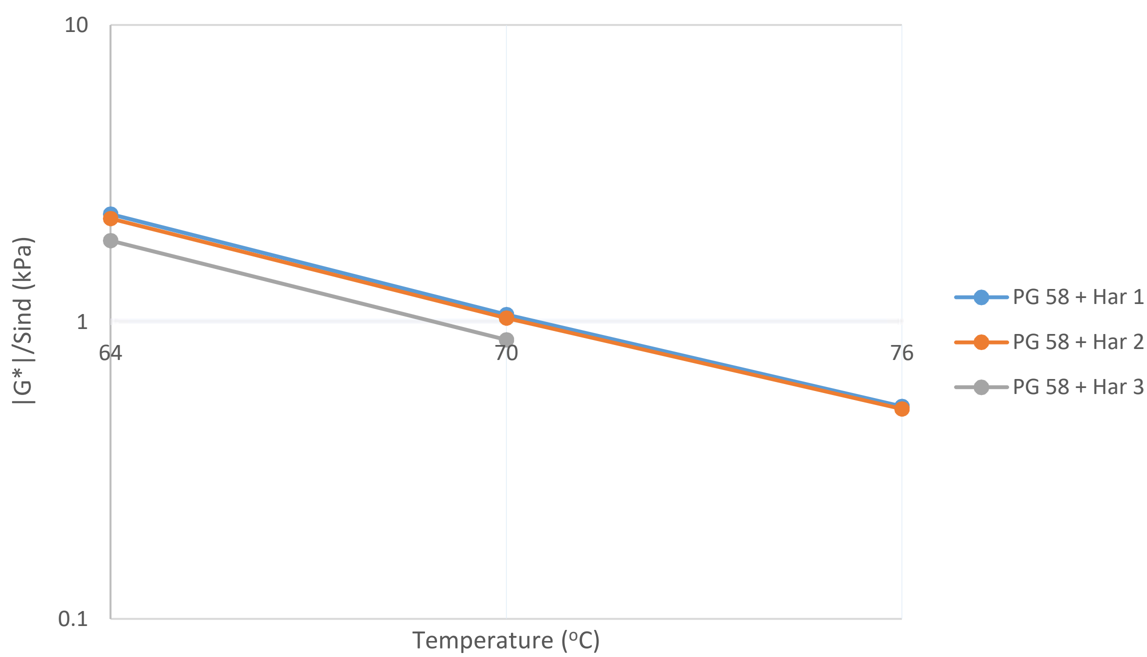

Figure 6-4: DSR Results of PG 58-28 and Harrison RAP Binder Blends (Unaged)

Table 6-10: DSR Results of PG 58-28 + 30% Highland 1 RAP (Unaged)

Temperature	$\|G^*\|/\sin\delta$ (kPa)		δ^o (Phase Angle)	
^oC	Mean	Std. Deviation	Mean	Std. Deviation
64	2.47	0.01	84.23	0.02
70	1.15	0.01	85.99	0.07
76	0.57	0.01	87.45	0.04

Table 6-11: DSR Results of PG 58-28 + 30% Highland 2 RAP (Unaged)

Temperature	$\|G^*\|/\sin\delta$ (kPa)		δ^o (Phase Angle)	
^oC	Mean	Std. Deviation	Mean	Std. Deviation
64	2.45	0.01	84.28	0.01
70	1.15	0.01	86.09	0.03
76	0.56	0.01	87.49	0.02

Table 6-12: DSR Results of PG 58-28 + 30% Highland 3 RAP (Unaged)

Temperature	$\|G^*\|/\sin\delta$ (kPa)		δ^o (Phase Angle)	
^oC	Mean	Std. Deviation	Mean	Std. Deviation
64	2.41	0.01	84.32	0.05
70	1.13	0.01	86.15	0.01
76	0.56	0.01	87.52	0.02

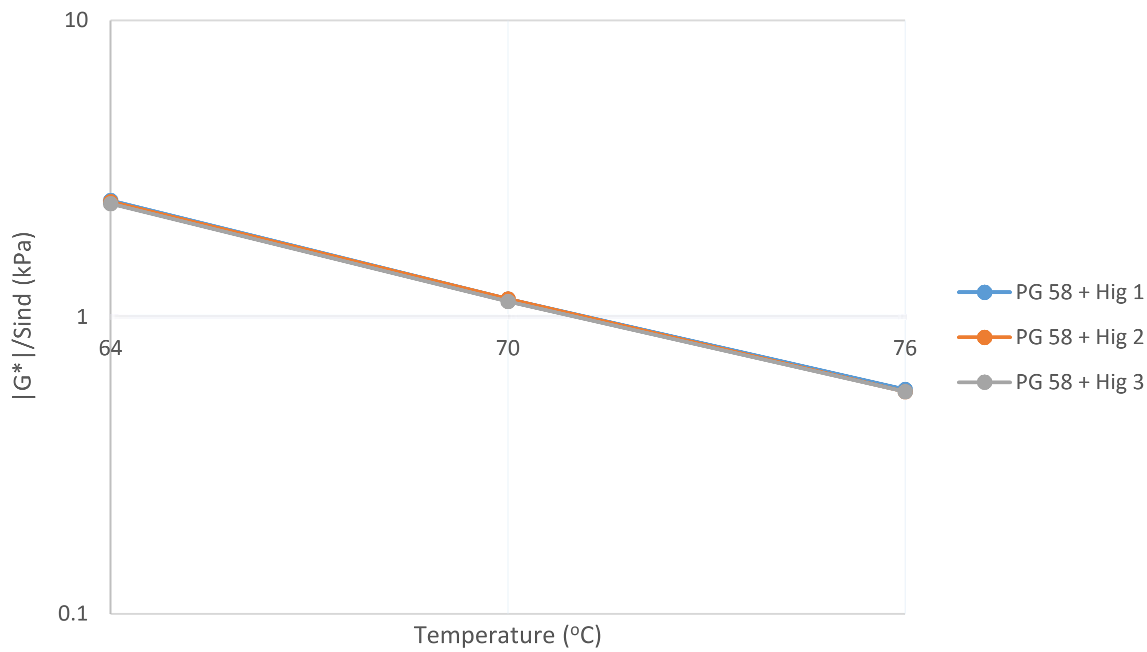

Figure 6-5: DSR Results of PG 58-28 and Highland RAP Binder Blends (Unaged)

Table 6-13: DSR Results of PG 58-28 + 30% Sims 1 RAP (Unaged)

Temperature ºC	|G*|/sinδ (kPa)		δº (Phase Angle)	
	Mean	Std. Deviation	Mean	Std. Deviation
64	4.33	0.03	81.02	0.01
70	2.02	0.01	83.12	0.06
76	0.98	0.01	85.04	0.04

Table 6-14: DSR Results of PG 58-28 + 30% Sims 2 RAP (Unaged)

Temperature ºC	|G*|/sinδ (kPa)		δº (Phase Angle)	
	Mean	Std. Deviation	Mean	Std. Deviation
64	5.52	0.03	80.39	0.02
70	2.54	0.02	82.63	0.07
76	1.23	0.01	84.55	0.10
82	0.62	0.01	86.11	0.10

Table 6-15: DSR Results of PG 58-28 + 30% Sims 3 RAP (Unaged)

Temperature °C	|G*|/sinδ (kPa)		δ° (Phase Angle)	
	Mean	Std. Deviation	Mean	Std. Deviation
64	4.05	0.05	81.40	0.03
70	1.90	0.02	83.43	0.11
76	0.94	0.01	85.16	0.05

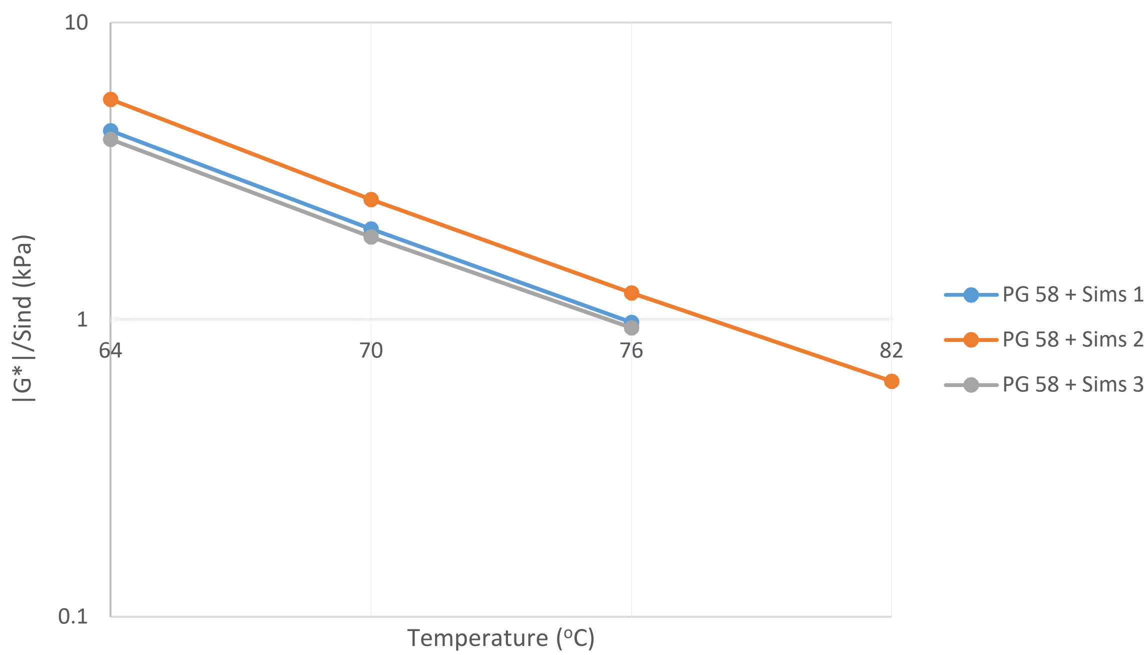

Figure 6-6: DSR Results of PG 58-28 and Sims RAP Binder Blends (Unaged)

It was observed from the tests on Harrison RAP binders that Harrison 1 binder showed the highest stiffness followed by Harrison 2 and finally, Harrison 3 binder. From the figure above it can be seen that similar ranking was observed in the blends with the virgin binder PG 58-28 for the range of temperatures tested. Blends with Harrison 1 and Harrison 2 RAP binders qualified for a high temperature grade of 70 whereas, blend with Harrison 3 RAP binder qualified for a high temperature grade of 64.

In the case of Highland RAP binders, again blends with Highland 1 RAP binder showed higher stiffness than blends with Highland 2 and Highland 3 RAP binders. Although, blends with Highland 2 RAP binder showed higher stiffness than blends with Highland 3 RAP binder even though Highland 2 and Highland 3 RAP binders exhibited similar stiffness values in this temperature range. All the three Highland RAP binder blends with PG 58-28 qualified for a high temperature PG grade of 70.

In the case of Sims RAP binders, blends with Sims 2 RAP binder showed greater stiffness compared to blends with Sims 1 and Sims 3 RAP binders. Blends with Sims 1 RAP binder showed greater stiffness compared to blends with Sims 3 RAP binder. When compared to the stiffness values and the trend exhibited by the three Sims RAP binders, this trend is different in that, Sims 2 RAP binder showed highest stiffness followed by Sims 1 and Sims 3 RAP binders which exhibited similar stiffness values. Sims 1 and Sims 3 binder blends with PG 58-28 qualified for a high temperature PG grade of 70 whereas, Sims 2 binder blend qualified for a high temperature PG grade of 76 in their unaged state.

Table 6-16 through Table 6-24 and Figure 6-7 through Figure 6-9 show the properties for the blended binders at high temperatures with PG 64-22 as the base virgin binder blended with the selected nine RAP binders from the three stockpiles.

Table 6-16: DSR Results of PG 64-22 + 30% Harrison 1 RAP (Unaged)

Temperature °C	|G*|/sinδ (kPa)		δ° (Phase Angle)	
	Mean	**Std. Deviation**	**Mean**	**Std. Deviation**
64	3.98	0.03	83.23	0.05
70	1.82	0.01	85.23	0.02
76	0.86	0.01	86.79	0.02

Table 6-17: DSR Results of PG 64-22 + 30% Harrison 2 RAP (Unaged)

Temperature °C	|G*|/sinδ (kPa)		δ° (Phase Angle)	
	Mean	**Std. Deviation**	**Mean**	**Std. Deviation**
64	3.80	0.06	83.86	0.04
70	1.74	0.02	85.75	0.04
76	0.83	0.01	87.21	0.02

Table 6-18: DSR Results of PG 64-22 + 30% Harrison 3 RAP (Unaged)

Temperature °C	|G*|/sinδ (kPa)		δ° (Phase Angle)	
	Mean	**Std. Deviation**	**Mean**	**Std. Deviation**
64	3.34	0.01	84.28	0.03
70	1.53	0.01	86.08	0.04
76	0.73	0.01	87.51	0.01

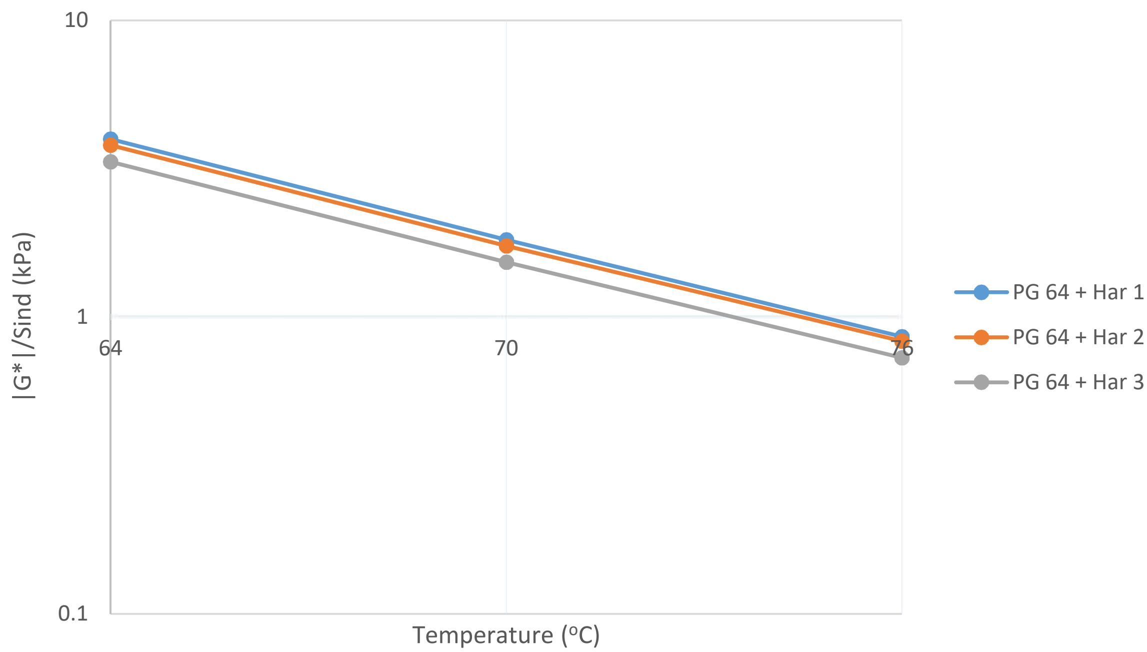

Figure 6-7: DSR Results of PG 64-22 and Harrison RAP Binder Blends (Unaged)

Table 6-19: DSR Results of PG 64-22 + 30% Highland 1 RAP (Unaged)

Temperature	|G*|/sinδ (kPa)		δº (Phase Angle)	
ºC	Mean	Std. Deviation	Mean	Std. Deviation
64	4.26	0.08	82.52	0.04
70	1.96	0.03	84.55	0.03
76	0.93	0.01	86.21	0.01

Table 6-20: DSR Results of PG 64-22 + 30% Highland 2 RAP (Unaged)

Temperature	|G*|/sinδ (kPa)		δº (Phase Angle)	
ºC	Mean	Std. Deviation	Mean	Std. Deviation
64	3.86	0.05	83.01	0.03
70	1.79	0.01	85.02	0.07
76	0.85	0.01	86.65	0.02

Table 6-21: DSR Results of PG 64-22 + 30% Highland 3 RAP (Unaged)

Temperature °C	|G*|/sinδ (kPa)		δ° (Phase Angle)	
	Mean	Std. Deviation	Mean	Std. Deviation
64	4.00	0.04	82.85	0.06
70	1.85	0.01	84.86	0.08
76	0.89	0.01	86.50	0.01

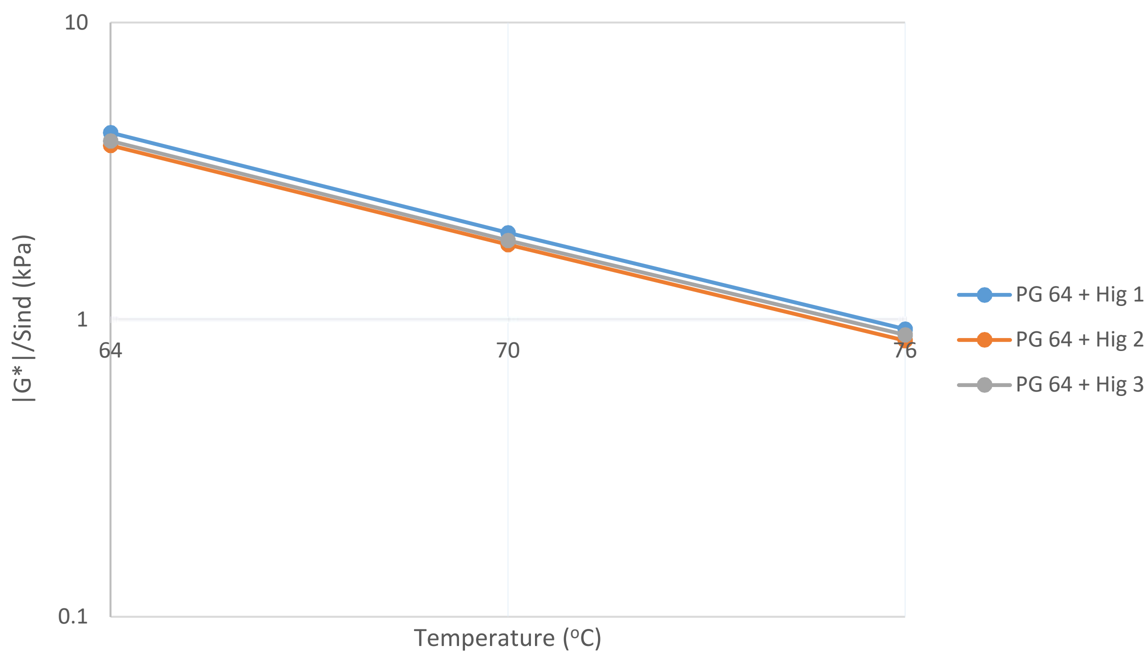

Figure 6-8: DSR Results of PG 64-22 and Highland RAP Binder Blends (Unaged)

