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Impact of Binders from Waste Materials on Performance of Surface Mixtures

Dr. N. Paul Khosla, Ph.D.
Haritha Y. Musty
Department of Civil, Constriction and
Environmental Engineering
North Carolina State Univeristy

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by

Dr. N. Paul Khosla
Haritha Musty

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Department of Civil Engineering
North Carolina State University

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16. Abstract

Increase in travel demand, reduced availability of virgin materials and budgetary constraints have prompted the use of waste materials in new asphalt mixes. Recycled asphalt pavement (RAP) and recycled asphalt shingles (RAS) are the two waste materials that receive the most importance as they offer a partial substitute for virgin aggregates and asphalt binder. Mixtures incorporating higher amounts of RAP or RAS will have higher stiffness due to blending of aged and virgin binders. This results in the mixture being more susceptible to cracking, therefore limiting the amount of recycled material that can be added to asphalt mixtures. The current state of practice in the industry is to place limits on the percentage by weight of total mixture that has been replaced by RAP, RAS, or a combination of both. The need exists to determine if changes in specifications are warranted to limit recycled materials based on the percent recycled binder they contribute to the total binder percentage instead of the percent by total weight of mixture. The main objectives of this study are to determine recycled binder limits for S9.5C and S9.5D mixes which use a virgin binder grade of PG 70-22 and PG 76-22, respectively. In this study, limits for allowable recycled binder were determined by conducting dynamic shear rheometer (DSR) tests at high and intermediate temperatures. Blending charts were developed and regression analysis was done to estimate the allowable recycled binder limits for virgin binders to satisfy the performance grade (PG) specifications for S9.5C and S9.5D mixes. These limits were used to design recycled asphalt concrete mixtures. These mixtures were tested using the Asphalt Mixture Performance Tester (AMPT) for measuring dynamic modulus. The dynamic modulus values of the mixtures and rheological properties of blended binders were used to predict the performance of the mixtures with respect to fatigue cracking and rutting using AASHTOWare Pavement M-E Design software. The predicted performance data and binder test results were used to determine limits for the recycled materials based on the recycled binder percentage in the mix.

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EXECUTIVE SUMMARY

Increase in travel demand, reduced availability of virgin materials and budgetary constraints have prompted the use of waste materials in new asphalt mixes. Recycled asphalt pavement (RAP) and recycled asphalt shingles (RAS) are the two waste materials that receive the most importance as they offer a partial substitute for virgin aggregates and asphalt binder. Mixtures incorporating higher amounts of RAP or RAS will have higher stiffness due to blending of aged and virgin binders. This results in the mixture being more susceptible to cracking, therefore limiting the amount of recycled material that can be added to asphalt mixtures.

The current state of practice in the industry is to place limits on the percentage by weight of total mixture that has been replaced by RAP, RAS, or a combination of both. The need exists to determine if changes in specifications are warranted to limit recycled materials based on the percent recycled binder they contribute to the total binder percentage instead of the percent by total weight of mixture. The main objectives of this study are to determine recycled binder limits for S9.5C and S9.5D mixes which use a virgin binder grade of PG 70-22 and PG 76-22, respectively.

In this study, limits for allowable recycled binder were determined by conducting Dynamic Shear Rheometer (DSR) tests at high and intermediate temperatures. Blending charts were developed and regression analysis was done to estimate the allowable recycled binder limits for virgin binders to satisfy the performance grade (PG) specifications for S9.5C and S9.5D mixes. These limits were used to design recycled asphalt concrete mixtures. These mixtures were tested using the Asphalt Mixture Performance Tester (AMPT) for measuring dynamic modulus. The dynamic modulus values of the mixtures and rheological properties of blended binders were used to predict the performance of the mixtures with respect to fatigue cracking and rutting using AASHTOWare Pavement M-E Design software. The predicted performance data and binder test results were used to determine limits for the recycled materials based on the recycled binder percentage in the mix.

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CHAPTER 1 - INTRODUCTION

1.1 Background

The National Asphalt Pavement Association (NAPA) estimates that approximately 94 percent of about 2.5 million miles of paved roads in the United States are constructed with asphalt [1]. Recent emphasis on sustainability and budgetary constraints have prompted highway agencies to use green paving technologies like warm-mix asphalt and recycled materials in new pavements. Use of recycled materials is one of the most widely followed and economical ways of achieving the sustainability goal of transportation industry. Recycled asphalt pavement (RAP) and recycled asphalt shingles (RAS) are the two recycled materials that receive most importance in asphalt pavements as they offer a partial substitute for virgin aggregates and asphalt binder. Pavement recycling is one of the major rehabilitation methods for asphalt pavements where materials that are removed from the existing degraded pavements are reused in the construction of a new asphalt layer. The use of RAP in hot mix asphalt (HMA) has been widely investigated for different design conditions and materials by several agencies. When properly designed and constructed, mixtures containing low RAP contents of about 20-25 percent by weight of mixtures have shown equal, if not better performance when compared to virgin mixtures [2].

Asphalt shingles account for almost 80 percent of residential roofing applications in the United States [3]. Asphalt shingles contain 20 to 35 percent asphalt binder and other materials such as fine aggregates that can be reused in asphalt pavements and hence there has been growing interest in recycling asphalt shingles for paving applications. RAS is of two types, manufacturer waste recycled asphalt shingles (MRAS) and post-consumer recycled asphalt shingles (PRAS) [3]. Manufacturer waste shingles are the waste products of shingle manufacturing process while post-consumer shingles are tear-off shingles obtained from roofs of buildings after their service. RAS typically contain 15 to 30 percent asphalt by weight. The asphalt used in roofing shingles is much harder and stiffer because it is air-blown during production to increase the viscosity of the asphalt for roofing applications [4]. Benefits of using RAP and RAS include lower costs, preservation of the environment and conservation of natural resources and energy. Mixtures incorporating higher amounts of RAP or RAS will have higher stiffness due to blending of aged and virgin binders. This may lead to a mixture being more susceptible to cracking and thus, limiting the amount of recycled material that can be added to asphalt mixtures.

1.2 Problem Statement

The current state of practice in the industry is to place limits on the percentage by weight of total mixture that has been replaced by RAP, RAS, or a combination of both. The contributed binder content is then computed and is shown along with the reduced percentage of virgin asphalt binder added to the mix. The need exists to determine if changes in specifications are warranted to limit recycled materials based on the percent recycled binder they contribute to the total binder percentage instead of the percent by total weight of mixture. Changing the specification to determine the percentage of allowable recyclable material based on percent binder contributed will allow greater control over mixture performance with respect to pavement distresses.