Table 6-22: DSR Results of PG 64-22 + 30% Sims 1 RAP (Unaged)

Temperature °C	|G*|/sinδ (kPa)		δ° (Phase Angle)	
	Mean	Std. Deviation	Mean	Std. Deviation
64	6.94	0.04	79.43	0.11
70	3.18	0.02	81.68	0.07
76	1.52	0.01	83.71	0.03
82	0.76	0	85.39	0.06

Table 6-23: Results of PG 64-22 + 30% Sims 2 RAP (Unaged)

Temperature ºC	|G*|/sinδ (kPa)		δº (Phase Angle)	
	Mean	Std. Deviation	Mean	Std. Deviation
64	10.06	0.24	78.21	0.11
70	4.53	0.11	80.85	0.13
76	2.13	0.03	83.11	0.13
82	1.04	0.02	85.03	0.06
88	0.54	0.01	86.58	0.05

Table 6-24: Results of PG 64-22 + 30% Sims 3 RAP (Unaged)

Temperature ºC	|G*|/sinδ (kPa)		δº (Phase Angle)	
	Mean	Std. Deviation	Mean	Std. Deviation
64	7.30	0.16	79.29	0.10
70	3.33	0.05	81.63	0.07
76	1.58	0.02	83.64	0.08
82	0.79	0.01	85.28	0.04

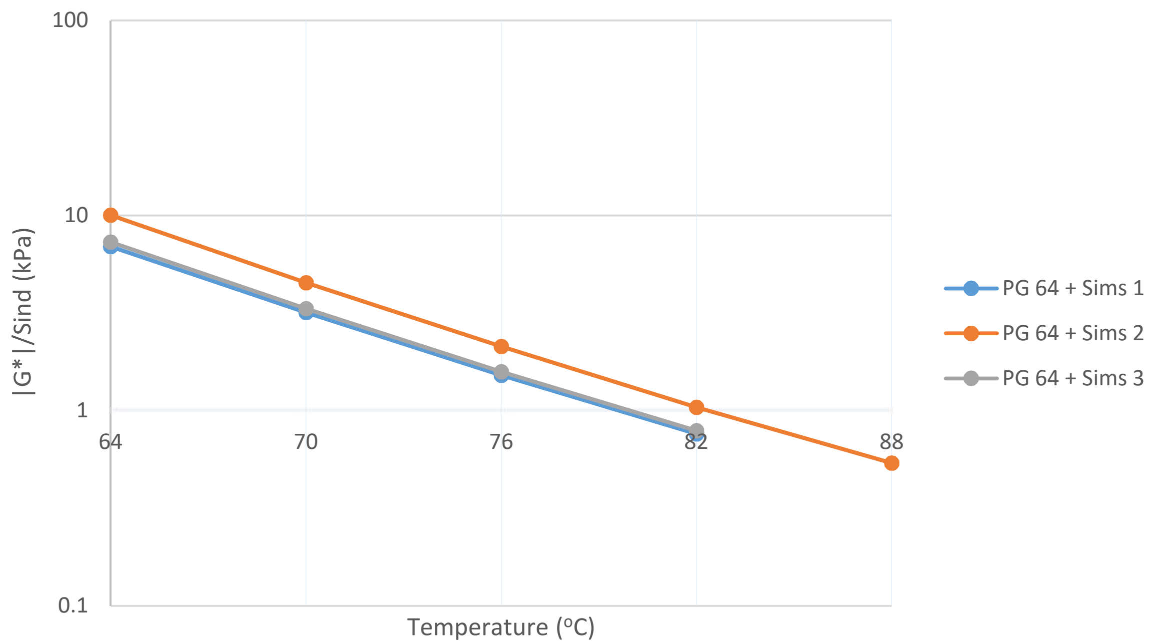

Figure 6-9: DSR Results of PG 64-22 and Sims RAP Binder Blends (Unaged)

The results shown in the tables and figures above indicate that blends of PG 64-22 virgin binder with the binder from Sims stockpile labeled Sims 2 showed the greatest stiffness values followed by Sims 3 and finally, Sims 1 RAP binder. This trend however, is different from that shown by pure Sims RAP binders in their unaged state where Sims 2 RAP binder showed highest stiffness followed by both Sims 1 and Sims 3 RAP binders showing comparable stiffness values. Sims 1 and Sims 3 RAP binder blends with PG 64-22 qualified for a high temperature PG grade of 76 whereas, Sims 2 RAP binder blend qualified for a high temperature PG grade of 82 in their unaged state.

For the RAP binders from Highland stockpile, blends with Highland 1 RAP binder showed greater stiffness than the blend with Highland 3 RAP binder followed by the blend with Highland 2 RAP binder. This is similar to the trend observed with pure Highland RAP binders. All the three Highland RAP binder blends with PG 64-22 qualified for a high temperature grade of 70 in their unaged state.

In the case of RAP binders from Harrison stockpile, the blend with Harrison 1 RAP binder showed higher stiffness values than the blend with Harrison 2 RAP binder and finally, the blend with Harrison 3 RAP binder. All the three Harrison RAP binder blends with PG 64-22 qualified for a high temperature grade of 70 in their unaged state.

6.2.2. Blended Binders in RTFO Aged Conditions

The blended binders described in the previous sections were aged in an RTFO to simulate short term aging and the rheological properties of the RTFO aged blended binder were determined in accordance with AASHTO T315 "Test Method for Determining the Rheological Properties of Asphalt Binder Using a Dynamic Shear Rheometer". Again, three samples of each of the blended binders were tested to determine the mean values of $|G^*|/\sin\delta$ and standard deviation.

Table 6-25 through Table 6-33 and Figure 6-10 through Figure 6-12 show the properties for the RTFO aged blended binders at high temperatures with PG 58-28 as the base virgin binder blended with the selected nine RAP binders from the three stockpiles.

Table 6-25: DSR Results of PG 58-28 + 30% Harrison 1 RAP (RTFO Aged)

Temperature	$\|G^*\|/\sin\delta$ (kPa)		δ^o (Phase Angle)	
^oC	Mean	Std. Deviation	Mean	Std. Deviation
64	5.11	0.03	80.63	0.07
70	2.32	0.02	83.12	0.1
76	1.11	0.01	85.19	0.04

Table 6-26: DSR Results of PG 58-28 + 30% Harrison 2 RAP (RTFO Aged)

Temperature	$\|G^*\|/\sin\delta$ (kPa)		δ^o (Phase Angle)	
^oC	Mean	Std. Deviation	Mean	Std. Deviation
64	4.99	0.02	81.25	0.05
70	2.27	0.02	83.71	0.07
76	1.09	0.01	85.68	0.05

Table 6-27: DSR Results of PG 58-28 + 30% Harrison 3 RAP (RTFO Aged)

Temperature	$\|G^*\|/\sin\delta$ (kPa)		δ^o (Phase Angle)	
^oC	Mean	Std. Deviation	Mean	Std. Deviation
64	4.06	0.01	82.01	0.02
70	1.89	0.01	84.23	0.10

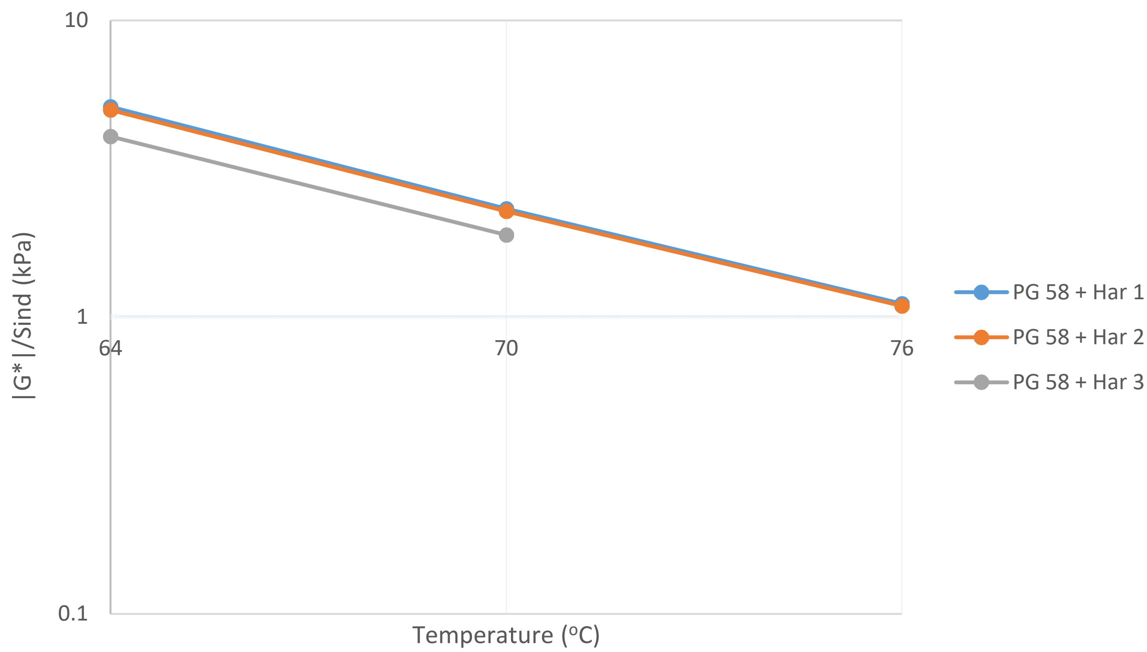

Figure 6-10: DSR Results of PG 58-28 and Harrison RAP Binder Blends (RTFO Aged)

Table 6-28: DSR Results of PG 58-28 + 30% Highland 1 RAP (RTFO Aged)

Temperature	|G*|/sinδ (kPa)		δº (Phase Angle)	
ºC	Mean	Std. Deviation	Mean	Std. Deviation
64	5.91	0.03	79.54	0.02
70	2.71	0.01	82.17	0.02
76	1.29	0.01	84.41	0.06

Table 6-29: DSR Results of PG 58-28 + 30% Highland 2 RAP (RTFO Aged)

Temperature	|G*|/sinδ (kPa)		δº (Phase Angle)	
ºC	Mean	Std. Deviation	Mean	Std. Deviation
64	5.83	0.08	79.57	0.06
70	2.69	0.03	82.17	0.03
76	1.28	0.02	84.37	0.02

Table 6-30: DSR Results of PG 58-28 + 30% Highland 3 RAP (RTFO Aged)

Temperature	$\lvert G^*\rvert/\sin\delta$ (kPa)		δ^o (Phase Angle)	
^oC	Mean	Std. Deviation	Mean	Std. Deviation
64	5.78	0.04	79.64	0.02
70	2.66	0.02	82.19	0.04
76	1.26	0.01	84.45	0.02

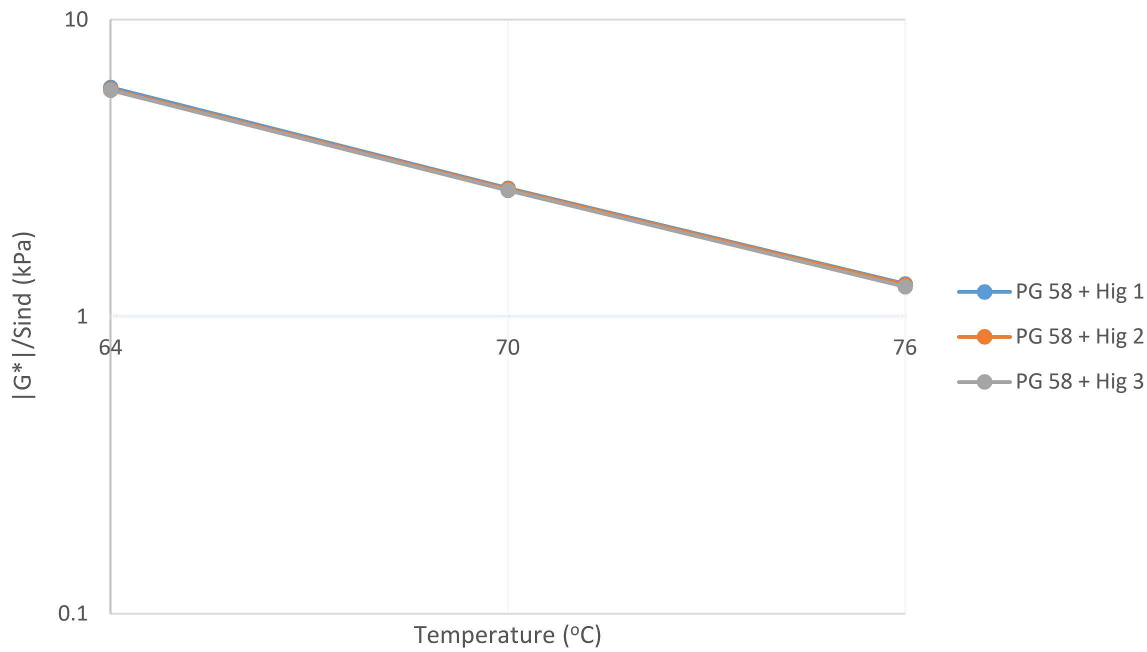

Figure 6-11: DSR Results of PG 58-28 and Highland RAP Binder Blends (RTFO Aged)

Table 6-31: DSR Results of PG 58-28 + 30% Sims 1 RAP (RTFO Aged)

Temperature °C	$\|G^*\|/\sin\delta$ (kPa)		δ^o (Phase Angle)	
	Mean	**Std. Deviation**	**Mean**	**Std. Deviation**
64	12.06	0.07	74.39	0.05
70	5.60	0.06	77.28	0.07
76	2.71	0.03	79.98	0.05
82	1.34	0.01	82.38	0.08

Table 6-32: DSR Results of PG 58-28 + 30% Sims 2 RAP (RTFO Aged)

Temperature °C	$\|G^*\|/\sin\delta$ (kPa)		δ^o (Phase Angle)	
	Mean	**Std. Deviation**	**Mean**	**Std. Deviation**
64	13.19	0.08	74.81	0.13
70	6.09	0.05	77.74	0.03
76	2.90	0.01	80.39	0.06
82	1.42	0.01	82.78	0.02

Table 6-33: DSR Results of PG 58-28 + 30% Sims 3 RAP (RTFO Aged)

Temperature °C	$\|G^*\|/\sin\delta$ (kPa)		δ^o (Phase Angle)	
	Mean	**Std. Deviation**	**Mean**	**Std. Deviation**
64	10.89	0.11	75.27	0.05
70	5.14	0.02	78.14	0.01
76	2.46	0.01	80.76	0.01
82	1.22	0.01	83.07	0.06

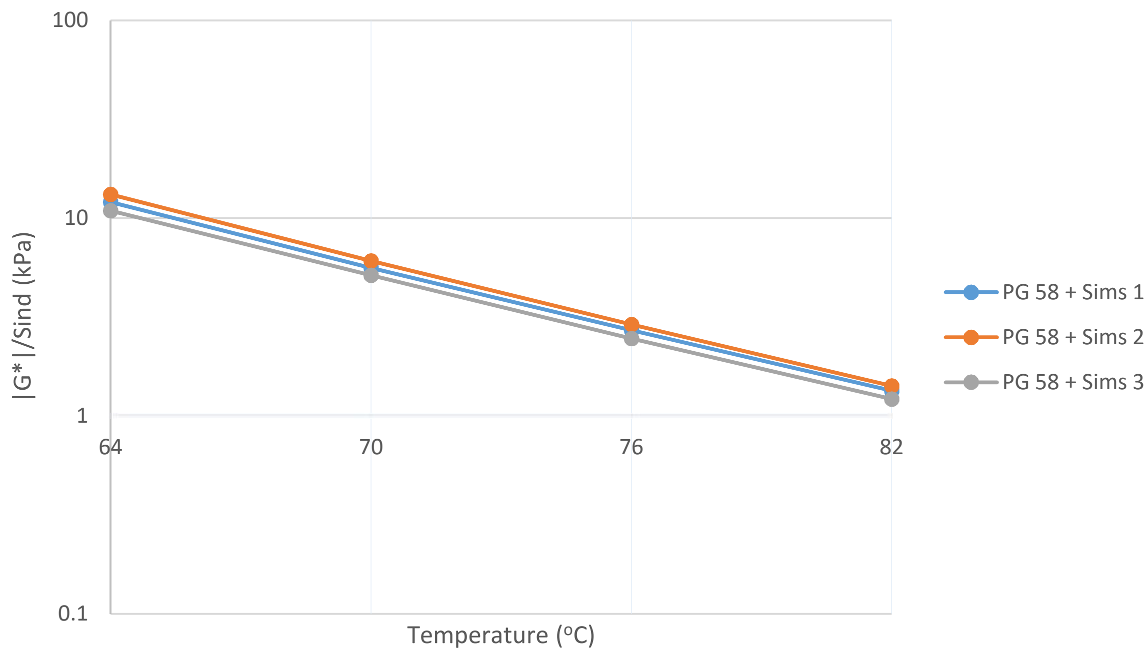

Figure 6-12: DSR Results of PG 58-28 and Sims RAP Binder Blends (RTFO Aged)

In their RTFO aged state, among the three binder blends with RAP binders from Harrison stockpile and PG 58-28, the blend with Harrison 1 RAP binder showed higher stiffness than the blend with Harrison 2 RAP binder followed by the blend with Harrison 3 RAP binder. This trend is similar to what was observed with the unaged blended binders with RAP binders from Harrison stockpile. Harrison 1 and Harrison 2 RAP binder blends with PG 58-28 qualified for a high temperature grade of 70 whereas, Harrison 3 RAP binder blend with PG 58-28 qualified for a high temperature grade of 64 in their RTFO aged state.

In the case of Highland RAP binders, again blends with Highland 1 RAP binder showed higher stiffness than blends with Highland 2 and Highland 3 RAP binders. Highland 1, Highland 2 and Highland 3 RAP binder blends with PG 58-28 binder qualified for a high temperature PG grade of 70 in their RTFO aged state.

In the case of binder blends with RAP binders from Sims stockpile, all the blends qualified for a high temperature PG grade of 76 in their RTFO aged state. Sims 2 binder blend showed higher stiffness values than that of Sims 1 binder blend followed by that of Sims 3 binder blend.

Table 6-34 through Table 6-42 and Figure 6-13 through Figure 6-15 show the properties for the RTFO aged blended binders at high temperatures with PG 64-22 as the base virgin binder.