The North Carolina Department of Transportation specifies the virgin binder grade to be used for different percentages of RAP based on mixture type as shown in Table 1.1. The NCDOT research project RP 2012-04, “Determining Recycled Asphalt Binder Limits Contributed by Waste Materials”, investigated various recycled asphalt material sources (RAP, MRAS and PRAS) to determine binder limits for S9.5B mixes. A virgin binder grade of PG 64-22 was used for all B Level mixes. The binder limits determined for S9.5B mixes are not directly applicable to S9.5C and S9.5D mixes, which use a virgin binder grade of PG 70-22 and PG 76-22, respectively. Two primary reasons to develop separate binder limits for S9.5C and S9.5D mixes are the varying gradation and virgin binder grade, both of which affect the mixture performance significantly.

The asphalt binder in RAS is much different than that found in RAP materials. RAS binder is highly oxidized and a stiff material that was not originally manufactured for paving applications. There are no standard specifications for using RAS in asphalt mixtures. The NCDOT specifications also do not provide virgin binder PG grade for percentages of RAP higher than 30%. The maximum amount of recycled materials when using a combination of RAP and RAS is limited to 20% by weight of total mixture, with a maximum RAS content of 6%. The need exists to determine the recycled binder limits of RAP, MRAS and PRAS for

S9.5C and S9.5D mixes. The proposed research also seeks to determine the recycled binder limits for RAP-RAS combinations.

Table 1.1 NCDOT Specifications for Superpave Mix Design Criteria for RAP Mixes [5]

Table 610-4 SUPERPAVE APPLICABLE VIRGIN ASPHALT GRADES			
Mix Type	Percentage of RAP by Weight in Mix		
	Category 1[A]	Category 2[B]	Category 3[C]
	RAP≤20%	21%≤RAP≤30%	RAP≥30%
All A and B Level Mixes I19.0C, B25.0C	PG 64-22	PG 64-22	Established by Engineer
S9.5C, S12.5C, I19.0D	PG 70-22	PG 64-22	Established by Engineer
S9.5D and S12.5D	PG 76-22	-	-

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.

1.3 Research Objectives

The main objectives of this study were to:

a) Investigate various recycled asphalt material sources (RAP, MRAS and PRAS) to determine recycled binder limits for S9.5C and S9.5D mixes
b) Determine the limits of the combination of RAP-RAS binders that can be allowed without any detrimental effect on performance of HMA mixes.

c) Develop a draft specification utilizing limits for recycled materials based on recycled binder percentage in the mix.

1.4 Report Organization

This report is divided into eight chapters. The first chapter covers a brief introduction on recyclable materials, problem statement, study objectives, and the outline of the report. Chapter 2 is the literature review which provides a background of recycled asphalt pavement (RAP) and recycled asphalt shingles (RAS) and an overview of prior research on the use of recycled materials and their effect on asphalt binder and asphalt mixture properties. Chapter 3 describes the materials used in this research and their properties. Chapter 4 presents rheological properties of blended binders and recycled binder limits at high and intermediate temperatures. Chapter 5 presents the Superpave mix designs developed in the laboratory for S9.5C and S9.5D virgin mixtures and recycled mixtures incorporating different amounts of RAP and RAS based on the recycled binder percentage in the mix. Chapter 6 describes the dynamic modulus test and discusses the results and related analysis. Chapter 7 presents the pavement performance prediction using AASHTOWare Pavement M-E Design software and economic analysis. Chapter 8 presents conclusions based on this study and recommendations for further study.

CHAPTER 2 - LITERATURE REVIEW

This chapter provides a background of recycled asphalt pavement (RAP) and recycled asphalt shingles (RAS) and an overview of prior research on the use of recycled materials and their effect on asphalt binder and asphalt mixture properties.

2.1 Recycled Asphalt Pavement (RAP)

Asphalt pavement recycling has become popular since 1970s due to the oil embargo and subsequent increase in the price of asphalt. In early 1990s, the Federal Highway Administration (FHWA) and Environmental Protection Agency (EPA) estimated that more than 90 million tons of asphalt pavements were reclaimed every year and more than 80 percent was recycled, making asphalt pavements the most recycled product in the United States [2]. RAP is any removed or reprocessed pavement material that primarily contains aggregates and asphalt cement. RAP is obtained during rehabilitation or reconstruction of existing asphalt pavements, or from utility cuts across the roadways which were necessary to gain access to underground utilities. Asphalt pavement is generally removed either by milling or by full-depth removal. Milling is typically done in rehabilitation projects where the existing wearing course is removed and then replaced to increase the pavement's functional adequacy and service life. Full-depth removal involves milling the existing HMA pavement structure in several passes, depending on existing depth of the structure, or by ripping and breaking the pavement into large pieces using rippers or a bull dozer. When RAP is properly crushed and screened, it will consist of high-quality aggregates coated with asphalt cement binder which can be used in a number of highway construction applications. These include its use as an aggregate substitute and asphalt cement supplement in new or recycled asphalt mixes, as granular base or sub-base, as a stabilized base aggregate, or as an embankment or fill material [2, 6]. Milling removes cracked and aged pavement surface, helps improve pavement smoothness, and maintains curb height, drainage inlets, and bridge clearances. Recycling helps reduce demand on non-renewable natural resources and reduces cost of construction.

2.1.1 Effect of RAP on Binder and Mixture Properties

The blending of aged and virgin binders is one of the major concerns related to the performance of recycled HMA mixes. McDaniel et al. (NCHRP) conducted a research study to determine whether RAP acts like a black rock or if some blending occurs between the aged and virgin binders [7]. Three different RAPs (low, medium and high stiffness), two different virgin binders (PG 52-34 and PG 64-22), and two RAP contents (10% and 40%) were investigated in the first phase of the project. Three cases simulating possible interactions between the old and new binders were studied to investigate the behavior of RAP blends. Black rock samples (BR) were made using virgin and recovered RAP aggregate (no RAP binder) with virgin binder. Actual practice samples (AP) were made using virgin binder, aggregate and RAP (with its binder intact). Total blending samples (TB) were made using virgin and recovered RAP aggregate. RAP binder was recovered and then blended with virgin binder at specified percentages before mixing. All samples were prepared on the basis of an equal volume of total binder. The different cases of blending were evaluated by various

Superpave shear tests at high temperatures and indirect tensile creep and strength tests at low temperatures. Results indicated that there is no significant difference at low RAP contents, but at high RAP contents blending of the old and new binders occurs to a significant extent. This illustrated that RAP does not act like a black rock and the hardened RAP binder must be accounted for in the virgin binder selection [7].