Table 6-34: DSR Results of PG 64-22 + 30% Harrison 1 RAP (RTFO Aged)

Temperature	**|G*|/sinδ (kPa)**		**δ° (Phase Angle)**	
°C	**Mean**	**Std. Deviation**	**Mean**	**Std. Deviation**
64	10.44	0.08	77.63	0.05
70	4.66	0.02	80.62	0.04
76	2.15	0.01	83.21	0.09

Table 6-35: DSR Results of PG 64-22 + 30% Harrison 2 RAP (RTFO Aged)

Temperature	**|G*|/sinδ (kPa)**		**δ° (Phase Angle)**	
°C	**Mean**	**Std. Deviation**	**Mean**	**Std. Deviation**
64	9.84	0.12	78.59	0.05
70	4.36	0.02	81.49	0.08
76	2.03	0.01	83.88	0.05

Table 6-36: DSR Results of PG 64-22 + 30% Harrison 3 RAP (RTFO Aged)

Temperature	|G*|/sinδ (kPa)		δ° (Phase Angle)	
°C	**Mean**	**Std. Deviation**	**Mean**	**Std. Deviation**
64	7.99	0.04	79.56	0.09
70	3.58	0.01	82.19	0.06
76	1.67	0.02	84.45	0.03

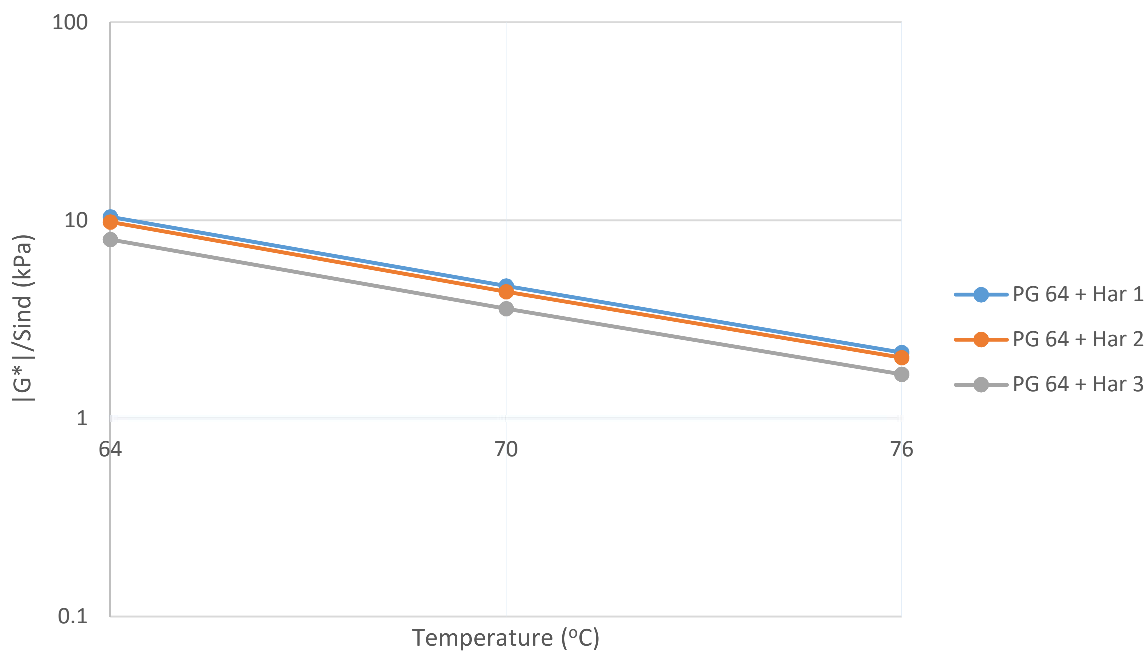

Figure 6-13: DSR Results of PG 64-22 and Harrison RAP Binder Blends (RTFO Aged)

Table 6-37: DSR Results of PG 64-22 + 30% Highland 1 RAP (RTFO Aged)

Temperature	|G*|/sinδ (kPa)		δ° (Phase Angle)	
°C	Mean	Std. Deviation	Mean	Std. Deviation
64	11.94	0.08	76.54	0.05
70	5.32	0.04	79.55	0.04
76	2.49	0.01	82.17	0.06
82	1.20	0.01	84.41	0.03

Table 6-38: DSR Results of PG 64-22 + 30% Highland 2 RAP (RTFO Aged)

Temperature	|G*|/sinδ (kPa)		δ° (Phase Angle)	
°C	Mean	Std. Deviation	Mean	Std. Deviation
64	11.33	0.04	76.85	0.02
70	5.11	0.06	79.85	0.04
76	2.38	0.01	82.41	0.07
82	1.14	0.01	84.59	0.03

Table 6-39: DSR Results of PG 64-22 + 30% Highland 3 RAP (RTFO Aged)

Temperature	|G*|/sinδ (kPa)		δ° (Phase Angle)	
°C	Mean	Std. Deviation	Mean	Std. Deviation
64	11.09	0.06	76.92	0.04
70	4.98	0.04	79.92	0.06
76	2.31	0.01	82.49	0.03
82	1.12	0.01	84.66	0.08

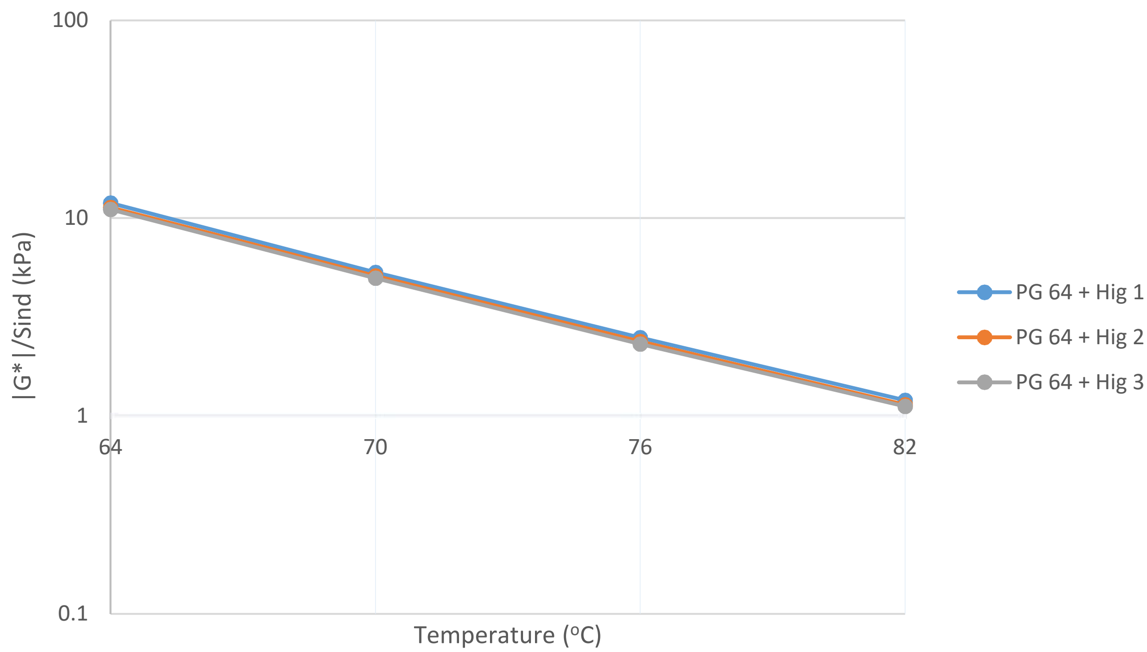

Figure 6-14: DSR Results of PG 64-22 and Highland RAP Binder Blends (RTFO Aged)

Table 6-40: DSR Results of PG 64-22 + 30% Sims 1 RAP (RTFO Aged)

Temperature	|G*|/sinδ (kPa)		δº (Phase Angle)	
ºC	Mean	Std. Deviation	Mean	Std. Deviation
64	21.45	0.19	72.24	0.04
70	9.77	0.09	75.36	0.03
76	4.56	0.04	78.31	0.03
82	2.21	0.02	80.95	0.14
88	1.11	0.01	83.16	0.00

Table 6-41: DSR Results of PG 64-22 + 30% Sims 2 RAP (RTFO Aged)

Temperature	$\|G^*\|/\sin\delta$ (kPa)		δ^o (Phase Angle)	
^oC	Mean	Std. Deviation	Mean	Std. Deviation
64	27.51	0.72	71.51	0.07
70	12.53	0.33	74.57	0.17
76	5.86	0.09	77.69	0.12
82	2.76	0.03	80.50	0.09
88	1.33	0.02	82.93	0.12

Table 6-42: DSR Results of PG 64-22 + 30% Sims 3 RAP (RTFO Aged)

Temperature	$\|G^*\|/\sin\delta$ (kPa)		δ^o (Phase Angle)	
^oC	Mean	Std. Deviation	Mean	Std. Deviation
64	21.65	0.23	72.37	0.05
70	9.87	0.04	75.51	0.04
76	4.63	0.03	78.43	0.07
82	2.24	0.02	81.05	0.03
88	1.12	0.01	83.30	0.02

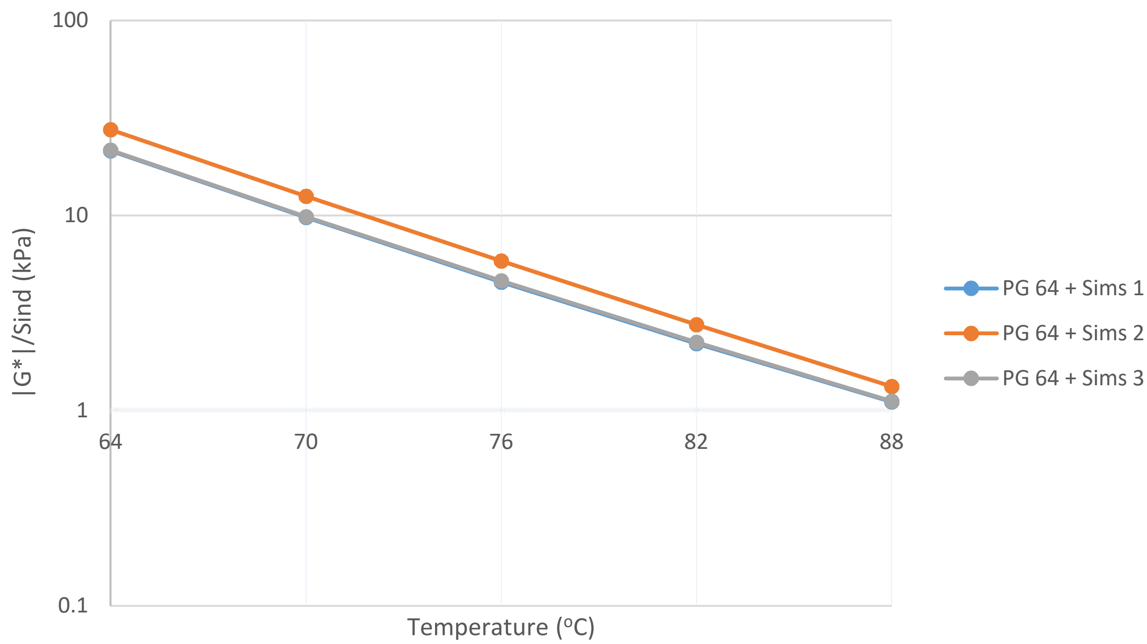

Figure 6-15: DSR Results of PG 64-22 and Sims RAP Binder Blends (RTFO Aged)

The RTFO aged blended binder of Sims 2 RAP binder with PG 64-22 binder showed higher stiffness values than that of Sims 1 and Sims 3 RAP binder with PG 64-22 which showed comparable stiffness values. All the three Sims RAP binder blends qualified for a high temperature PG grade of 82.

The RTFO aged blended binders of Highland 1 RAP binder showed higher stiffness values among the three Highland RAP binder blends followed by Highland 2 RAP binder and Highland 3 RAP binder blends. This trend is different from what was observed with unaged binder blends where Highland 3 RAP binder blend showed greater stiffness than that of Highland 2 RAP binder blend. One reason that can be attributed is that Highland 2 RAP binder blend showed a greater rate of aging than that of Highland 3 RAP binder blend. All the three

Highland RAP binder blends with PG 64-22 qualified for high temperature grade of 76 in their RTFO aged state.

In the case of RTFO aged blended binders of Harrison RAP stockpile, binder blend with Harrison 1 showed greater stiffness than Harrison 2 binder blend followed by Harrison 3 binder blend. All the three binder blends with Harrison RAP binders qualified for a high temperature PG grade of 70.

6.2.3. Blended Binders in PAV Aged Conditions

The RTFO aged blended binders were further aged in a PAV to simulate long term field aging during service to determine the intermediate temperature rheological properties. Three samples for each of the binders were tested at intermediate testing temperatures in accordance with AASHTO T315 “Test Method for Determining the Rheological Properties of Asphalt Binder Using a Dynamic Shear Rheometer” to determine the mean values of $|G^*|\sin\delta$ and standard deviation.

Table 6-43 through Table 6-51 and Figure 6-16 through Figure 6-18 show the properties for the PAV blended binders at intermediate temperatures with PG 58-28 as the base virgin binder blended.

Table 6-43: DSR Results of PG 58-28 + 30% Harrison 1 RAP (PAV Aged)

Temperature	$\|G^*\|\sin\delta$ (kPa)		δ^o (Phase Angle)	
^oC	Mean	Std. Deviation	Mean	Std. Deviation
16	9979.08	288.70	38.65	0.20
19	7488.34	294.35	40.87	0.13
22	5468.98	242.45	43.50	0.14
25	3811.67	130.04	45.79	0.52
28	2631.79	90.03	48.34	0.57

Table 6-44: DSR Results of PG 58-28 + 30% Harrison 2 RAP (PAV Aged)

Temperature	$\|G^*\|\sin\delta$ (kPa)		δ^o (Phase Angle)	
^oC	Mean	Std. Deviation	Mean	Std. Deviation
16	9787.34	559.73	39.69	0.48
19	7365.78	326.74	41.15	0.30
22	5197.80	92.87	43.73	0.38
25	3691.44	53.51	46.09	0.17
28	2574.96	95.72	48.95	0.54

Table 6-45: DSR Results of PG 58-28 + 30% Harrison 3 RAP (PAV Aged)

Temperature	$\|G^*\|\sin\delta$ (kPa)		δ^o (Phase Angle)	
^oC	Mean	Std. Deviation	Mean	Std. Deviation
16	9333.89	124.55	39.50	0.39
19	6531.83	211.44	42.03	0.54
22	4614.37	224.30	44.43	0.11
25	3338.13	149.09	46.33	0.56
28	2304.81	124.21	48.87	0.66

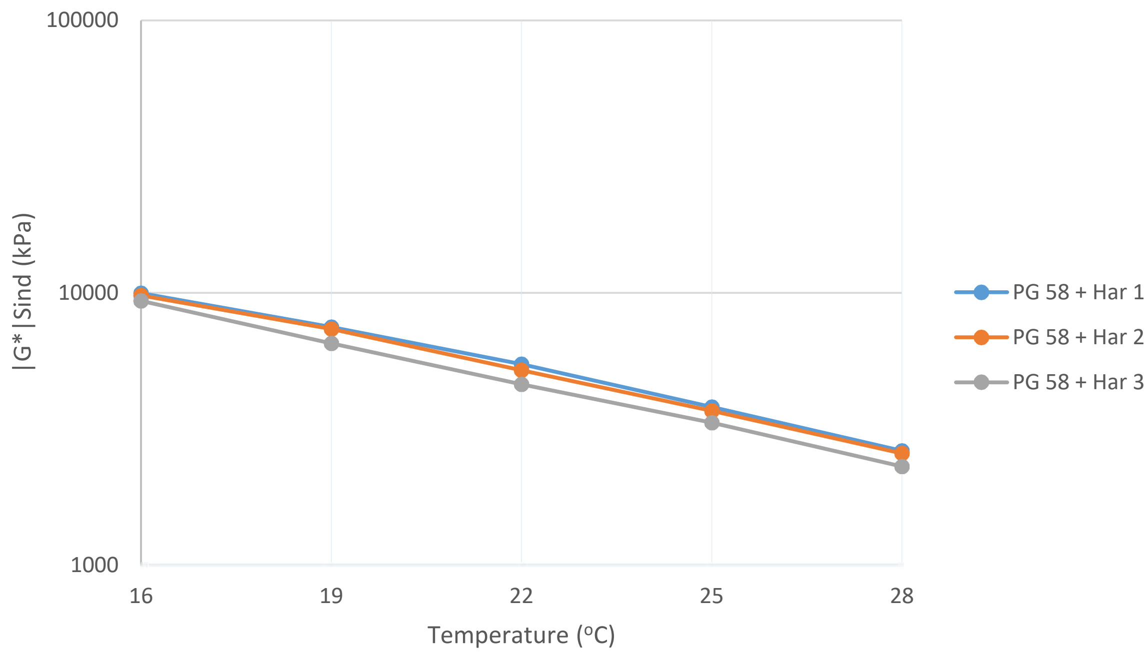

Figure 6-16: DSR Results of PG 58-28 and Harrison RAP Binder Blends (PAV Aged)

Table 6-46: DSR Results of PG 58-28 + 30% Highland 1 RAP (PAV Aged)

Temperature	**|G*|sinδ (kPa)**		**δº (Phase Angle)**	
ºC	**Mean**	**Std. Deviation**	**Mean**	**Std. Deviation**
16	9988.18	13.26	39.35	0.31
19	7081.28	35.68	41.29	0.51
22	5100.05	43.00	43.60	0.58
25	3742.04	39.52	45.81	0.82
28	2591.23	15.90	48.11	0.69

Table 6-47: DSR Results of PG 58-28 + 30% Highland 2 RAP (PAV Aged)

Temperature	$\|G^*\|\sin\delta$ (kPa)		δ^o (Phase Angle)	
^oC	Mean	Std. Deviation	Mean	Std. Deviation
16	10204.23	191.92	39.52	0.27
19	7211.20	67.72	41.99	0.80
22	5209.94	50.04	44.46	1.17
25	3763.19	132.93	46.33	0.79
28	2630.32	58.73	48.86	0.37

Table 6-48: DSR Results of PG 58-28 + 30% Highland 3 RAP (PAV Aged)

Temperature	$\|G^*\|\sin\delta$ (kPa)		δ^o (Phase Angle)	
^oC	Mean	Std. Deviation	Mean	Std. Deviation
16	10078.47	54.98	39.49	0.04
19	7297.28	122.12	41.11	0.45
22	5239.67	62.53	43.40	0.64
25	3739.71	43.24	46.51	0.12
28	2579.46	33.40	49.08	0.22