The next phase of this study investigated the effects of RAP content and stiffness on the blended binder properties. Three RAPs and two virgin binders were evaluated at RAP binder contents of 0%, 10%, 20%, 40%, and 100%. The blended binders were tested according to AASHTO MP1 binder tests. The critical high and intermediate temperatures from dynamic shear rheometer (DSR) tests and critical low temperatures from the bending beam rheometer (BBR) tests were determined. The complex shear modulus (G*) and phase angle (δ) from the DSR tests and stiffness and m-value from the BBR tests were studied. It was found that at low RAP contents, the effects of RAP binder were negligible. At intermediate RAP contents, these effects can be compensated by using a virgin binder that is one grade softer on both the high- and low- temperature grades. Higher RAP contents require the use of blending charts to determine the appropriate virgin binder grade [7].

Kennedy et al. conducted a study to determine the effect of reclaimed asphalt pavement on binder properties [8]. In this study, rheological properties were measured for different combinations and percentages of aged binder and virgin binders. Superpave binder tests were conducted on unaged, rolling thin film oven (RTFO) aged and pressure aging vessel (PAV) aged blended binders at corresponding high, intermediate and low temperature ranges. Two binders were chosen to be aged to simulate RAP binder and then combined with four virgin binders at different percentages (0%, 15%, 25%, 55% and 100%). PG grade of virgin-RAP blends were determined by dynamic shear rheometer (DSR) and bending beam rheometer (BBR). The DSR results for high temperature values indicated that the stiffness, measured by G*/sinδ, increased with increasing levels of RAP in the blend. Again, at the intermediate and low temperature values, higher percentages of RAP had the greatest effect on the stiffness of the blend. Lower temperatures and higher percent RAP binder increased both G*sinδ and the rate increase of G*sinδ. The BBR results indicated that low temperature values, higher percentages of RAP had the greatest effect on the creep stiffness of the blend. Kennedy et al. concluded that conducting Superpave testing on blended binders is a legitimate procedure for determining the percentage of RAP that can be used in order to produce a blend that meets the specified binder criteria [8].

Kandhal and Foo developed a procedure for selecting the performance grade (PG) of virgin asphalt binder in a recycled HMA mixture based on the Superpave PG grading system [9]. They proposed testing binders with varying percentages of reclaimed binder over a range of temperatures in order to establish the blend's Superpave performance grade. Blending charts were constructed and evaluated based on test parameters obtained from the dynamic shear rheometer (DSR) and therefore only high and intermediate test temperatures were considered. The temperatures at which a blend's Superpave performance criteria are fulfilled are then plotted against the percentage of virgin binder. This established the blending curve that Kandhal and Foo called the “iso-stiffness line”. These charts indicated a linear relationship between the logarithm of binder shear stiffness and percent of virgin asphalt in a virgin and RAP binder blend. These temperature sweep blending charts were evaluated for their effectiveness in determining how much virgin asphalt binder is needed such that the high and intermediate temperature value of the recycled asphalt binder meet the requirement of a specific PG grade [9].

The NCHRP study by McDaniel et al. also investigated the effects of RAP on total mixture properties. RAP contents of 0%, 10%, 20% and 40% were evaluated [7]. Shear tests and indirect tensile tests were conducted at high, intermediate, and low temperatures (the results of testing the actual practice (AP) samples from the black rock study were included). Beam fatigue testing was also conducted at intermediate temperatures. The test results confirmed that recycled mixtures with RAP content greater than 20% have a lower fatigue life than virgin mixtures. The results indicated that high RAP contents increase the mixture stiffness, and therefore, a softer virgin binder must be used to improve the fatigue and low-temperature cracking resistance of the mixtures [7].

Li et al. investigated the effect of various types and percentages of RAP on asphalt binder and asphalt mixture properties [10]. Ten mixtures were developed using three RAP percentages (0%, 20% and 40%), two asphalt binders (PG 58-28 and PG 58-34) and two RAP sources identified as millings-RAP obtained from a single source and RAP-RAP combined from a number of sources and crushed at the HMA plant. Stiffness and moisture susceptibility tests were used to determine the effect of RAP on the asphalt mixture properties. Moisture susceptibility results indicated that all mixtures met the minimum specified tensile strength ratio. Dynamic modulus test and indirect tensile (IDT) creep and strength tests were performed on all mixtures. They reported that addition of RAP to a mixture generally increased the complex modulus and mixture stiffness and asphalt binder grade and RAP source had a significant effect on mixture stiffness. [10].

A comprehensive evaluation was done by McDaniel et al. to determine if the tiered approach of the Federal Highway Administration and Superpave RAP specifications are applicable to the materials obtained from Indiana, Michigan, and Missouri. In that study, laboratory mixtures were compared to plant-produced mixtures with the same materials at RAP contents between 15% and 25% [11]. Additional mixtures were designed and tested in the laboratory, with RAP content up to 50%, to determine the effect of recycled materials on mix performance. Prepared mixes were tested using Superpave shear tester. Results showed that plant-produced mixes were similar in stiffness to laboratory mixtures at the same RAP content for the Michigan and Missouri samples. Mixtures with up to 50% RAP could be designed with Superpave, provided RAP gradation and aggregate quality satisfied the design specifications. Linear blending charts were found to be appropriate in most cases. It was observed that increasing RAP content in a mixture increased stiffness and decreased shear strain, indicating increased resistance to rutting. It was concluded that when RAP properties are appropriately accounted for in the material selection and mix design process, Superpave mixtures with RAP can perform very well [11].

Sondag et al. reported the results of a study on recycled asphalt pavement (RAP) mixtures [12]. Research involved characterization of RAP gradations and binder properties and to develop a mix design methodology using the Superpave approach, to proportion the materials in mixtures containing RAP. The asphalt content of the RAP was determined by both ignition oven and solvent extraction methods and the PG grade of recovered binder was determined. The RAP aggregate properties were also determined. Samples were compacted using Superpave gyratory compactor and contained 0% to 40% RAP from either of two sources - MnDOT District 6 or District 8 and either of PG 58-28, PG 52-34 or PG 46-40 virgin binder. Samples were tested for resilient modulus, complex modulus and moisture sensitivity. Two samples from each mixture were tested for resilient modulus in accordance with ASTM D 4123. Results indicated that the resilient modulus increased with addition of RAP to a mixture and also depends on the source of RAP, stiffness of the material. Software developed at the University of Minnesota was used to perform the complex modulus test using the indirect tensile test (IDT) setup with specific temperature and frequency test parameters. Results indicate that addition of RAP decreases the mixture phase angle, which corresponds to an increase in the elastic properties and a decrease in the viscous properties. It was reported that the source of RAP affected the complex modulus results. District 8 RAP binder had a higher PG grade than District 6 RAP and accordingly yielded a higher complex modulus and lower phase angle. The moisture sensitivity results indicated that the tensile strength ratios (TSR) for 18 mixtures evaluated were all above 95%. No significant difference in TSR values was found with variation in RAP content. Researchers concluded that the percentage of RAP and the respective asphalt binder grade is necessary to yield the stiffness similar to virgin mixture [12].