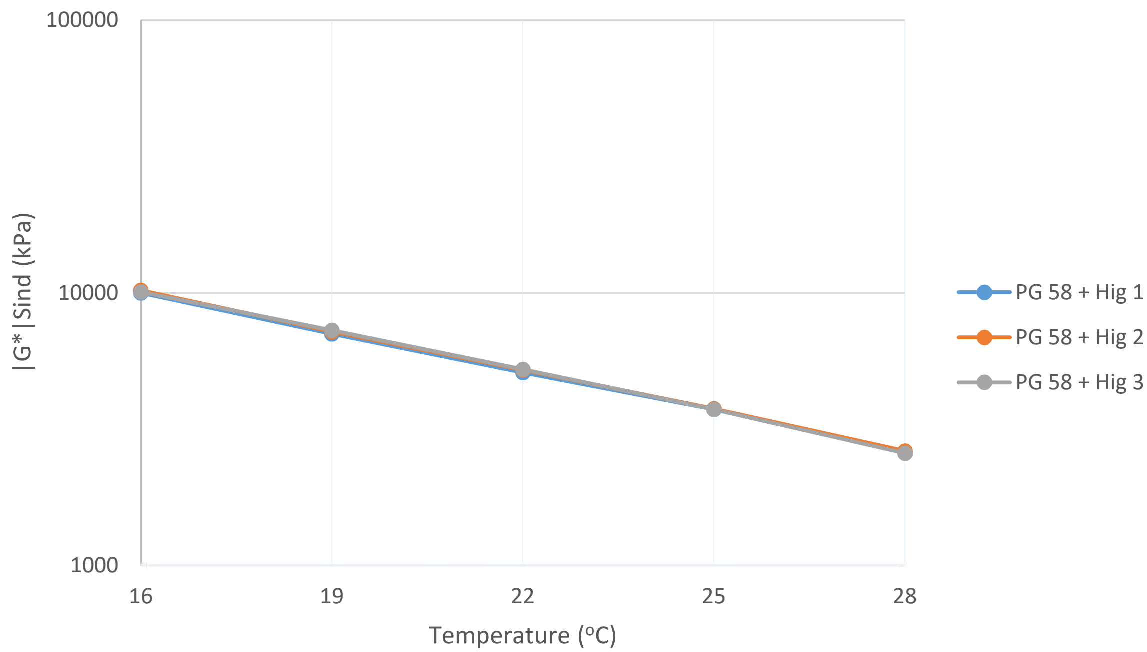

Figure 6-17: DSR Results of PG 58-28 and Highland RAP Binder Blends (PAV Aged)

Table 6-49: DSR Results of PG 58-28 + 30% Sims 1 RAP (PAV Aged)

Temperature	|G*|sinδ (kPa)		δº (Phase Angle)	
ºC	Mean	Std. Deviation	Mean	Std. Deviation
16	12324.4	326.82	38.01	0.05
19	9891.94	448.96	39.83	0.31
22	7081.11	312.14	42.06	0.26
25	5027.46	168.56	44.44	0.42

Table 6-50: DSR Results of PG 58-28 + 30% Sims 2 RAP (PAV Aged)

Temperature	$\|G^*\|\sin\delta$ (kPa)		δ^o (Phase Angle)	
^oC	Mean	Std. Deviation	Mean	Std. Deviation
16	13958.80	618.78	37.26	0.35
19	10394.52	640.22	39.18	0.79
22	7657.56	410.66	41.34	0.96
25	5461.13	196.00	43.63	0.71
28	3864.94	92.97	46.44	0.58

Table 6-51: DSR Results of PG 58-28 + 30% Sims 3 RAP (PAV Aged)

Temperature	$\|G^*\|\sin\delta$ (kPa)		δ^o (Phase Angle)	
^oC	Mean	Std. Deviation	Mean	Std. Deviation
16	13221.5	172.18	37.87	0.11
19	9399.37	165.23	39.65	0.24
22	6867.42	110.18	41.96	0.16
25	4866.39	98.97	44.27	0.03

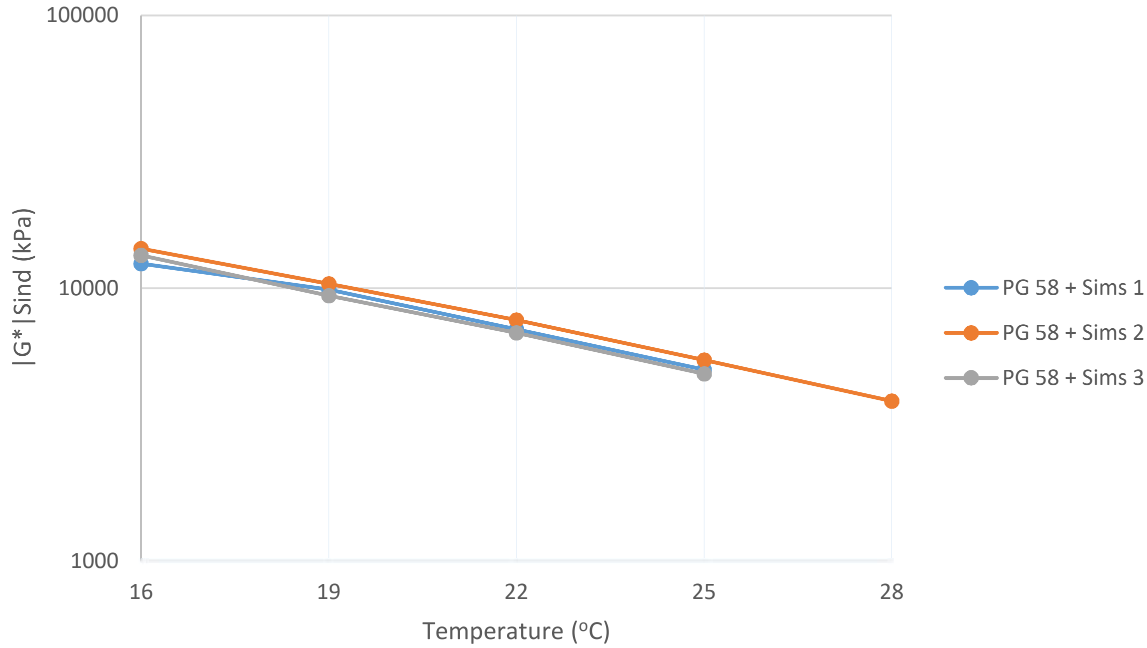

Figure 6-18: DSR Results of PG 58-28 and Sims RAP Binder Blends (PAV Aged)

The binders that showed the highest stiffness in RTFO aged conditions also showed the highest stiffness after long term aging. PAV aged blended binder with Harrison 1 RAP binder and PG 58-28 showed greater stiffness than the blended binder of Harrison 2 followed by blended binder of Harrison 3 RAP binder.

In the case of Highland RAP binders, again all the blends showed comparable stiffness values. In the case of Sims RAP binders, blends with Sims 2 RAP binder showed greater stiffness compared to blends with Sims 1 and Sims 3 RAP binders. Blends with Sims 1 RAP binder showed comparable stiffness values to blends with Sims 3 RAP binder in their PAV aged state.

Table 6-52 through Table 6-60 and Figure 6-19 through Figure 6-21 show the properties for the PAV aged blended binders at intermediate temperatures with PG 64-22 as the base virgin binder blended with the selected nine RAP binders from the three stockpiles.

Table 6-52: DSR Results of PG 64-22 + 30% Harrison 1 RAP (PAV Aged)

Temperature	|G*|sinδ (kPa)		δº (Phase Angle)	
ºC	Mean	Std. Deviation	Mean	Std. Deviation
16	12934.23	253.9	34.35	0.11
19	9680.26	180.17	36.17	0.25
22	7377.71	101.52	38.42	0.52
25	5530.37	133.67	40.55	0.38
28	3990.62	46.8	42.83	0.15

Table 6-53: DSR Results of PG 64-22 + 30% Harrison 2 RAP (PAV Aged)

Temperature	|G*|sinδ (kPa)		δº (Phase Angle)	
ºC	Mean	Std. Deviation	Mean	Std. Deviation
16	13118.33	306.93	34.74	0.08
19	10683.57	242.79	36.42	0.39
22	8000.05	51.10	38.71	0.49
25	5935.70	5.27	40.88	0.55
28	4268.65	13.47	43.07	0.28

Table 6-54: DSR Results of PG 64-22 + 30% Harrison 3 RAP (PAV Aged)

Temperature	|G*|sinδ (kPa)		δ° (Phase Angle)	
°C	Mean	Std. Deviation	Mean	Std. Deviation
16	12693.60	460.38	35.12	0.46
19	9379.30	84.00	36.70	0.14
22	7010.93	81.77	39.26	0.09
25	5102.68	80.72	41.75	0.28
28	3600.59	79.89	44.23	0.26

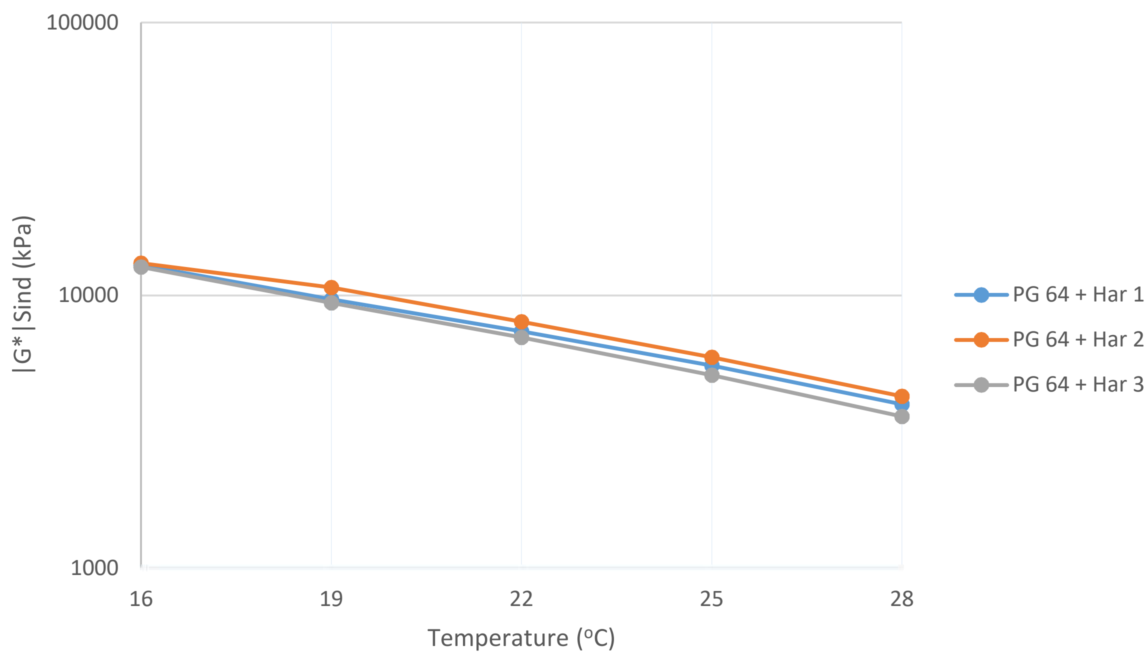

Figure 6-19: DSR Results of PG 64-22 and Harrison RAP Binder Blends (PAV Aged)

Table 6-55: DSR Results of PG 64-22 + 30% Highland 1 RAP (PAV Aged)

Temperature	$\|G^*\|\sin\delta$ (kPa)		δ^o (Phase Angle)	
^{o}C	Mean	Std. Deviation	Mean	Std. Deviation
16	13956.50	171.08	34.40	0.27
19	10476.77	239.32	35.70	0.54
22	7852.02	207.59	38.11	0.59
25	5724.52	135.28	40.62	0.66
28	4165.75	71.86	43.59	0.38

Table 6-56: DSR Results of PG 64-22 + 30% Highland 2 RAP (PAV Aged)

Temperature	$\|G^*\|\sin\delta$ (kPa)		δ^o (Phase Angle)	
^{o}C	Mean	Std. Deviation	Mean	Std. Deviation
19	9485.37	103.94	37.92	0.1
22	7650.71	36.53	40.63	0.06
25	5620.12	85.67	43.23	0.27
28	4045.50	59.6	44.54	0.01

Table 6-57: DSR Results of PG 64-22 + 30% Highland 3 RAP (PAV Aged)

Temperature	$\|G^*\|\sin\delta$ (kPa)		δ^o (Phase Angle)	
^{o}C	Mean	Std. Deviation	Mean	Std. Deviation
19	9466.56	361.77	37.90	0.08
22	7026.65	294.13	40.03	0.84
25	5261.32	189.58	42.50	1.07
28	3803.35	77.63	44.53	0.09

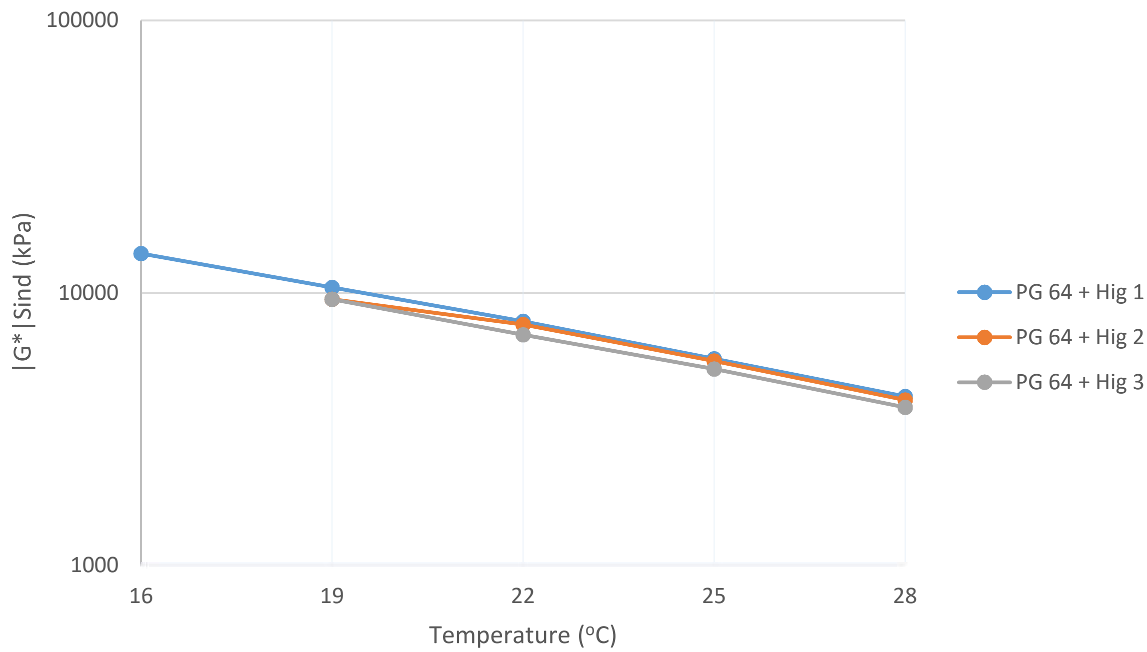

Figure 6-20: DSR Results of PG 64-22 and Highland RAP Binder Blends (PAV Aged)

Table 6-58: DSR Results of PG 64-22 + 30% Sims 1 RAP (PAV Aged)

Temperature ºC	|G*|sinδ (kPa)		δº (Phase Angle)	
	Mean	**Std. Deviation**	**Mean**	**Std. Deviation**
16	16688.73	420.03	33.28	0.18
19	13799.07	237.2	34.58	0.14
22	10697.27	189.43	36.76	0.16
25	7985.26	181.45	39.13	0.19
28	5826.01	113.42	41.62	0.28
31	4151.89	88.37	43.79	0.11

Table 6-59: DSR Results of PG 64-22 + 30% Sims 2 RAP (PAV Aged)

Temperature	$\lvert G^* \rvert \sin\delta$ (kPa)		δ^o (Phase Angle)	
^oC	Mean	Std. Deviation	Mean	Std. Deviation
16	18631.83	346.68	31.33	0.30
19	16118.07	643.56	32.37	0.94
22	12318.97	529.11	34.35	1.14
25	9425.75	347.42	36.77	1.17
28	6972.22	251.89	39.00	1.08
31	5033.38	130.76	41.04	1.37

Table 6-60: DSR Results of PG 64-22 + 30% Sims 3 RAP (PAV Aged)

Temperature	$\lvert G^* \rvert \sin\delta$ (kPa)		δ^o (Phase Angle)	
^oC	Mean	Std. Deviation	Mean	Std. Deviation
16	14782.37	82.33	34.24	0.33
19	11838.07	554.12	35.85	0.74
22	8955.29	428.28	38.28	1.28
25	6512.95	227.36	40.14	0.75
28	4700.13	151.29	42.33	0.81

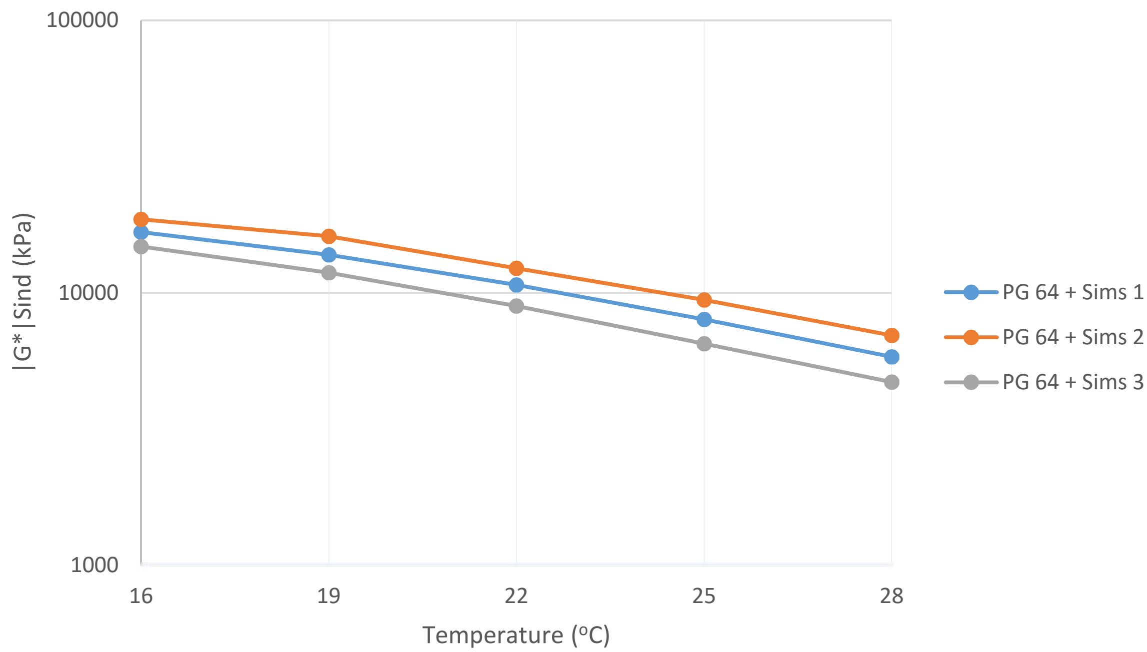

Figure 6-21: DSR Results of PG 64-22 and Sims RAP Binder Blends (PAV Aged)

Among the three blended binders with RAP binders from Harrison stockpile, PAV aged blended binder with Harrison 2 RAP binder showed greater stiffness than the PAV aged blended binder with Harrison 1 RAP binder and finally, PAV aged blended binder with Harrison 3 RAP binder. This trend is different from what was observed in RTFO aged blended binders with Harrison RAP binders where, RTFO aged blended binder with Harrison 1 RAP binder showed greater stiffness than that with Harrison 2 RAP binder. One reason for this reversal in trend could be attributed to the difference in aging process in RTFO and PAV.

Among the PAV aged blended binders with Highland RAP binders and PG 64-22 virgin binder, Highland 1 based blend showed greatest stiffness followed by Highland 2 based blend and finally, Highland 3 based blend.

In the case of PAV aged blended binders with RAP binders from Sims stockpile and PG 64-22 virgin binder, Sims 2 based blended binders were the stiffest followed by Sims 1 based blend and finally, Sims 3 based blend.

Table 6-61 below summarizes the PG grades of all the blended binders in different aged states. The high temperature grade of a binder is the temperature at which the conditions of $|G^*|/\sin\delta > 1.0$kPa for unaged binders and $|G^*|/\sin\delta > 2.2$kPa for RTFO aged binders are met simultaneously. The intermediate temperature grade of a binder is the lowest temperature at which the condition of $|G^*|\sin\delta < 5000$kPa is satisfied.   The last column in the table shows the high temperature PG grade of the blended binders determined by taking the minimum of the two PG grades in the 'Unaged' and 'RTFO Aged' columns.

Table 6-61: Summary of DSR Test Results on Blended Binders

Blended Binder Type	Unaged	RTFO Aged	PAV Aged	High PG
PG 58 + 30% Harrison 1	70	70	25	70
PG 58 + 30% Harrison 2	70	70	25	70
PG 58 + 30% Harrison 3	64	64	22	64
PG 58 + 30% Highland 1	70	70	25	70
PG 58 + 30% Highland 2	70	70	25	70
PG 58 + 30% Highland 3	70	70	25	70
PG 58 + 30% Sims 1	70	76	28	70
PG 58 + 30% Sims 2	76	76	28	76
PG 58 + 30% Sims 3	70	76	25	70
PG 64 + 30% Harrison 1	70	70	28	70
PG 64 + 30% Harrison 2	70	70	28	70
PG 64 + 30% Harrison 3	70	70	28	70
PG 64 + 30% Highland 1	70	76	28	70
PG 64 + 30% Highland 2	70	76	28	70
PG 64 + 30% Highland 3	70	76	28	70
PG 64 + 30% Sims 1	76	82	31	76
PG 64 + 30% Sims 2	82	82	34	82
PG 64 + 30% Sims 3	76	82	28	76

The high temperature grades of the blended binders obtained by blending the nine RAP binders from the selected three stockpiles varied from 64 to 82. The intermediate temperature grade varied from 22 to 34. The data obtained from these binder blends for the nine RAP binders and the two virgin binders were used to plot blending charts which in turn would be used to determine the maximum and minimum amounts of the corresponding RAP binder that can be blended with the two virgin binders and still satisfy the Superpave criteria at a given temperature.

CHAPTER 7 : - BLENDING CHARTS AND ANALYSIS OF RESULTS

This chapter discusses the preparation of blending charts from the rheological properties of RAP binders and, virgin and blended binders obtained in chapter 4 and chapter 6, respectively. For each of the selected RAP binders to be blended with each of the two virgin binders PG 58-22 and PG 64-22, blending charts were prepared that plot the increase of stiffness values at a given temperature with increase in proportion of RAP in a blended binder. Since, Superpave specifications define necessary criteria for asphalt binders in unaged, RTFO aged and PAV aged conditions, blending charts were plotted for each of the three aged conditions. Since nine RAP binders were selected from the three stockpiles and blended with each of the two virgin binders, a total of eighteen blending charts were prepared for each one of the three aged conditions.

Superpave specifications suggests that to minimize rutting in an asphalt pavement, the $|G^*|/\sin\delta$ must be a minimum of 1.0kPa for unaged asphalt binder and a minimum of 2.2kPa for RTFO aged asphalt binder at high service temperatures. The high temperature grade of an asphalt binder is the temperature at which both the aforementioned criteria are satisfied. PG 64-22 is the most commonly used binder grade in the state of North Carolina and so the focus is to study and formulate a criteria for the variation observed in RAP binders and blended binders such that all the blended binders qualify for a high temperature PG grade of 64. Therefore, the blending charts for unaged and RTFO aged conditions if necessary were plotted at 64^{o}C to determine the minimum amount of RAP binder that on blending with a virgin binder results in a high temperature PG grade of 64. Since, the stiffness of binders only increased with addition of RAP binder, all blended binders with the base virgin binder of PG 64-22 would satisfy the criteria and no minimum limits on the amount of RAP binder were necessary for the PG 64-22 binder blends. As was discussed in the previous chapter, blends were also prepared with PG 58-28 as the virgin binder to be able to use high proportions of RAP binder. Since PG 58-28 is softer than PG 64-22, some minimum amount of RAP binder would be needed to be blended with PG 58-28 virgin binder to bump the high temperature grade to 64. Therefore, minimum limits on the amount of RAP binder were necessary for PG 58-28 binder.

Superpave specifications places the requirement that $|G^*|\sin\delta < 5000$kPa for PAV aged asphalt binders in order to perform well under cyclic loading and resist fatigue failure. With an increase in the proportion of RAP binder, the stiffness of a binder increased as was observed from the results in the previous chapter. Therefore, the criteria of $|G^*|\sin\delta < 5000$kPa at the intermediate temperature grade will limit the maximum amount of RAP binder that can be blended with a virgin binder and still satisfy the condition. Since, the intermediate temperature grade of PG 64-22 is 25, the blending charts for PAV aged binders were plotted at a temperature of 25^{o}C for both the virgin binders. These blending charts will help to place maximum limits on the different RAP binders used in the study.

7.1. Blending Charts with PG 58-28 as Virgin Binder

As described earlier, blending charts for PG 58-28 virgin binder with the nine selected RAP binders were developed in their unaged, RTFO aged and PAV aged state. The blending charts in unaged and RTFO aged state will determine the minimum amounts of RAP binders needed to be blended with PG 58-28 binder in order for the blended binder to be qualified for a PG

64-22 binder. Figure 7-1 and Figure 7-2 show the blending charts at a temperature of 64^{o}C with all the nine selected RAP binders for unaged and RTFO aged conditions, respectively. For example, the top left plot in Figure 7-1 titled "58-Har1-Un" shows the blending chart for PG 58-28 binder blended with Harrison 1 RAP binder in unaged condition, and the top left plot in Figure 7-2 titled "58-Har1-RTFO" shows the blending chart for PG 58-28 binder blended with Harrison 1 RAP binder in RTFO aged condition. The ln(|G*|/sinδ) values for the binders were plotted on the Y-axis and the percent RAP binder in the blend on the X-axis. The y-values corresponding to a 0% on the X-axis are the ln(|G*|/sinδ) values for PG 58-28 at 64^{o}C. The values corresponding to a 30% on the X-axis are the ln(|G*|/sinδ) values for the blended binders. The ln(|G*|/sinδ) values corresponding to a 100% on X-axis are the stiffness values for pure RAP binders. The blue line represents a linear relationship between the ln(|G*|/sinδ) values and percent RAP binder in the blend. The grey band around the fitted line is the amount of uncertainty in the relationship. Owing to the fact that there were just three observations to fit the relationship, even a slight deviation from collinearity would result in large uncertainty. The goal is to predict the percent RAP binder for which the |G*|/sinδ values equal 1.0kPa in unaged conditions and 2.2kPa in RTFO aged conditions. Linear models of the form shown in Equation 7-1 were fit to the nine sets of data for each of the unaged and RTFO aged conditions and these relationships were used to predict the percent RAP binders for which |G*|/sinδ values equal 1.0kPa for unaged and 2.0kPa for RTFO aged conditions.

Equation 7-1: $$\ln\left(\frac{|G*|}{sin\partial}\right) = \boldsymbol{A} + \boldsymbol{B} * (\%\ \boldsymbol{RAP})$$

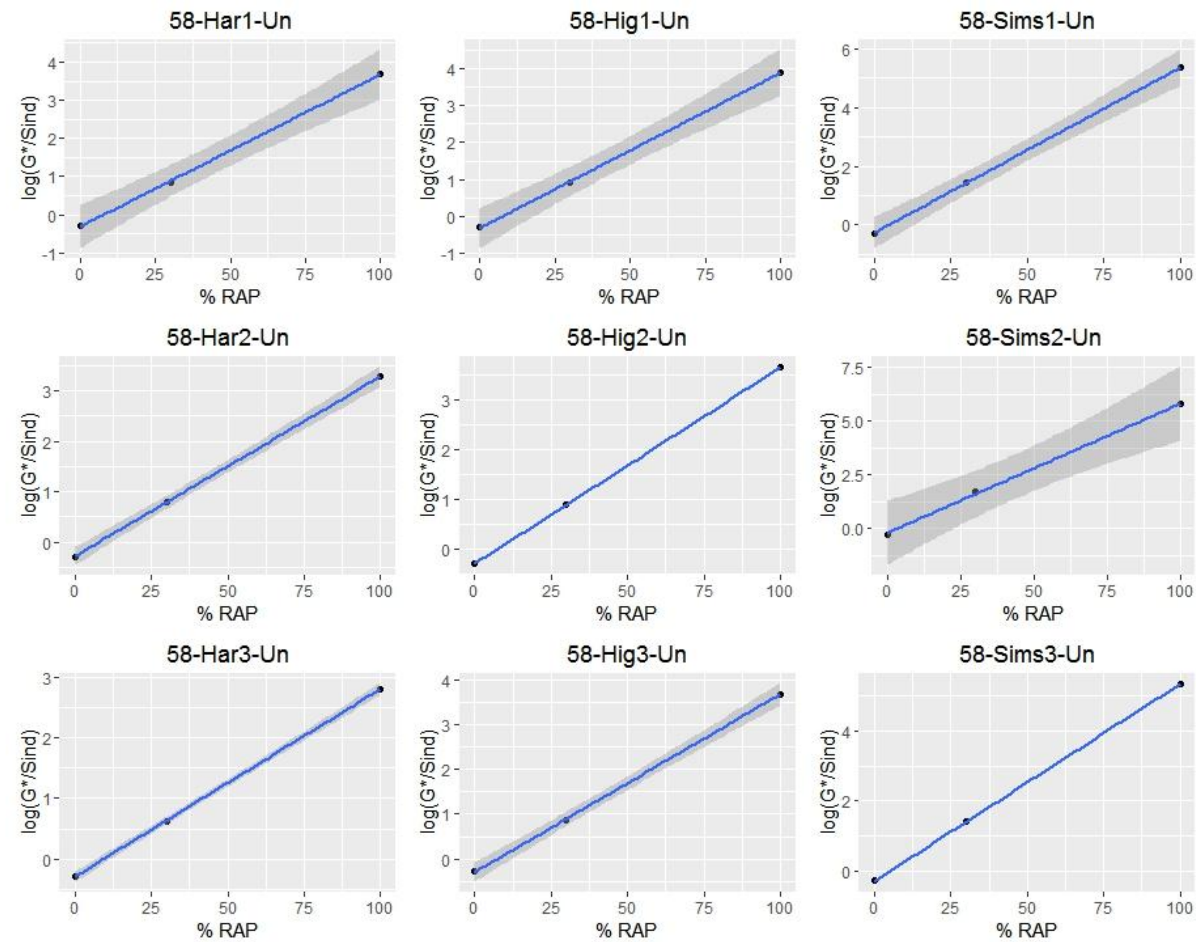

Figure 7-1: Blending Charts for PG 58-28 at 64°C (Unaged)

The parameters A and B will be unique for each of the relationships in the blending charts and would also be unique for each of the aged conditions.

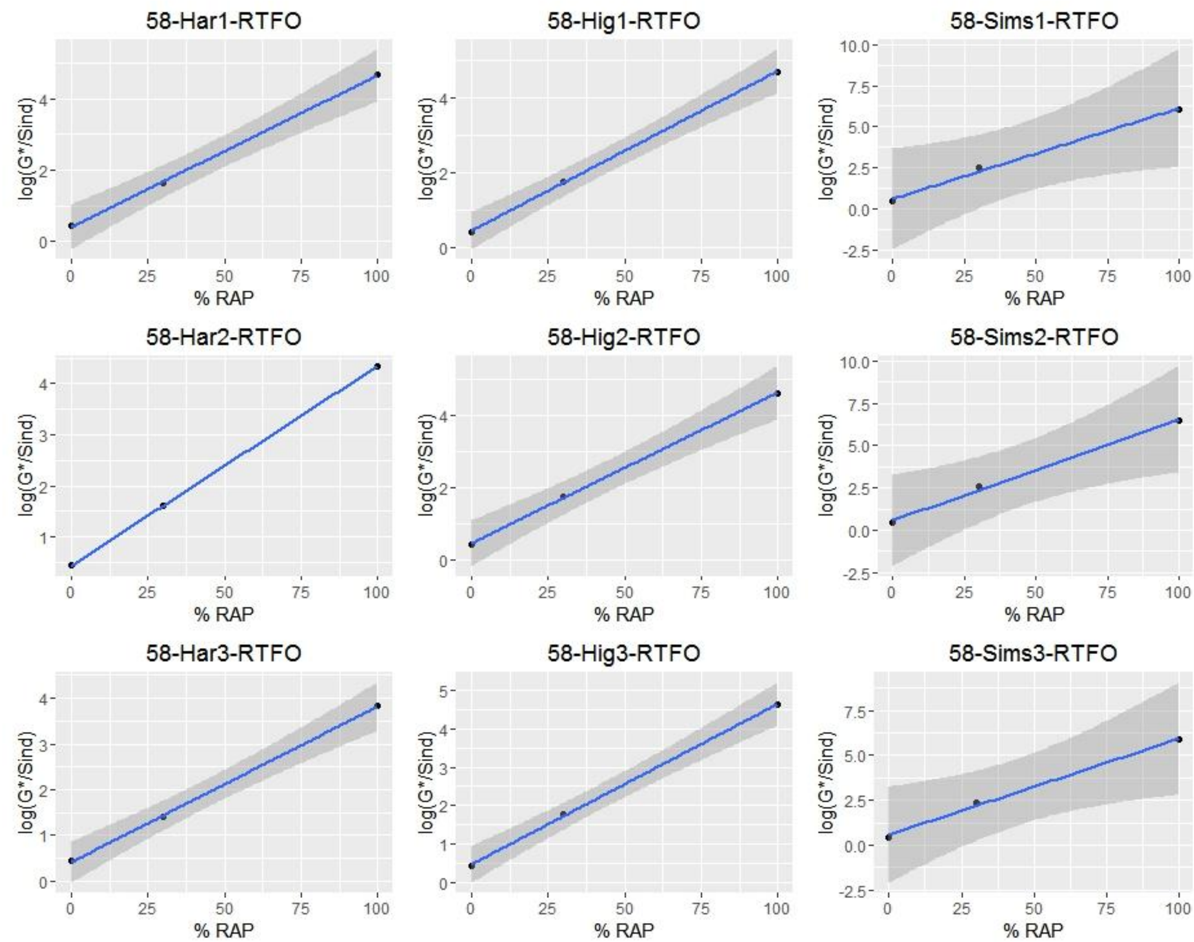

Figure 7-2: Blending Charts for PG 58-28 at 64ºC (RTFO Aged)

Table 7-1 below lists the values of the parameters A and B estimated from the blending charts for unaged and RTFO aged conditions. The '% RAP' column is the predicted percentage of RAP binder needed to meet the criteria of |G*|/sinδ > 1.0kPa for unaged conditions and the criteria of |G*|/sinδ > 2.2kPa for RTFO aged conditions. The 'Min. Limits' column is the maximum of the two percentages for each of the blend type and is the minimum amount of RAP binder that should be blended with the virgin binder PG 58-28 for its high temperature grade to bump to 64.

Table 7-1: Parameter Estimates and Minimum Binder Limits (PG 58-28)

Blend Type	Unaged			RTFO			Min. Limits
	A	B	%RAP	A	B	%RAP	
PG 58 + Harrison 1	-0.318	0.0399	8	0.405	0.0425	10	10%
PG 58 + Harrison 2	-0.278	0.0356	8	0.4379	0.0390	9	9%
PG 58 + Harrison 3	-0.292	0.0310	10	0.4145	0.0340	11	11%
PG 58 + Highland 1	-0.316	0.0421	8	0.4646	0.0425	8	8%
PG 58 + Highland 2	-0.286	0.0394	8	0.4716	0.0415	8	8%
PG 58 + Highland 3	-0.299	0.0398	8	0.4637	0.0418	8	8%
PG 58 + Sims 1	-0.260	0.0562	5	0.6006	0.0553	4	5%
PG 58 + Sims 2	-0.209	0.0602	4	0.5804	0.0599	4	4%
PG 58 + Sims 3	-0.290	0.0563	6	0.5795	0.0536	4	6%

From the table it can be observed that the minimum limits of RAP binders for PG 58-28 varied from 4% to 11%.

For determining the maximum amounts of RAP binders that can be blended with PG 58-28 virgin binder, blending charts were developed for PAV aged conditions at 25^{o}C. The ln(|G*|sinδ) values were plotted on the Y-axis and percent RAP binder on the X-axis. The y-values corresponding to 0%, 30% and 100% on X-axis are the ln(|G*|sinδ) values for PAV aged PG 58-28, blended binders and pure RAP binders at 25^{o}C, respectively. For these blending charts Equation 7-2 below was fit to the data and the parameters A and B estimated.

Equation 7-2: $$\ln(|\boldsymbol{G}*|\boldsymbol{sin\partial}) = \boldsymbol{A} + \boldsymbol{B} * (\%\,\boldsymbol{RAP})$$

From the estimates of the parameters A and B, percentages were calculated for each RAP binder such that |G*|sinδ values equal 5000kPa. These percentages serve as the maximum limits for the corresponding RAP binders. Figure 7-3 below shows the blending charts for the binders in PAV aged conditions at 25^{o}C.