Huang et al. evaluated the laboratory fatigue characteristics of asphalt mixtures containing RAP at a varying percentage between 0% and 30%. Indirect tensile strength (IDT), beam fatigue, and semi-circular fatigue tests (SCB) were conducted on the mixtures [13]. Half of the specimens were subjected to laboratory long-term aging prior to performance tests. IDT test results showed that increasing the RAP content generally increased the tensile strengths, and decreased toughness indices for both unaged and aged mixes. Increasing RAP percentages had significantly different effects in IDT properties for mixtures with PG 64-22 than those with PG 76-22, especially for mixtures subjected to laboratory long-term aging. Results indicated that the increase of RAP had more tensile strength gains, no tensile strain loss at failure and less decrease in post-failure toughness index, suggesting that the recycled mixes would have an increased fatigue life [12]. SCB fatigue test results show that the inclusion of RAP generally increased the fatigue life of the mixtures in this study, as well as the total dissipated energy. For mixes subjected to long-term aging, the slope of load vs log(N_f) fatigue curves increased significantly when the RAP increased to 30% which indicates potential lower fatigue life for these mixes at lower stress levels. Results of beam fatigue tests indicated that RAP generally increased the flexural stiffness of the mixtures. The percentage of increase in fatigue life is more significant for long-term aged mixtures with PG 64-22 asphalt than those with PG 76-22. For mixtures with PG 76-22 asphalt, without long-term aging, the fatigue life decreased with the inclusion of RAP [13].

Al-Qadi et al. conducted a study to determine the amount of blending occurring in a recycled mix that could be readily implemented into the mix design procedure [14]. An experimental program was developed to determine the amount of working RAP binder in a mix and the contribution of RAP to overall mixture behavior. Six different job mix formulae were developed using three RAP contents (0%, 20%, and 40%) and two aggregate and RAP sources. Specimens were prepared with recovered RAP materials (binder and aggregate) to evaluate the effect of stiff binder/virgin binder combinations. The HMA designs with 20% and 40% RAP included four various sets of specimens:

- Set 1- Actual RAP used with the assumption of 100% binder mobilization (current Illinois DOT assumption)
- Set 2- Recovered aggregates and no recovered binder used to replicate 0% binder mobilization (black rock assumption)
- Set 3- Recovered aggregates and recovered binder used to replicate 50% binder mobilization
- Set 4- Recovered aggregates and recovered binder used to replicate 100% binder mobilization

These sets were used for comparison with actual practice mixes where the amount of working binder is unknown. Two binder grades, PG 64-22 and PG 58-28, were used in this study. The PG 58-28 grade binder was used for mixing with selected HMA specimens containing 40% RAP to illustrate the impact of "double grade bumping" of the binder when higher percentages of RAP was used. Double grade bumping was accomplished by reducing both the high and low temperature grades available in the Performance Graded (PG) Binder System. Mixes containing 0%, 20%, and 40% RAP were prepared and the dynamic modulus testing results of these mixtures were compared to illustrate the effect of RAP on HMA. Tests on recovered, virgin, and blended binders were also conducted using the dynamic shear rheometer (DSR). Extracted binders from the RAP sources used in this study were tested in addition to testing blends of virgin PG 64-22 binder with 20% and 40% RAP binder. Virgin PG 64-22 grade binder was also tested to provide baseline data for comparisons of binder properties. Scanning electron microscopy (SEM) was performed to determine if the blending effects of the virgin and RAP binder could be observed after the mixing process. Limited fracture testing was conducted to determine how RAP percentages affect the thermal cracking properties of the HMA. Results indicated that up to 20% RAP in HMA does not require a change in binder grade. The researchers reported that at 40% RAP in HMA, double bumping the binder grade, the use of a PG 58-58 binder instead of a PG 64-22 binder appeared to increase the level of binder blending [14].

Al-Qadi et al. conducted a study to characterize the performance of HMA with high amounts of RAP and to identify special considerations that must be met to use these higher RAP contents [15]. Eight 3/4-in. nominal maximum aggregate size (NMAS) N90 binder mix designs were developed using two material sources from two districts. Two control (0% RAP) and three mixtures with 30%, 40% and 50% RAP for each district was prepared. A base asphalt binder (PG 64-22) was used in the mix design process and the effect of soft binders on the performance of mixtures with RAP was also evaluated using two relatively soft binders (PG 58-22 and PG 58-28). The Bailey method of aggregate packing was used to develop all the mix designs. The performance of all the mixes was determined using various performance tests, including complex modulus, beam fatigue, fracture, wheel tracking, and moisture susceptibility. Results showed that the presence of RAP reduced the mixture rutting potential, improved fatigue behavior as measured by the fatigue curve slope. Single bumping PG 58-22 proved to be effective in improving fatigue behavior. The low temperature fracture energy of HMA decreased when 30% RAP or more was added when compared to control mix. The double bumped asphalt binder grade (PG 58-28) was found effective in counteracting the RAP's stiff residual asphalt binder and in helping to retain the original properties of the virgin mixture. Researchers concluded that it is possible to design high-quality HMA with up to 50% RAP that meets the required volumetric and desired performance criteria. Researchers also recommended proper processing and fractionation of the RAP material to ensure consistent, high quality production of HMA with RAP [15].

2.2 Recycled Asphalt Shingles (RAS)

Asphalt shingles are the most common roofing material nationwide. It has been estimated that more than 11 million tons of waste asphalt shingles are land filled every year [3, 4]. The majority of waste shingles are tear-off shingles from building activities like reroofing; however, waste is also produced by shingle manufacturers. Common asphalt shingles are 30 to 35 percent asphalt, 5 to15 percent mineral fiber and 30 to 50 percent mineral granules. Fiber glass shingles have lesser amounts of asphalt at 15 to 20 percent, with other constituents at similar percentages as common shingles. Since the shingles contain a high percentage of asphalt binder and other materials such as fine aggregates that can be reused in asphalt pavements, there has been growing interest in recycling asphalt shingles for paving applications [4]. More stringent RAS processing guidelines and a better understanding of the properties of the constituent materials has led to more widespread usage of RAS materials in recent years. The asphalt binder in RAS is much different than that found in RAP materials. RAS binder is air blown asphalt and is a very stiff and highly oxidized material that was originally manufactured for roofing applications. Like RAP, several benefits arise from recycling shingles, including conservation of materials and energy, preservation of the environment and reduction in cost.