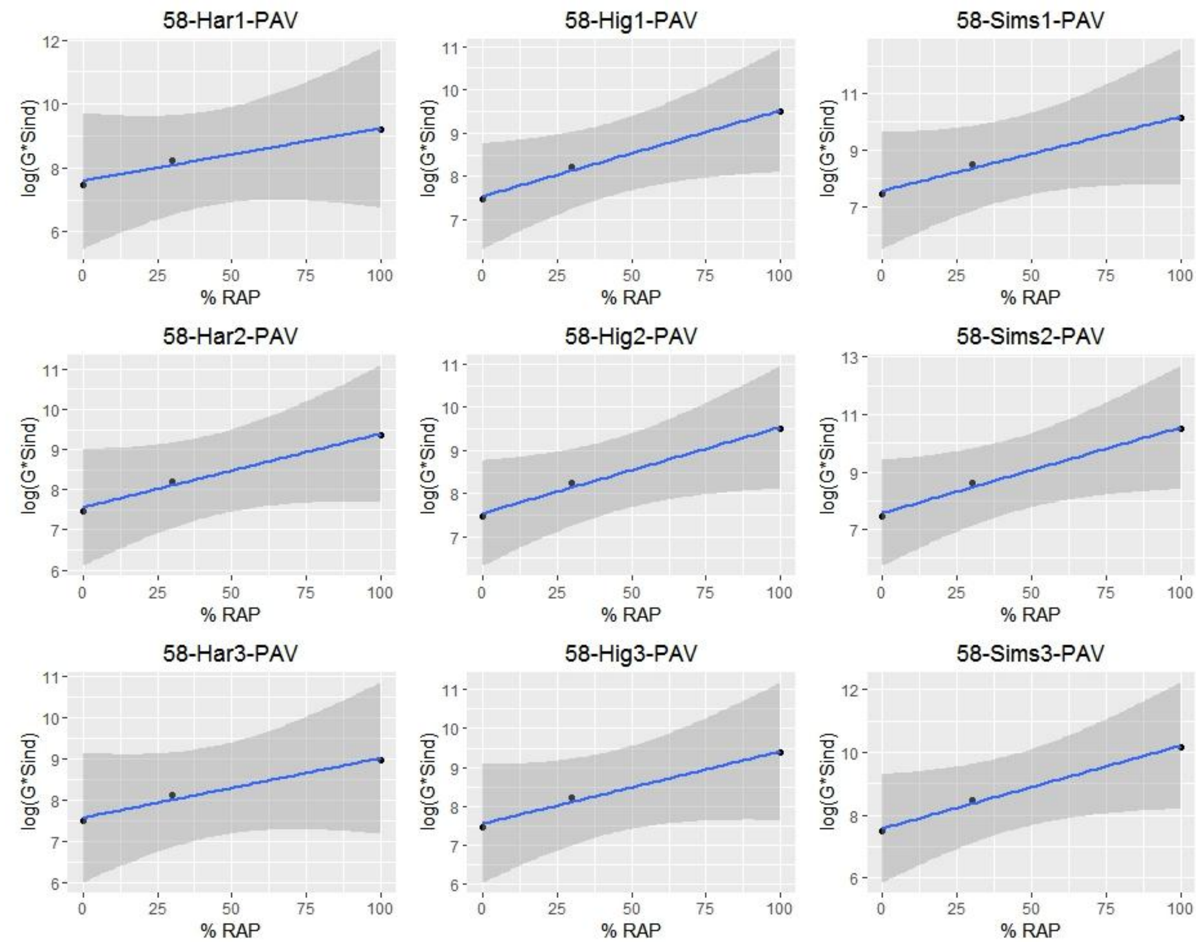

Figure 7-3: Blending Charts for PG 58-28 at 25ºC (PAV Aged)

Table 7-2 below lists the estimates of the parameters A and B and the maximum amounts of RAP binders for each blend type calculated from the PAV blending charts.

Table 7-2: Parameter Estimates and Maximum Binder Limits (PG 58-28)

Blend Type	A	B	Max. Limits
PG 58 + Harrison 1	7.589	0.0165	57%
PG 58 + Harrison 2	7.553	0.0184	53%
PG 58 + Harrison 3	7.560	0.0145	67%
PG 58 + Highland 1	7.541	0.0198	50%
PG 58 + Highland 2	7.541	0.0199	49%
PG 58 + Highland 3	7.557	0.0185	52%
PG 58 + Sims 1	7.585	0.0261	36%
PG 58 + Sims 2	7.574	0.0298	32%
PG 58 + Sims 3	7.568	0.0264	36%

The maximum limits for the RAP binders with the virgin binder PG 58-28 varied from 32% to 67%. The limits for Harrison stockpile varied between 53 to 67%. The limits for Highland and Sims stockpiles varied from 49% to 52% and, 32% to 36%, respectively.

7.2. Blending Charts with PG 64-22 as Virgin Binder

As described earlier in this chapter, blending charts for PG 64-22 virgin binder with the nine selected RAP binders were developed only in the PAV aged state to determine the maximum amounts of RAP binders that can be safely blended with PG 64-22 virgin binder and still meet the Superpave fatigue resistance criterion of $|G^*|\sin\delta < 5000$kPa at 25ºC . The blending charts for PG 64-22 and the nine RAP binders for the PAV aged state were plotted in similar manner as in the case for PG 58-28 virgin binder. Figure 7-4 below shows the blending charts at a temperature of 25ºC with all the nine selected RAP binders for PAV aged conditions. The $\ln(|G^*|\sin\delta)$ values were plotted on the Y-axis and percent RAP binder on the X-axis. The y-values corresponding to 0%, 30% and 100% on X-axis are the $\ln(|G^*|\sin\delta)$ values for PAV aged PG 64-22, blended binders and pure RAP binders at 25ºC, respectively. The same Equation 7-2 was fit to the data and the parameters A and B estimated.

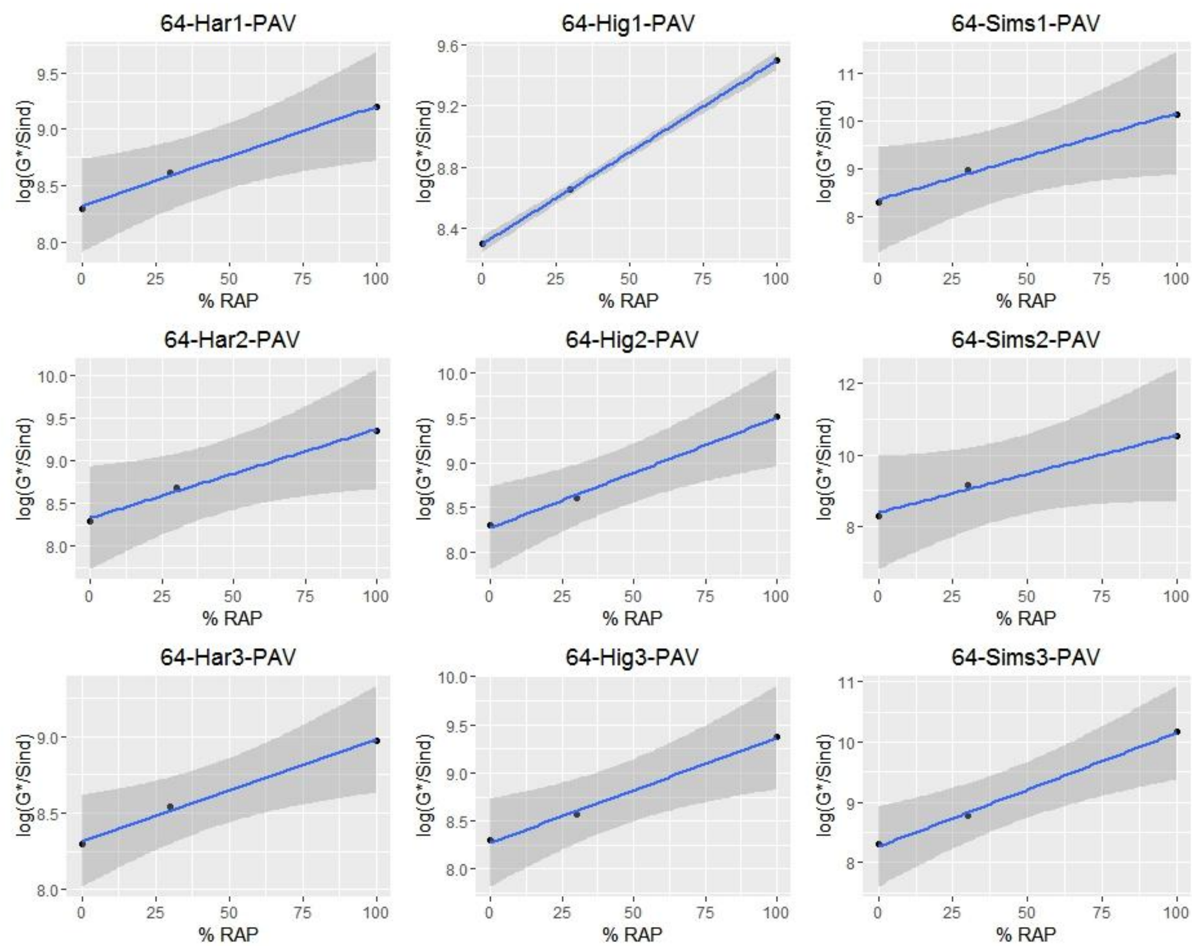

Figure 7-4: Blending Charts for PG 64-22 at 25ºC (PAV Aged)

Table 7-3 below lists the estimates of the parameters A and B and the maximum amounts of RAP binders for each blend type calculated from the PAV blending charts.

Table 7-3: Parameter Estimates and Maximum Binder Limits (PG 64-22)

Blend Type	A	B	Max. Limits
PG 64 + Harrison 1	8.322	0.0088	23%
PG 64 + Harrison 2	8.332	0.0104	18%
PG 64 + Harrison 3	8.316	0.0066	31%
PG 64 + Highland 1	8.297	0.0120	19%
PG 64 + Highland 2	8.276	0.0123	20%
PG 64 + Highland 3	8.276	0.0109	23%
PG 64 + Sims 1	8.358	0.0181	9%
PG 64 + Sims 2	8.384	0.0216	7%
PG 64 + Sims 3	8.265	0.0189	14%

The maximum limits for the RAP binders with the virgin binder PG 64-22 varied from 7% to 31%. The limits for Harrison stockpile varied from 18% to 31%, the limits for Sims stockpile varied from 7% to 14% and, the limits for Highland stockpile ranged from 19% to 23%.

7.3. Statistical Analysis

One of the goals of the study was to identify the amount of variation that would be observed in relevant properties of RAP binder sampled from within a stockpile. Sampling of RAP from three locations within a stockpile randomly helps in understanding the variability within a stockpile. The variability in limits determined for the three RAP binders sampled from within a stockpile lead to the conclusion that there does exist a variation within a stockpile. Table 7-4 below shows the sample means, the sample standard deviations and the coefficients of variation for the estimated percent RAP binder limits.

Table 7-4: Summary Statistics for RAP Binder Limits

Combination	Min Limit	Max Limit	SD	CV
PG 58 + Harrison	10%	-	1.00	10.0%
PG 58 + Highland	8%	-	0.00	0%
PG 58 + Sims	5%	-	1.00	20.0%
PG 58 + Harrison	-	59%	7.21	12.2%
PG 58 + Highland	-	50%	1.53	3.0%
PG 58 + Sims	-	34%	2.31	6.7%
PG 64 + Harrison	-	24%	6.56	27.3%
PG 64 + Highland	-	21%	2.08	10.1%
PG 64 + Sims	-	10%	3.60	36.1%

The coefficient of variation for the minimum limits for PG 58-28 show that the highest variation was within Sims stockpile followed by Harrison stockpile and the least for Highland stockpile. For the maximum limits for PG 58-28 the highest variation was observed in the Harrison stockpile followed by Sims stockpile and the least in Highland stockpile. The trend was however different for the variation observed when blended with PG 64-22 virgin binder where Sims stockpile showed the highest variation followed by Harrison stockpile and finally, Highland stockpile.

The sample standard deviations and the estimates of the means of binder limits for the various binder combinations were used to construct confidence intervals for the means of the limits. For the confidence intervals it was assumed that the observations within a stockpile followed a normal distribution and that the observations were independent of each other. Since, there were just three observations within each stockpile, robust statistical methods such as non-parametric statistical methods would not carry much power and therefore the assumption was necessary to draw any conclusions or make any inferences. Since, samples were taken from the stockpile randomly and the RAP that is stored in stockpiles is a random collection from various aged pavements of different grades and designs, there is no reason to believe that the assumption of normality would be violated by large margins. The confidence intervals (CI's) were calculated for each of the virgin-stockpile combinations using Equation 7-3.

Equation 7-3: $CI = \mu +/- (sd/\sqrt{n})*t_{\alpha/2, (n-1)}$

Where:

μ = mean of the three limits for a stockpile

sd = sample standard deviation for each stockpile

n = sample size, 3

$t_{\alpha/2, (n-1)}$ = student t-distribution critical value with (n-1) degree of freedom and (1-α)% CI

The Table 7-5 below shows the 90% confidence intervals of the RAP binder limits for the three stockpiles with the two virgin binders. Owing to the large variation observed within Harrison stockpile, the confidence intervals were large compared to the intervals for the other two stockpiles. The confidence intervals were also plotted on a graph and Figure 7-5 below shows these intervals.

Table 7-5: Confidence Intervals for RAP Binder Limits

Combination	Min Limit	Max Limit	90% CI
PG 58 + Harrison	10%	-	8.3% – 11.7%
PG 58 + Highland	8%	-	8%
PG 58 + Sims	5%	-	3.3% - 6.7%
PG 58 + Harrison	-	59%	46.8% - 71.2%
PG 58 + Highland	-	50%	47.8% - 52.9%
PG 58 + Sims	-	34%	30.8% - 38.6%
PG 64 + Harrison	-	24%	12.9% - 35.1%
PG 64 + Highland	-	21%	17.2% - 24.2%
PG 64 + Sims	-	10%	3.9% - 16.1%

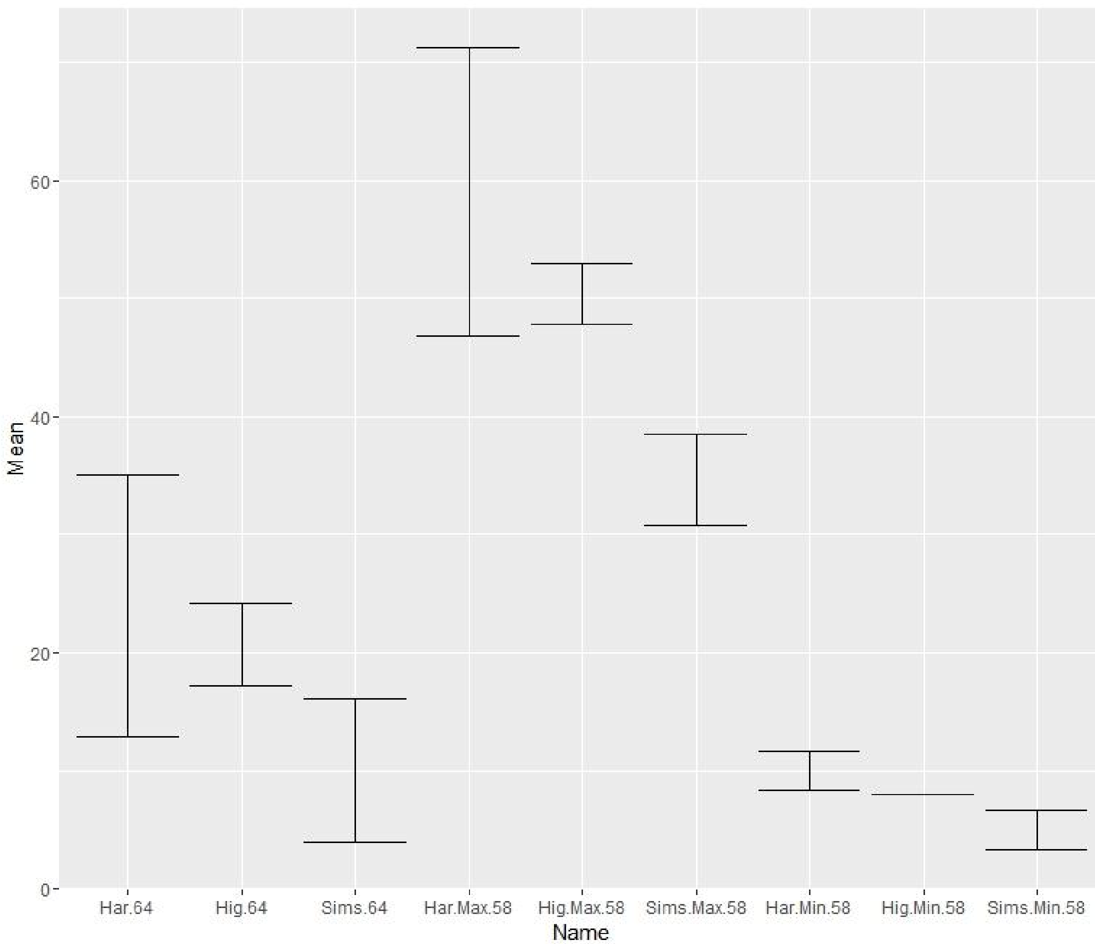

Figure 7-5: Confidence Intervals for Mean Minimum and Maximum Limits

There is clearly a difference in the intervals for the three selected stockpiles. For the limits for virgin binder PG 64-22 with RAP binder from the three stockpiles, the 90% CI for Highland stockpile does not overlap the 90% CI for Sims stockpile. It can be concluded that the RAP from the two stockpiles are significantly different. The wide CI for Harrison stockpile owing to high variation does overlap with the CI for Highland and Sims stockpiles. Therefore, it is not possible to reject that RAP binder from Harrison stockpile is different from RAP binder from Sims or Highland stockpile.

For the maximum limits for the virgin binder PG 58-28, there is a clear distinction between RAP binder from Sims stockpile with that of RAP binders from Harrison and Highland stockpile. The CI for the maximum limits of Harrison stockpile overlapped with the CI for the maximum limits of Highland stockpile. Therefore, in this case it cannot be stated that there is a significant difference between these two stockpiles. For the minimum limits for the virgin binder PG 58-28, the limits clearly differed between the stockpiles. Every stockpile was significantly different from the others. The variation however, was considerably lower than the variation observed in the maximum limits. One reason for the difference in variation could be that the minimum limits were obtained from the high temperature testing of the binders whereas, the maximum limits were obtained from the intermediate temperature testing of the binders after long term aging. At intermediate temperatures after long term aging, the same precision in sample preparation and testing is not achievable as in the case of high temperature testing, especially when the binders are extracted recycled binders or blended binders.

The confidence intervals by themselves, however, are not reasonable for practices in the industry. For practice in industry, it is easier to follow single value limits instead of a range of limits for a stockpile. To make sensible conclusions from these values, it is important to understand how the presence of RAP in a HMA affects the performance of the pavement. It is well known that for certain pavement structures, with an increase in proportion of RAP in HMA, the fatigue performance of the pavement could be compromised. Therefore, it is critical to identify maximum and minimum limits such that pavements with any kind of structural design, designed with these limits in consideration would perform with a desired reliability. In light of the above, the confidence intervals were used to modify the maximum and minimum limits for each of the RAP binders such that 95% reliability would be attained. The lower value of the confidence intervals for the maximum limits and the higher value of the confidence intervals for the minimum limits are recommended for conservative reasons. Since, the confidence intervals were constructed with a significance level of 90%, taking one end of the interval would give a reliability of 95% for the limits. Table 7-6 shows the modified list of limits for the RAP binders with the two virgin binders.

The Harrison stockpile was selected for blending with the virgin binders because the RAP binders sampled from this stockpile showed the least stiffness among all the RAP binders. Despite being the softest, the within stockpile variability of the Harrison stockpile led to maximum limits to be as low as 12.9% for PG 64-22 virgin binder and 46.8% for PG 58-28 virgin binder to achieve a reliability of 95%. The maximum limits for the Sims stockpile were modified to 3.9% for PG 64-22 and 30.8% for PG 58-28 virgin binders for a reliability of 95%. The maximum limits for the Highland stockpile were modified to 17.2% for PG 64-22 and

47.8% for PG 58-28 virgin binders for a reliability of 95%. Finally, the minimum limits for Harrison, Highland and Sims stockpiles for PG 58-28 were 12.9%, 8% and 6.7%, respectively.

Table 7-6: Modified RAP Binder Limits with 95% Reliability

Combination	Min Limit	Max Limit
PG 58 + Harrison	11.7%	-
PG 58 + Highland	8%	-
PG 58 + Sims	6.7%	-
PG 58 + Harrison	-	46.8%
PG 58 + Highland	-	47.8%
PG 58 + Sims	-	30.8%
PG 64 + Harrison	-	12.9%
PG 64 + Highland	-	17.2%
PG 64 + Sims	-	3.9%

In order to generalize the recycled binder limits for RAP sampled from any one of the nine stockpiles, calculations initially were done assuming that the nine stockpiles constituted the entire population of RAP for the state of North Carolina and that the probability of sampling from any of the nine stockpiles was the same for all stockpiles. Recall from chapter 5 that, the 27 RAP binders from different stockpiles were grouped into quartiles and selection of three stockpiles among the nine stockpiles was based on the grouping of each of the RAP binders into the four quartiles. For the purpose of generalization, it was required to assign probabilities for each of the three selected stockpiles which in turn would be used to generalize the limits applicable for RAP sampled from any set of stockpiles in North Carolina. For the estimation of the probabilities, data in Table 5-4 was sorted in the ascending order of $|G^*|\sin\delta$ values and point probabilities were assigned to each of the RAP binders assuming the 27 RAP binders constituted the entire population.

The Table 7-7 below shows these probabilities for the 27 RAP binders. The column 'Prob.' shows the point probabilities for each of the RAP binders estimated by '1/n' where, 'n' is the total number of RAP binders in the study i.e. 27 in this case. The column 'Cum. Prob.' is the cumulative probabilities calculated by taking the running total of the point probabilities. The cumulative probabilities, thus, are an estimator of the probability of a RAP binder to exhibit a $|G^*|\sin\delta$ value less than or equal to the $|G^*|\sin\delta$ value corresponding to the cumulative probability in the table.

For the process of generalization it was assumed that it is unusual for a RAP stockpile to exhibit stiffness values as high as the values shown by Sims stockpile. Therefore, a probability of 3*1/27 (0.11) was assigned to the Sims stockpile for generalization. The Harrison stockpile was assumed to be representative of all the RAP binders grouped in the 1st quartile and was assigned a probability of 0.25 and the Highland stockpile was assumed to be representative of all the other RAP binders with a probability of 0.64 (1-0.25-0.11). With these assumptions, and the assumption that the RAP binder samples within each of the stockpile exhibited binder limits following a normal distribution, the pooled mean and variance for the minimum and maximum limits were calculated as described subsequently

Table 7-7: Probabilities for All the RAP Binders

Location	|G*|sinδ	Quartile	Prob.	Cum. Prob.
Harrison 3	7887.74	1	0.0370	0.0370
Pineville 3	9095.35	1	0.0370	0.0741
Harrison 1	9850.15	1	0.0370	0.1111
Weaverville 2	9901.52	1	0.0370	0.1481
Weaverville 1	10657.7	1	0.0370	0.1852
Sunrock 1	11458.63	1	0.0370	0.2222
Harrison 2	11571.43	1	0.0370	0.2593
Highland 3	11799.35	2	0.0370	0.2963
Maymead 3	12095.27	2	0.0370	0.3333
Sunrock 3	12144.53	2	0.0370	0.3704
Pineville 1	12408.7	2	0.0370	0.4074
Weaverville 3	12996	2	0.0370	0.4444
Sunrock 2	13030.37	2	0.0370	0.4815
Maymead 2	13282.7	3	0.0370	0.5185
Highland 1	13295.9	3	0.0370	0.5556
Burlington 2	13454.7	3	0.0370	0.5926
Highland 2	13525.9	3	0.0370	0.6296
Wilmington 1	13594.97	3	0.0370	0.6667
Pineville 2	13699.87	3	0.0370	0.7037
Burlington 1	13871.57	3	0.0370	0.7407
Wilmington 3	15357.27	4	0.0370	0.7778
Wilmington 2	15503.03	4	0.0370	0.8148
Burlington 3	17703.45	4	0.0370	0.8519
Maymead 1	18166.53	4	0.0370	0.8889
Sims 1	25494.73	4	0.0370	0.9259
Sims 2	26078.87	4	0.0370	0.9630
Sims 3	36641.4	4	0.0370	1.0000

If the limits (Y_i) for a stockpile 'i' were treated as a random variable following a normal distribution with mean μ_i and variance σ_i^2 within a stockpile, then the limits for cumulative of all the stockpiles (ΣY_i) by weighting would have a mean of $\Sigma p_i \mu_i$ and a variance of $\Sigma p_i^2 \sigma_i^2$, where p_i is the probability of selecting the stockpile. In such a scenario, the pooled mean and variance for the nine stockpiles assuming the three selected RAP stockpiles with assigned probabilities represented the nine stockpiles are:

$$\mu_{total} = 0.25*\mu_{harrison} + 0.64*\mu_{highland} + 0.11*\mu_{sims}$$

$$\sigma^2_{total} = (0.25)^2*\sigma^2_{harrison} + (0.64)^2*\sigma^2_{highland} + (0.11)^2*\sigma^2_{sims}$$

The confidence intervals for the pooled mean can be estimated in similar manner as that of a single stockpile case, however, some adjustments will be needed to account for the fact that the individual stockpile variances are unknown and are being estimated by the sample standard deviations. For this, the following statistical theory will be useful and will be employed for constructing the confidence intervals.

In statistical theory, if a sample $X_1, X_2 \ldots . X_n$ is drawn from a normal distribution with mean μ_x and variance σ^2, and that an independent sample $Y_1, Y_2 \ldots Y_m$ is drawn from another normal distribution that has mean μ_y and the same variance σ^2, then the following holds true:

$$If, X \sim N(\mu_x\,, \sigma^2)\ and\ Y \sim N(\mu_y\,, \sigma^2)$$

$$Then, \overline{X} \sim N\left(\mu_x\,, \frac{\sigma^2}{n}\right)\ and\ \overline{Y} \sim N\left(\mu_y\,, \frac{\sigma^2}{m}\right),$$

$$aX + bY \sim N(a\mu_x + b\mu_y\,, a^2\sigma^2 + b^2\sigma^2),$$

$$and\ a\overline{X} + b\overline{Y} \sim N(a\mu_x + b\mu_y\,, \frac{a^2\sigma^2}{n} + \frac{b^2\sigma^2}{m})$$

If the variance σ^2 is known, then a confidence interval for the linear combination of the means can be constructed. Generally, σ^2 is not known and must be estimated from the sample data by calculating the pooled sample variance (s_p^2).

$$s_p^2 = \frac{(n-1)s_x^2 + (m-1)s_y^2}{m+n-2}$$

Where, $s_x^2 = (n-1)^{-1}\sum_{i=1}^{n}(X_i - \overline{X})$ and similarly for s_y^2. The confidence interval for $a\mu_x + b\mu_y$ is then constructed as follows:

$$\left(a\overline{X} + b\overline{Y}\right) \pm t_{\alpha/2,m+n-2}s_p\sqrt{\frac{a^2}{n} + \frac{b^2}{m}}$$

This, however, is only true for the case when both distributions have the same variance. In reality, this may not be true and a case should be considered where the distributions have different variances. In such a case, the confidence interval for $a\mu_x + b\mu_y$ is constructed as follows:

$$\left(a\overline{X} + b\overline{Y}\right) \pm t_{\alpha/2,df}\sqrt{\frac{a^2 s_x^2}{n} + \frac{b^2 s_y^2}{m}}$$

Where, df $= \dfrac{[\,s_x^2/n + s_y^2\,]^2}{\frac{s_x^2/n}{n-1} + \frac{s_y^2/m}{m-1}}$ is the adjusted error degrees of freedom and is rounded to the nearest integer. Although, the above theory is defined for combining only two samples, it can be easily replicated for any number of samples.

Using the above theory, the confidence intervals for the mean of the limits for combination of the three selected stockpiles; Harrison, Highland and Sims were constructed.

From Table 7-4 it can be seen that the sample standard deviations for the minimum limits of all three stockpiles with PG 58-28 virgin binder were small and not very different. Therefore, for the minimum limits, an assumption of equal variance was made and confidence intervals for minimum limits were constructed. However, the assumption of equal variance does not stand valid for the maximum limits as the sample standard deviations are highly different. Therefore, for the maximum limits, confidence intervals were constructed using the adjusted error degrees of freedom. Table 7-8 shows the mean minimum and maximum limits with their respective 90% confidence intervals.

Table 7-8: General RAP Binder Limits at 95% Reliability

Combination	**Min Limit**	**Max Limit**	**CI**
PG 58-28	8.2%	-	7.5% - 8.8%
PG 58-28	-	50.8%	47.3% - 54.3%
PG 64-22	-	20.3%	17.7% - 23%

Generalizing the limits for the entire set of stockpiles with the aforementioned assumptions, the limits for RAP binder limits are adjusted to a maximum of 17.7% for PG 64-22 virgin binder, 47.3% for PG 58-28 virgin binder and a minimum of 8.8% for PG 58-28 virgin binder. It should be noted, however, that the general limits determined are based on certain assumptions which might not be robust and should be adjusted depending on industry practices.

7.4. Comparison with Existing NCDOT Specifications

The goal of this research project is to recommend a set of specifications for limiting the amount of RAP in HMA mixtures of North Carolina by taking into consideration the variability observed within stockpiles and among stockpiles. Since, the NCDOT has already laid out specifications for the use of recycled materials in HMA in their manual "Asphalt Quality Management System (QMS) - 2016", the determined recycled binder limits from this study were compared to the existing NCDOT specifications. Table 7-9 below shows the NCDOT's specifications for S9.5B RAP mixtures. The NCDOT QMS manual only defines limits for RAP by weight of the total mix and these limits were used to derive the limits by binder proportion assuming a 6% optimum asphalt content for the recycled HMA and a 5% asphalt binder content for the RAP material. It was also assumed that the HMA design was performed by adjusting the total binder content by accounting for the binder contributed by RAP material in the mix.

Table 7-9: NCDOT Specifications for Recycled Asphalt Pavements

Virgin Binder	Limits (RAP)	
	By Wgt. of Mix	By Binder Proportion [D]
PG 64	0% - 20%[A]	0% - 17%
	20% - 30%[B]	17% - 25%
TBD	> 30%[C]	> 25%

A. Category 1 RAP has been processed to a maximum size of 2".
B. Category 2 RAP has been processed to a maximum size of 1" by either crushing and or screening to reduce variability in the gradations.
C. Category 3 RAP has been processed to a maximum size of 1", fractionating the RAP into 2 or more sized stockpiles.
D. Estimated proportions based on assumption that recycled HMA's optimum asphalt content is 6% and the asphalt content of RAP is 5%.

The NCDOT's current specifications propose higher limits for RAP material that has been processed to a smaller size of 1" to accommodate the reduction in variability due to processing of the RAP material to a finer gradation. These specifications, however, do not account for the variability in the RAP binder or the stiffness of it, which do not vary with processing of the RAP material into a finer gradation. Therefore, in the case when limits for recycled materials are based on the proportion of RAP binder contributed to the total binder in the recycled mixture, the limits need to be independent of the processed size of RAP. The limits determined for PG 64-22 virgin binder by accounting for the variability in the RAP binders among stockpiles only allow a maximum of 17.7% (Table 7-8) by proportion of RAP binder in the total binder content of the mixture. This is lower than the maximum limit proposed by the NCDOT in its current specifications which is 25% for processed RAP. Therefore, it is recommended that the specifications be adjusted accordingly to account for the variability in RAP binder properties. The high limit of 25% in the current specifications also exceeds the maximum limits determined for any of the three stockpiles that were evaluated in this study: a maximum limit of 12.9% for Harrison stockpile, 17.2% for Highland stockpile, and 3.9% for Sims stockpile (Table 7-6). Therefore, a need exists to revise the current specifications to account for the variability in the RAP binder properties which is a result of variability within a stockpile and also among stockpiles. Considering the difference in the limits between the current specifications and the determined limits from this study, a proposal for revised specifications is detailed in Table 7-10 below.

Table 7-10: Proposed Limits for RAP in HMA for S9.5B Mixes

Virgin Binder	Limits (RAP)	
	By Binder Proportion	By Wgt. of Mix
PG 64-22	0% - 17.7%	0% - 21.2%
PG 58-28	8.8% - 47.3%	10.6% - 56.8%

The above results can be summarized as: for the design of S9.5B mixtures with PG 64-22 virgin binder, the maximum allowable proportion of RAP by weight of total mixture is 21.2%, and for the design with virgin binder grade of PG 58-28, the range of limits is 10.6% to 56.8%. It is, however, recommended that at higher proportions of recycled materials in HMA, care must be taken to ensure that the aggregate gradation requirements are also met simultaneously since RAP is known to contribute a large fraction of aggregate fines. Again, some of the important assumptions made for arriving at these revised limits are:

- The limits have been generalized by assigning certain probabilities to stockpiles and assuming the selected nine stockpiles constitute the entire population of RAP stockpiles in North Carolina
- The optimum asphalt content for the recycled HMA mixture is 6%
- The asphalt binder content of the RAP material is 5%
- Total blending takes place between virgin binder and RAP binder in the mixture

CHAPTER 8 : - SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

8.1. Summary

The objective of this research study was to characterize the various RAP binders sampled from stockpiles across the state of North Carolina. As part of this objective, it was one of the requirements to study and document the order of variability that would be observed by sampling RAP from different stockpiles. With an increase in demand for paving materials, degree of recycling has been on the rise to relax the demand for virgin materials. And recycling of asphalt pavement, although, cost effective requires higher degree of quality control. The higher degree of quality control can be achieved only by a deeper understanding and documentation of the properties of RAP from various stockpiles.

The state of North Carolina has regulated the use of RAP by placing limits on the amount of RAP by weight of the total mix that can be incorporated into HMA. These specifications do not take into consideration the difference in properties of RAP that would be observed by sampling RAP from different stockpiles. Therefore, this study focused on accounting for this variation in properties of RAP binders sampled from various stockpiles across the state. This was done by selecting nine stockpiles, three from each of the three geographic regions of the state and sampling RAP from three locations within each stockpile. Rheological testing was conducted on these 27 RAP binders in their unaged, RTFO aged and PAV aged conditions and the observed properties were in turn used to prove if the variability between stockpiles was significant.

Three stockpiles were selected subsequent to rheological testing and the nine RAP binders from these three stockpiles were blended with two virgin binders to study how the variation in pure RAP binders affected the minimum and maximum limits of RAP binders that can be blended with the selected virgin binders and still meet the Superpave specifications. The following summarizes the observations and the results from the testing and analysis of RAP, virgin and blended binders.

8.1.1. RAP Binder Rheology

- For the unaged RAP binders, upon rheological testing at high temperatures under standard conditions on a DSR, the $|G^*|/\sin\delta$ values decreased with temperature. The phase angle values, which are indicative of how viscous the binder is, increased with temperature.

- In their unaged conditions, RAP binder sampled from Sims stockpile labeled as Sims 2 showed the highest value of $|G^*|/\sin\delta$. The high temperature PG grade of the Sims 2 RAP binder determined only from unaged binder testing was 118. The RAP binder sampled from Harrison stockpile labeled as Harrison 3 showed the least value and the high temperature PG grade of the Harrison 3 RAP binder determined from only unaged binder testing was 82.

- All the RAP binders from Sims stockpile showed very high stiffness values compared to the other 8 stockpiles. The high temperature grade of both Sims 1 and Sims 3 RAP binders determined from only unaged binder testing was 112. None of the binders sampled from one single stockpile clearly showed lower |G*|sinδ values than the rest of the RAP binders. Although, Harrison 3 RAP binder was the softest overall and Harrison 2 RAP binder was the next softest, Harrison 1 RAP binder showed higher stiffness values than some RAP binders from other stockpiles.

- The minimum high temperature grade from unaged RAP binder testing was 82 and the maximum high temperature grade was 118. The median high temperature grade of the RAP binders selected and tested was 94.
- For the RTFO aged RAP binders, the |G*|/sinδ values also decreased with temperature and the phase angle values increased.
- In RTFO aged conditions, again Sims 2 RAP binder showed the highest value of |G*|/sinδ and the high temperature PG grade determined from RTFO aged binder testing was 112. Harrison 3 RAP binder showed the lowest value of |G*|/sinδ and the high temperature grade determined from RTFO aged binder testing was 82. The median high temperature grade of the RAP binders in their RTFO aged state was again 94.
- For the PAV aged RAP binders, the |G*|sinδ values lowered with an increase in temperature. The intermediate temperature grade of the PAV aged RAP binders varied from a low of 31 to a high of 49. The median intermediate temperature grade of the PAV aged RAP binders was 37.
- Sims 2 RAP binder qualified for the highest intermediate temperature grade of 49. Sims 1 and Sims 3 RAP binders qualified for an intermediate temperature grade of 46. Like

in their unaged state, the three binders from Sims stockpile exhibited the highest stiffness values among all RAP binders. Harrison 3 RAP binder showed the lowest intermediate temperature grade of 31 among all RAP binders.

- Combining the high temperature grades of the RTFO aged binders and the unaged binders, the highest high temperature PG grade of all the RAP binders tested was 112 and the lowest high temperature PG grade was 82. The median high temperature PG grade was 94.

- The 27 RAP binders were grouped into one of the four quartiles calculated from the range of $|G^*|\sin\delta$ at 25^{o}C in their PAV aged state and all the three binders from the Harrison stockpile were grouped into the first quartile. All the three binders from Sims stockpile were grouped into the fourth quartile. The three binders from Highland stockpile were grouped into either the second or the third quartile.

- Harrison stockpile was selected for blending with virgin binders as being representative of the stockpile with the softest RAP binders. Sims stockpile was selected for blending with virgin binders as being representative of the stockpile with the stiffest RAP binders. Highland stockpile was selected as being a good representation of binders from the median range of $|G^*|\sin\delta$ values.

8.1.2. Virgin and Blended Binder Rheology

- The virgin binders PG 58-28 and PG 64-22 were tested on the DSR in various aged conditions and were proven to be of high temperature grades 58 and 64, respectively.

From the intermediate temperature test results, it was also proven that PG 58-28 and PG 64-22 in fact were graded as -28 and -22, respectively.

- The blended binders of PG 58-28 with 30% Harrison 3 RAP binder exhibited a high temperature grade of 64 in unaged and RTFO aged conditions, thereby qualifying it for a high temperature grade of 64. From the intermediate temperature grade of 22, this blended binder qualified for a low temperature grade of -28. The two blended binders of PG 58-28 with 30% Harrison 1 and 30% Harrison 2 RAP binders exhibited a high temperature grade of 70 in their unaged and RTFO aged conditions, thereby qualifying them for a high temperature grade of 70. From the intermediate temperature grade of 25, these blended binders qualified for a low temperature grade of -28.