2.2.1 Effect of RAS on Binder and Mixture Properties

Goh and You conducted a study to evaluate the performance of asphalt mixtures incorporating recycled asphalt shingles using the universal testing machine and asphalt pavement analyzer (APA) [16]. In this study, base binder was kept constant and three mixtures were prepared with 0%, 5% and 10% RAS by weight. It was reported that during specimen fabrication, the number of gyrations was the same for all the mixtures but higher mixing and compaction temperatures were used for RAS mixtures. They found that the mixtures incorporating RAS had higher air voids and the air void levels increased with increase in RAS content. They concluded that this was because RAS mixture was stiffer than the virgin mixture and needed additional compaction effort or higher compaction temperatures. From dynamic modulus test results, it was found that at low testing temperature, dynamic modulus (|E*|) for control mixtures is significantly higher than both

5% and 10% RAS mixture. When the test temperature increased, the difference in |E*| between the RAS mixtures decreased and RAS mixtures were observed to have the highest dynamic modulus values at temperatures close to 40 ˚C. Based on dynamic modulus results they concluded that RAS mixtures performed better in terms of cracking and rutting when compared to virgin mixture. From APA test results they found that final rut depth after 8000 cycles decreased by 72% and 94% for mixtures containing 5% and 10% RAS, respectively. They concluded that the use of RAS could significantly improve the rutting performance of the asphalt pavement [16].

Johnson et al. investigated the incorporation of RAS in HMA through a laboratory study and field investigation [17]. Seventeen different mixtures with different amounts of RAS and RAP were developed. The effect of asphalt binder grade and content, RAP source and content (0%, 15%, 25%, and 30%) and RAS type (tear-off scrap shingles [TOSS], which is equivalent to PRAS and manufacturer waste scrap shingles [MWSS], which is equivalent to MRAS) and proportions (3% and 5%) on HMA mixture and binder properties were evaluated. Asphalt binders recovered from virgin, RAP and RAS mixtures were tested for high temperature stiffness and low temperature creep stiffness and m-value. The binder testing results indicated that TOSS binder material is stiffer than MWSS. The use of a softer grade (from PG 58-28 to a PG 51-34) reduced the stiffness of the RAP/RAS asphalt mixtures. The performance of HMA mixtures was tested in terms of stiffness, moisture sensitivity and rutting susceptibility by dynamic modulus test, Lottman analysis and asphalt pavement analyzer (APA). Dynamic modulus test results indicated that the stiffness of mixtures containing RAS/RAP was significantly higher than mixtures containing no recycled materials at high temperatures/low frequencies. The differences between MWSS and TOSS, as well as the softening effects of the softer grade binder (PG 51-34) were confirmed with the APA rut testing. Moisture sensitivity test results indicated that the TOSS may be more susceptible to moisture damage than MWSS [17].

Scholz conducted a study on asphalt mixtures containing 5% post-consumer RAS (tear-off shingles) with different proportions of RAP (0%, 10%, 20%, 30%, 40% and 50%) to determine how the addition of these materials would affect the Superpave performance grade of the blended binder [18]. Virgin binder grade of PG 70-28 was used for all the mixtures. The virgin binder and asphalt binders recovered from RAP, RAS and batched mixtures were tested using bending beam rheometer, dynamic shear rheometer and direct tension test to determine the critical temperatures required for determining the performance grade of the binder. Results indicated that addition of 5% RAS (by total weight of mixture) and no RAP resulted in an increase in both the high and low temperature performance grades. Binders recovered from the mixtures containing both RAP and RAS indicated an increase in both high temperature and low temperature performance grades of the blended binder with increasing RAP contents up to about 30%. At RAP contents of 30% or more, in combination with 5% RAS, the low temperature grade exceeded that of the mixture containing only 5% RAS while the high temperature grade equaled that of the mixture containing only 5% RAS [18].

Wen et al. conducted a study to evaluate the performance of hot-mix asphalt containing recycled asphalt shingles [19]. They investigated field cores obtained from four experimental pavement sections of a three year old single RAS experimental project. Two of these sections were constructed without RAS (the control section) and other two sections contain 3% RAS. The performance of asphalt mixtures and recovered asphalt binders was evaluated with respect to rutting, fatigue and thermal cracking resistance via laboratory experiments. It was reported that the rutting resistance of the mixtures as well as the recovered binders improved with the addition of RAS. However, the fatigue and thermal cracking resistance of the mixtures was not significantly affected [19].

Zhou et al. conducted a comprehensive study on asphalt mixtures containing RAS. They evaluated both tear-off asphalt shingles (TOAS) and manufacturer waste asphalt shingles (MWAS) and found that TOAS binders were much stiffer that MWAS binders. Compared to the TOAS binders, the MWSA binders had less impact on the performance grade temperatures of virgin binders. Thus it is important to consider differentiating MWAS from TOAS when used in asphalt mixes. They reported that linear blending charts can be used if the RAS binder percentage is less than 30%. They also evaluated the impact of RAS on mixture properties and found that optimum asphalt content (OAC) of mix increased with increase in RAS content. Dynamic modulus testing was conducted and it was observed that there is no significant difference in the dynamic modulus master curves of the mixes containing up to 5% RAS. Rutting and cracking resistance of the designed RAS mixtures was evaluated and it was concluded that use of RAS improves rutting performance but decreases cracking resistance [20].

Ozer et al. evaluated the performance of low N-design mixtures prepared with different combinations of RAP and RAS at high asphalt binder replacement levels [21]. Three different percentages of fine fractionated recycled asphalt pavement (FRAP) (12.5%, 15% and 17.5%), RAS (2.5%, 5% and 7.5%) and 20% of coarse FRAP were used with a virgin binder PG 46-34. PG 58-28 was used with 7.5% RAS, 17.5% fine FRAP and 20% coarse FRAP. Asphalt binder replacement with RAP and RAS binder in the mix was about 43-64% of the total asphalt binder. All the designed mixes were tested for performance in terms of fatigue, complex modulus, fracture, permanent deformation, low temperature and reflective cracking. Results indicated that mixtures performed better in terms of permanent deformation with the use of RAS. There is a decrease in fatigue life with increase in RAS content in a mix. It was noted that fatigue performance and fracture energy improved when PG 46-34 binder was used at 64% asphalt binder replacement [21].

2.3 Summary of Literature Review

The literature review presented studies on use of RAP which concluded that RAP does not act like a black rock and a considerable degree of blending occurs between recycled and virgin binders. It was found that at low RAP contents, the binder effects are negligible and no modification is required in the mix design process. At intermediate RAP contents a binder that is one grade softer should be used to offset the stiff RAP binder. Higher RAP contents need the use of blending charts for the appropriate selection of virgin binder grade. RAS was incorporated into HMA at low percentages, up to 5% by weight of mixture. It was found that mixtures incorporating RAS performed equally well when compared to the conventional HMA mixtures. RAS, similar to RAP will require mix adjustments such as a softer binder grade due to the presence of highly aged binder in the RAS. It has also been found that addition of RAP/RAS increases the binder stiffness as well as the mixture stiffness. The increased stiffness may affect low temperature performance and fatigue life. On the other hand, increase in mix stiffness improved the rutting resistance.

CHAPTER 3 - MATERIAL CHARACTERIZATION

This chapter provides a detailed description of the materials used in this research and their properties. This study involved evaluating material properties of virgin aggregates, asphalt binder and recycled materials.

3.1 Virgin Aggregates

Granite aggregates were used in this study. These virgin aggregates and pond fines were procured from Martin Marietta's Quarry in Garner, North Carolina. Three different aggregate stockpiles - a coarse aggregate (#78M), washed screenings and manufactured sand were used to develop the design aggregate blend. Aggregates from each stockpile were sampled and washed sieve analyses were performed following AASHTO T11, " Materials Finer than 75 μm (No. 200) Sieve in Mineral Aggregates by Washing " and AASHTO T27, "Sieve Analysis of Coarse and Fine Aggregate". The individual aggregate single point gradations are given in Table 3.1. The specific gravities of all the aggregates were determined according to AASHTO T84, "Specific Gravity and Absorption of Fine Aggregate" and AASHTO T85, "Specific Gravity and Absorption of Coarse Aggregate". Table 3.2 shows the specific gravities of the virgin aggregates.

Table 3.1 Aggregate Gradations

Sieve Size, mm	% Passing		
	#78M	WS	MS
12.5	100	100	100
9.5	91	100	100
4.75	32	100	100
2.36	6	88	92
1.18	4	66	73
0.6	3	45	49
0.3	2	25	25
0.15	2	8	8
0.075	1.04	3.03	3.15

Table 3.2 Aggregate Specific Gravities

Aggregate Type	Bulk Specific Gravity	Apparent Specific Gravity
#78M	2.617	2.644
WS	2.597	2.652
MS	2.65	2.675
Pond Fines	2.597	2.647

3.2 Asphalt Binder

Asphalt binders PG 58-28, PG 64-22, PG 70-22 and PG 76-22 were used in this study. All the virgin binders except PG 76-22 were from NuStar’s Wilmington refinery in North Carolina. The asphalt binder PG 76-22 was from NuStar’s Savannah refinery in Georgia. Virgin binders were tested using the dynamic shear rheometer (DSR) to determine their rheological properties and verify the performance grade. Short term aging of the asphalt binders was achieved using the rolling thin film oven (RTFO) test according to AASHTO T240, “Standard Method of Test for Effect of Heat and Air on a Moving Film of Asphalt Binder (Rolling Thin-Film Oven Test)”, which simulates aging during construction. In this test, a moving film of asphalt binder is heated in an oven for 85 minutes at 163 ˚C. The moving film is created by pouring a specified amount of asphalt binder into a bottle, which is placed in a rack that rotates in the oven. The orifice of the bottle passes in front of an air jet during rotation. The rotating bottle continuously exposes fresh asphalt to heated air from the jet. Long term aging, which simulates several years of exposure to the environment was achieved using the pressure aging vessel (PAV) according to AASHTO R28, “Standard Practice for Accelerated Aging of Asphalt Binder Using a Pressurized Aging Vessel (PAV)”. The PAV is an oven-pressure vessel combination that takes RTFO aged binder samples and exposes them to high air pressure (2070 kPa) and temperature (100 ˚C) for 20 hours.

The unaged, RTFO and PAV aged binders were tested on the DSR according to AASHTO T315, “Test Method for Determining the Rheological Properties of Asphalt Binder Using a Dynamic Shear Rheometer” to determine the complex shear modulus (G*) and phase angle (δ) of the virgin binders at high and intermediate temperatures. Verification of the performance grade was done in accordance with AASHTO R29, “Standard Practice for Grading or Verifying the Performance Grade of an Asphalt Binder”. The Superpave binder specification uses a rutting factor, G*/sinδ, which is a measure of asphalt binder’s stiffness or rut resistance at high pavement service temperatures. The G*/sinδ must be a minimum of

1.00 kPa for the original asphalt binder and a minimum of 2.20 kPa for the RTFO aged asphalt binders when tested on DSR at the maximum pavement design temperature. The specification also uses a fatigue factor, G*sinδ, which represents asphalt binder resistance to fatigue cracking. G*sinδ has a maximum limit of 5000 kPa for the PAV aged binders tested at intermediate pavement service temperatures. Tables 3.3 through 3.5 show the rheological binder properties of the unaged, RTFO and PAV aged virgin binders.

Table 3.3 Rheological Properties of Unaged Virgin Binders

Virgin Binder	Average G*/sinδ (kPa) at Test Temperature			
	58˚C	64˚C	70˚C	76˚C
PG 58-28	2.03	0.98	0.5	0.26
PG 64-22	3.43	1.47	0.69	0.34
PG 70-22	-	2.45	1.17	0.6

Table 3.4 Rheological Properties of RTFO Aged Virgin Binders

Virgin Binder	Average G*/sinδ (kPa) at Test Temperature		
	64˚C	70˚C	76˚C
PG 58-28	3.38	1.66	0.84
PG 64-22	3.85	1.75	0.83
PG 70-22	7.17	3.14	1.71

Table 3.5 Rheological Properties of PAV Aged Virgin Binders

Virgin Binder	Average G*sinδ (kPa) at Test Temperature			
	28˚C	25˚C	22˚C	19˚C
PG 58-28	1151	1673	2511	3784
PG 64-22	2505	3681	5359	7690
PG 70-22	2626	3904	5767	-

3.3 Recycled Waste Materials

Three different recycled waste materials were used in this study: RAP (Recycled Asphalt Pavement), MRAS (Manufacturer Waste Recycled Asphalt Shingles) and PRAS (Post-Consumer Recycled Asphalt Shingles). MRAS and PRAS were treated differently in this study as the PRAS binders would be much stiffer than the asphalt binder in MRAS because PRAS comes from in-service roofing shingles that have experienced several years of aging whereas MRAS comes from waste produced during shingle manufacturing.