- The three blended binders of PG 58-28 with 30% Highland 1, 30% Highland 2 and, 30% Highland 3 RAP binders qualified for a high temperature grade of 70 from the DSR results on unaged and RTFO aged binders. All the three blended binders qualified for a low temperature grade of -28.

- The blended binders of PG 58-28 with 30% Sims 2 binder qualified for a high temperature grade of 76 and a low temperature grade of -28. The blended binder of PG 58-28 with 30% Sims 1, and the blended binder with 30% Sims 3 RAP binder both qualified for a high temperature grade of 70. The blended binder with Sims 1 RAP binder qualified for a low temperature grade of -22, whereas, the blended binder with Sims 3 RAP binder qualified for a low temperature grade of -28.

- The blended binders with PG 64-22 and the RAP binders were stiffer than the similar combinations with PG 58-28 as expected. The three blended binders of PG 64-22 with 30% Harrison 1, 30% Harrison 2 and 30% Harrison 3 RAP binders all qualified for a high temperature grade of 70 and a low temperature grade of -22.

- The three blended binders with PG 64-22 as virgin binder and 30% Highland 1, 30% Highland 2, and 30% Highland 3 RAP binders all qualified for a high temperature grade of 70 and a low temperature grade of -22. Although, Highland RAP binder blends were stiffer than the Harrison RAP binder blends, both of them showed similar PG grades. This is possible as the PG grade specifications only grade binders in discrete levels of 6^{o}C.

- The Sims RAP binder blends with PG 64-22 showed some variation compared to the other stockpiles and the blend with 30% Sims 1, and the blend with 30% Sims 3 RAP binder, both exhibited a high temperature grade of 76. The low temperature grades for the two blends were -22 and -28, respectively. The blend with 30% Sims 2 RAP binder exhibited a high temperature grade of 82 and qualified for a low temperature grade of -22.

8.1.3. Blending Charts

- The blending charts for the PG 58-28 virgin binder lead to the result that the minimum limits for this virgin binder with the Harrison 1, Harrison 2 and Harrison 3 RAP binders were 10%, 9% and 11%, respectively.

- The minimum limits for the PG 58-28 virgin binder with all the Highland RAP binders were 8%. Similarly, the minimum limits with the Sims 1, Sims 2 and Sims 3 RAP binders were 5%, 4% and 6%, respectively.
- The maximum limits for the PG 58-28 virgin binder with the Harrison 1, Harrison 2 and Harrison 3 RAP binders were 57%, 53% and 67%, respectively. The large variation in the limits with the RAP binders from the Harrison stockpile was due to the softness of these RAP binders and the inherent variability within the stockpile.
- The maximum limits for the PG 58-28 virgin binder with the Highland 1, Highland 2 and Highland 3 RAP binders were 50%, 49% and 52%, respectively. Similarly, the maximum limits with Sims 1, Sims 2 and Sims 3 RAP binders were 36%, 32% and 36%, respectively.
- There were no minimum limits determined for the PG 64-22 virgin binder as the Superpave high temperature requirements were already satisfied by this grade virgin binder at 64^{o}C.
- The maximum limits for the PG 64-22 virgin binder with the Harrison 1, Harrison 2 and Harrison 3 RAP binders were 23%, 18% and 31%, respectively. The large variation in the limits with the Harrison stockpile RAP binders was due to the softness of these RAP binders and the variability of the RAP binders within the stockpile.
- The maximum limits for the PG 64-22 virgin binder with the Highland 1, Highland 2 and Highland 3 RAP binders were 19%, 20% and 23% respectively. Similarly, the

maximum limits with the Sims 1, Sims 2 and the Sims 3 RAP binders were 9%, 7% and 14%, respectively.

- The highest coefficient of variation for the minimum limits for the PG 58-28 virgin binder was observed in blends with RAP binders from the Sims stockpile (20%), followed by the blends with RAP binders from the Harrison stockpile (10%). No variation was observed in limits for PG 58-28 virgin binder with RAP binders from Highland stockpile.

- The highest coefficient of variation for the maximum limits for the PG 58-28 virgin binder was observed in blends with RAP binders from the Harrison stockpile (12.2%) followed by blends with Sims stockpile (6.7%). The least coefficient of variation was observed in blends with RAP binders from Highland stockpile (3%).

- In the case of PG 64-22 virgin binder, the highest coefficient of variation was observed in the blends with Sims RAP binders (36.1%) followed by blends with Harrison RAP binders (27.3%) and finally, the blends with Highland RAP binders (10.1%).

- The 90% confidence intervals for the minimum limits for the PG 58-28 virgin binder with RAP binders from Harrison stockpile, Highland stockpile and Sims stockpile are 8.3% - 11.7%, 8% and, 3.3% - 6.7%, respectively.

- The 90% confidence intervals for the maximum limits for the PG 58-28 virgin binder with RAP binders from Harrison stockpile, Highland stockpile and Sims stockpile are 46.8% - 71.2%, 47.8% - 52.9% and, 30.8% - 38.6%, respectively.

- The 90% confidence intervals for the maximum limits for the PG 64-22 virgin binder with RAP binders from Harrison stockpile, Highland stockpile and Sims stockpile are 12.9% - 35.1%, 17.2% - 24.2% and, 3.9% - 16.1%, respectively.

8.2. Conclusions

The results from the testing and analysis were used to make the following conclusions:

- The statistical analysis of the rheological properties of PAV aged RAP binders at 25^{o}C led to the conclusion that the effect of stockpile is significant in determining the rheological properties of RAP binders.

- The confidence intervals constructed for the RAP binder limits for the three selected RAP stockpiles did not overlap leading to the conclusion that the effect of stockpile is significant in determining the RAP binder limits.

- RAP binders from within a stockpile showed substantial variation in stiffness values and this variation varied from stockpile to stockpile. The variation in the limits for the RAP binders sampled from three locations within each of the three stockpiles, evident from the coefficient of variation for the limits derived for both PG 58-28 and PG 64-22 virgin binders, leads to the conclusion that variation is present within stockpiles to varying degrees.

- The 95% reliability single value minimum limits for the PG 58-28 virgin binder with Harrison, Highland and Sims stockpile RAP binders were 11.7%, 8% and 6.7% respectively. Similarly, the maximum limits for the PG 58-28 virgin binder with

Harrison, Highland and Sims stockpile RAP binders were 46.8%, 47.8% and 30.8%, respectively.

- The 95% reliability single value maximum limits for the PG 64-22 virgin binder with Harrison, Highland and Sims stockpile RAP binders were 12.9%, 17.2% and 3.9%, respectively.
- With the assumptions discussed in chapter 7, the 95% reliability limits generalized for overall RAP in the state of North Carolina are:
    - Minimum 8.8% recycled binder by total weight of total binder for PG 58-28 virgin binder
    - Maximum 47.3% recycled binder by total weight of total binder for PG 58-28 virgin binder
    - Maximum 17.7% recycled binder by total weight of total binder for PG 64-22 virgin binder.
- The proposed limits in percentage RAP material by weight of total mix with the assumptions discussed in chapter 7 are:
    - Minimum 10.6% RAP by total weight of the mix for PG 58-28 virgin binder
    - Maximum 56.8% RAP by total weight of the mix for PG 58-28 virgin binder
    - Maximum 21.2% RAP by total weight of the mix for PG 64-22 virgin binder.

8.3. Recommendations

The recycled binder limits determined from this study take into consideration the variability in the rheological properties of the RAP binders sampled from various stockpiles. These limits are solely based on the expected blended binder properties and do not account for the aggregate gradations of the RAP material. Often times, there is a high proportion of fines in RAP and this might be a limiting factor when high percentages of RAP are incorporated into HMA. Therefore, the limits should be followed carefully by considering for how the proportions defined by the limits affect the aggregate gradations of the overall HMA mix. The limits obtained in this research study are based on some underlying assumptions and if such assumptions stand invalid, the limits could lead to detrimental results. Therefore, it is recommended to study the industry practices on the selection criteria for RAP stockpiles in pavement projects and adjust the limits accordingly. Additionally, the results could be tuned further if blending was done with the RAP binders from the remaining stockpiles and limits determined. Having the limits from all the nine stockpiles would help in obtaining more robust generalized limits. Finally, this research assumed 100% blending between virgin and RAP binders which may not be essentially true in practice. In such cases, consideration should be given to how fractional blending would affect the limits.

IMPLEMENTATION AND TECHNOLOGY TRANSFER PLAN

The research products from this study are the draft specifications defining the recycled binder limits for RAP for the state of North Carolina. Also included are the guidelines for replicating the study when deemed necessary by the NCDOT for RAP exhibiting very high or very low stiffness values.

The research products from this study are recommended for use by the NCDOT personnel and specific guidelines are mentioned in the appendix for replicating the study and no training is required for implementation.

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APPENDICES

APPENDIX A

Table A.1 |G*|sinδ (kPa) Values for All RAP Binders

Temperature	Pineville 1	Pineville 2	Pineville 3	Maymead 1	Maymead 2	Maymead 3	Wilmington 1	Wilmington 2	Wilmington 3
16	24731.93	26453.50	18906.23	30320.93	22809.90	22210.93	27717.77	30550.83	29797.37
19	19960.80	21607.57	15280.57	25704.17	19145.60	18221.90	21973.27	24411.10	24423.63
22	15864.80	17225.63	11867.27	21764.27	16036.87	14968.40	17416.80	19612.43	19579.13
25	12408.70	13699.87	9095.35	18166.53	13282.70	12095.27	13594.97	15503.03	15357.27
28	9507.17	10589.33	6861.62	14984.13	10882.73	9612.39	10453.67	12050.70	11975.67
31	7207.47	8123.57	5086.05	12203.83	8786.62	7542.63	7911.71	9260.10	9150.94

Temperature	Highland 1	Highland 2	Highland 3	Sunrock 1	Sunrock 2	Sunrock 3	SIMS 1	SIMS 2	SIMS 3
16	24452.17	25123.63	24031.05	22995.77	23799.77	21798.37	45658.73	57525.20	43968.90
19	21131.77	21248.63	18200.90	18058.93	20384.20	18388.50	38483.73	51451.83	39477.27
22	16941.60	17086.30	14796.90	14597.07	16503.27	15117.10	31319.90	43916.53	32423.07
25	13295.90	13525.90	11799.35	11458.63	13030.37	12144.53	25494.73	36641.40	26078.87
28	10227.90	10382.53	9144.76	8896.35	10007.65	9486.28	20102.53	29732.07	20376.27
31	7762.35	7859.84	6988.27	6742.99	7646.50	7230.91	15610.37	23783.80	15783.90

Temperature	Weaverville 1	Weaverville 2	Weaverville 3	Burlington 1	Burlington 2	Burlington 3	Harrison 1	Harrison 2	Harrison 3
16	20667.87	18132.80	22416.07	26142.00	28133.07	30723.40	18690.67	21668.57	15807.07
19	16735.40	15018.73	19332.67	21577.57	21465.57	27911.25	15044.90	17705.13	12361.90
22	13512.30	12478.10	16003.60	17330.27	17228.20	22493.30	12258.30	14489.90	9947.13
25	10657.70	9901.52	12996.00	13871.57	13454.70	17703.45	9850.15	11571.43	7887.74
28	8295.98	7713.24	10320.47	10778.70	10357.43	13626.40	7711.13	8932.25	5989.74
31	6407.61	5934.49	8081.95	8162.50	7820.22	10323.85	6001.26	6821.74	4464.47

APPENDIX B

Guidelines for RAP Testing and Determination of Limits

This section provides guidelines for determining the RAP binder limits for RAP stockpiles if certain binder properties of RAP binders extracted from random samples sampled from a RAP stockpile exhibit unusual values. The guidelines are split into two sections and only applicable for designing S9.5B mixtures for North Carolina:

1. For projects that only use RAP from a single stockpile.
2. For projects that use RAP from multiple stockpiles.

Although, the guidelines are specific for S9.5B mixtures, the procedure can easily be reproduced for other mixtures.

B.1 Single Stockpile Limits

This section applies to pavement projects that incorporate RAP from only one selected stockpile. Guidelines are provided for; sampling of RAP, PG binder grade testing of RAP binders, constructing blending charts, determining binder limits from blending chats, constructing confidence intervals, and deriving meaningful conclusions from confidence intervals.

B.1.1 Sampling of RAP and Extraction of RAP Binder

In order for the properties of sampled materials to be applicable for the entire stockpile, it is important to ensure that the sampled material is representative of the entire stockpile as a whole. If the sampling procedures are administered in an incorrect manner, the results might lead to biased conclusions. Therefore, it is recommended that proper sampling procedures for

RAP stockpiles be administered as mentioned in the QMS manual or relevant standards. The task of sampling material from stockpile will be left to the judgement of quality control technicians who are familiar with the practice and hence, the process of sampling of stockpiles will not be discussed here. It is recommended, however, to have at least three random samples from a single stockpile in order to determine if the need exists to develop blending charts and determine stockpile specific limits. The accuracy of the results will increase with an increase in number of samples selected and therefore, attempts should be made to have as many number of samples as possible. Subsequent to sampling of material from stockpiles, appropriate methods shall be exercised to perform quantitative extraction and recovery of RAP binder from these samples for testing and analysis.

B.1.2 Performance Grade Testing

The extracted binders from the random samples shall be tested in accordance with AASHTO T315 “Test Method for Determining the Rheological Properties of Asphalt Binder Using a Dynamic Shear Rheometer” to determine their Superpave PG grade. Testing shall be conducted on unaged and RTFO aged binders at temperatures such that $|G^*|/\sin\delta$ values are obtained at 64^{o}C also. Additionally, when testing PAV aged RAP binders, it must be ensured that $|G^*|\sin\delta$ values at 25^{o}C are also obtained. The temperatures of 64^{o}C and 25^{o}C are selected since the target is to meet the Superpave binder specifications corresponding to a binder of grade PG 64-22. These values will be needed to construct blending charts. Similar testing should be performed on the virgin binders selected for the project and blended binders obtained by blending a known proportion of RAP binder sample with the virgin binder to obtain

$|G^*|/\sin\delta$ values at 64°C in unaged and RTFO aged conditions, and $|G^*|\sin\delta$ values at 25°C in PAV aged conditions.

B.1.3 Blending Charts and RAP Binder Limits

Once the test results have been obtained, construct blending charts for the selected virgin binder and the RAP binder samples and derive the RAP binder limits using the following guidelines:

- For unaged binders plot using $\log(|G^*|/\sin\delta)$ values at 64°C on the Y-axis and percentage RAP binder in total binder on the X-axis for determining minimum limits. Plot similarly for RTFO aged binders. For every kind of RAP binder, and a given virgin binder, the plot should contain one point for the virgin binder, one point for the blended binder at a known RAP binder percentage, and one point for the RAP binder. Fit a straight line between the three points and estimate the percentage RAP binder needed to meet the criterion of $|G^*|/\sin\delta > 1.0$kPa in the case of unaged binders and the criterion of $|G^*|/\sin\delta > 2.2$kPa in the case of RTFO aged binders. For a given RAP binder sample, take the maximum of the two percentages derived from the blending charts of unaged and RTFO aged binders to serve as the minimum limits. This percentage RAP binder will serve as the minimum amount of RAP binder needed to be blended with the selected virgin binder for the blended binder to qualify for a high temperature grade of 64. Minimum limits should be estimated for all the RAP binders sampled from the stockpile in similar fashion. Calculate the standard deviation and mean of the limits for all the sampled RAP binders and calculate the confidence intervals for the stockpile using Equation B.1. If the softest grade of virgin binder to be used in the project is PG 64-22 then this step of plotting blending charts for minimum limits can be omitted.

$CI = \mu +/- (sd/\sqrt{n})*t_{\alpha/2, (n-1)}$ *Equation B.1*

Where:

μ = mean of the limits for all the samples from a stockpile

sd = sample standard deviation for each stockpile

n = sample size (no. of RAP samples)

$t_{\alpha/2, (n-1)}$ = student t-distribution critical value with (n-1) degree of freedom and (1-α)% CI

For a 95% reliability, use $\alpha = 0.10$ and take the upper confidence limits to be the final minimum limits for the RAP stockpile.

- Plot using log(|G*|sinδ) values at 25^{o}C of PAV aged binders on the Y-axis and percentage RAP binder in total binder on the X-axis for determining maximum limits. For every sample, the plot should contain one point for the virgin binder, one point for the blended binder at a known RAP binder percentage, and one point for RAP binder. Fit a straight line between the three points and estimate the percentage RAP binder needed to meet the criteria of |G*|sinδ < 5000kPa. This percentage RAP binder will serve as the maximum amount of RAP binder needed to be blended with the selected virgin binder for the blended binder to meet the intermediate temperature specifications of a PG 64-22 binder. Maximum limits should be estimated for all the RAP binders sampled from the stockpile in similar fashion. Calculate the standard deviation and mean of the limits for all the sampled RAP binders and calculate the confidence intervals for the stockpile using the same Equation B.1. For a 95% reliability, use $\alpha = 0.10$ and take the lower confidence limits to be the final maximum limits for the RAP stockpile.

B.1 Multiple Stockpile Limits

This section applies to pavement projects that incorporate RAP from multiple stockpiles. In addition to the guidelines already specified in the previous section, this section will list the adjustments to the guidelines for deriving a common minimum and maximum limits for RAP from multiple stockpiles. If the practice is to use RAP from different stockpiles for different sections of the project without mixing them, then the RAP binder limits should be determined like in the case of a single stockpile limit for the corresponding section. However, in the second case where, RAP from two or more stockpiles are mixed together during the process of mixture preparation, the single stockpile binder limits will no longer be applicable. For this case, it is required to know the proportions of RAP from various stockpiles mixed together.

The guidelines for sampling and extraction of RAP binders remain same as in the case of a single stockpile and should be performed for every stockpile. Performance grade testing of the RAP binder samples and construction of blending charts shall also be done according to the guidelines listed in the single stockpile case for every stockpile. The derivation of the binder limits for RAP sampled from multiple stockpiles is described as follows:

B.2.1 Blending Charts and RAP Binder Limits

Once, the limits for individual stockpiles have been calculated from the blending charts, the confidence intervals can be constructed using the statistical theory in chapter 7 for known proportions of RAP from various stockpiles as p_1, p_2, p_3…. p_k (k being number of RAP stockpiles). The confidence limits should be constructed using the theory for unequal variances and the adjusted error degrees of freedom.

For a 95% reliability, use $\alpha = 0.10$ and take the upper confidence limit calculated from the individual minimum limits to be the final minimum limit for the combination of RAP stockpiles.

For a 95% reliability, use $\alpha = 0.10$ and take the lower confidence limit calculated from the individual maximum limits to be the final maximum limit for the combination of RAP stockpiles.