Processed RAP was obtained from REA's West Raleigh Plant, PRAS was obtained from Greenville Paving (now owned by ST Wooten) and MRAS was supplied by ST Wooten's plant located in Youngsville. RAP was fractionated into coarse (C.F) and fine (F.F) fractions using #4 (4.75mm) sieve to limit variability in mixes containing higher percentages of RAP. Asphalt binder content in the waste materials was determined by conducting an ignition oven test following AASHTO T308, "Test Method for Determining the Asphalt Content of Hot Mix Asphalt (HMA) by Ignition Method". Percent asphalt binder contents are shown in Table 3.6. Asphalt content of PRAS is higher than MRAS because the tear-off shingles have lost a portion of their surface aggregate granules due to weathering. Washed sieve analysis was conducted on the extracted aggregates according to AASHTO test procedures to determine the gradations for the recycled materials. Table 3.7 and Figure 3.1 show the extracted aggregate gradations. Bulk specific gravity (G_{sb}) of RAP and RAS aggregate was back-calculated according to AASHTO R35-04, "Standard Volumetric Design for Hot-Mix

Asphalt (HMA)" using the respective theoretical maximum specific gravities (G_{mm}) and assumed percent asphalt absorption. Table 3.8 shows the back-calculated specific gravities.

Table 3.6 Asphalt Binder Contents of Waste Recycled Material

Waste Recycled Material	Percent Asphalt Binder Content
Total RAP	5
RAP C.F	3.2
RAP F.F	6.1
PRAS	18.6
MRAS	14.7

Table 3.7 Extracted Aggregate Gradations

Sieve Size, mm	% Passing		
	RAP	PRAS	MRAS
19	100	100	100
12.5	99	100	100
9.5	96	100	100
4.75	81	99	97
2.36	65	97	92
1.18	51	82	75
0.6	38	60	55
0.3	26	51	44
0.15	17	42	33
0.075	10.3	31.7	25.6

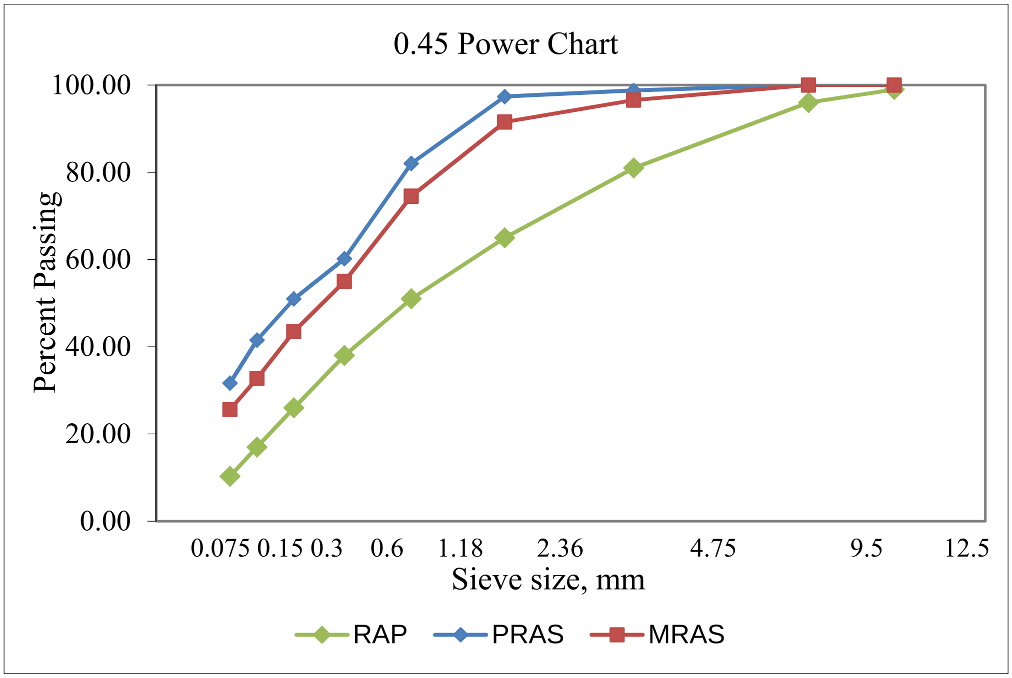


Figure 3.1 Gradations of Extracted Aggregates

Table 3.8 Bulk Specific Gravities of RAP and RAS Aggregates

Waste Recycled Material	Bulk Specific Gravity
RAP	2.632
PRAS	2.645
MRAS	2.644

CHAPTER 4 - BINDER TESTING

Rheological properties of blended binders obtained by blending known percentages of recycled binder with virgin binders are discussed in this chapter. Blending charts were developed and regression analysis was done to estimate the allowable recycled binder limits for virgin binders to satisfy the performance grade (PG) specifications for S9.5C and S9.5D mixes, which use a virgin binder grade of PG 70-22 and PG 76-22, respectively. Since RAP and RAS have different asphalt contents and performance grades, knowing which virgin binder to use or the amount of recycled binder to be added to the virgin binder to achieve a desired final performance grade.

4.1 RAP Binder Limits

Asphalt binder from recycled asphalt pavement (RAP) was extracted according to AASHTO T319, “Quantitative Extraction and Recovery of Asphalt Binder from Hot Mix Asphalt”. Virgin binders were blended with varying percentages of extracted RAP binder as shown in Table 4.1. The percentage represents the proportion of recycled binder by weight of total blended binder. Mixing of virgin and RAP binders was done using a mechanical blender and a hot plate.

Table 4.1 RAP-Virgin Binder Blend Matrix

Virgin Binder	% RAP Binder
PG 58-28	25%, 40%, 100%
PG 64-22	25%, 40%, 100%
PG 70-22	25%, 40%, 100%

The unaged RAP-virgin blended binders were tested on the dynamic shear rheometer (DSR) according to AASHTO T315, "Test Method for Determining the Rheological Properties of Asphalt Binder Using a Dynamic Shear Rheometer" to determine the complex shear modulus (G*) and phase angle (δ) at different high test temperatures. Three replicates for each blended binder were tested. The average G*/sinδ values of the three replicates at different test temperatures obtained upon testing the unaged blended binders are shown in Table 4.2. It can be observed that the stiffness of the blended binder increased with an increase in the proportion of RAP binder.

Table 4.2 G*/sinδ Values of Unaged RAP-Virgin Blended Binders

Blended Binder	Average G*/sinδ (kPa) at Test Temperature		
	64 ˚C	70 ˚C	76 ˚C
PG 58-28 + 25% RAP	2.27	1.09	0.55
PG 58-28 + 40% RAP	4.06	0.93	0.95
PG 64-22 + 25% RAP	3.32	1.52	0.73
PG 64-22 + 40% RAP	4.64	2.05	0.99
PG 70-22 + 25% RAP	3.81	1.81	0.91
PG 70-22 + 40% RAP	4.78	2.27	1.13
100% RAP	22.84	10.24	4.89

Blending charts were developed based on test parameters obtained from the DSR to determine the limits for allowable RAP binder that can be added to a virgin binder to meet the required Superpave binder specifications to satisfy PG 70-22 and PG 76-22 criteria. Blending charts for unaged blended binders with varying percentages of RAP binder at different testing temperatures are shown in Figures 4.1 and 4.2. These blending charts were used to determine the minimum amount of RAP binder required to be added to the virgin binders to obtain a high temperature grade of 70 ˚C and 76 ˚C for the resulting blended binder. This was achieved by determining the minimum percentage of RAP binder required to be added to a virgin binder to satisfy the condition G*/sinδ ≥ 1 kPa at each temperature.

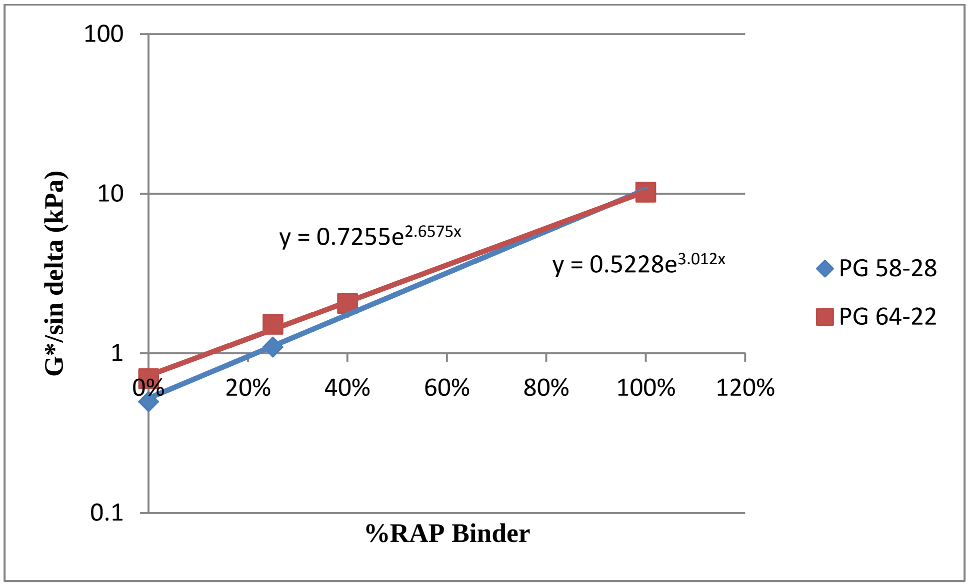


Figure 4.1 Blending Chart for Unaged RAP-Virgin Blended Binders at 70 ˚C

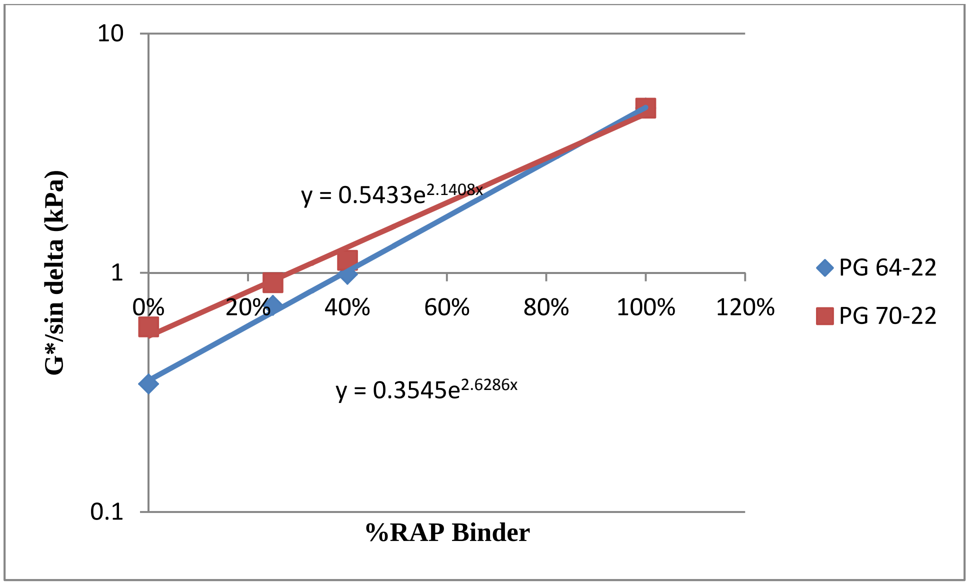


Figure 4.2 Blending Chart for Unaged RAP-Virgin Blended Binders at 76 ˚C

The minimum limits of RAP binder required for each virgin binder are shown in Table 4.3. PG 58-28 binder when blended with a minimum of 22% RAP binder the high temperature grade shifted from 58 ˚C to 70 ˚C. For PG 64-22 based blends, it can be observed that with a minimum of 12% RAP binder the high temperature grade of the blended binder shifted from 64 ˚C to 70 ˚C. It can also be noted that for a PG 64-22 virgin binder, a minimum of 40% RAP binder had to be added to obtain a high temperature grade of 76 ˚C. Similarly, for PG 70-22 virgin binder there is no need to add RAP binder to obtain high temperature grade of 70 ˚C. However, on blending the virgin binder PG 70-22 with a minimum of 29% RAP binder the high temperature grade of the blended binder has increased from 70 ˚C to 76 ˚C.

Table 4.3 Minimum Percentage of RAP Binder to Satisfy G*/sinδ = 1.0 kPa for Unaged Blended Binders

Virgin Binder	Minimum %RAP Binder	
	70˚C	76˚C
PG 58-28	22%	45%
PG 64-22	12%	40%
PG 70-22	-	29%

All the RAP-virgin blended binders were subjected to short term aging using the rolling thin film oven (RTFO) test according to AASHTO T240, “Standard Method of Test for Effect of Heat and Air on a Moving Film of Asphalt Binder (Rolling Thin-Film Oven Test)”, which simulates aging during construction. In this test, a moving film of asphalt binder is created by pouring a specified amount of asphalt binder into a bottle, which is placed in a rack that rotates in the oven for 85 minutes at 163 ˚C while simultaneously blowing hot air into the bottles to oxidize the binder samples. These RTFO aged blended binder samples were then tested on the DSR to determine complex modulus (G*) and phase angle (δ) at different temperatures. Three replicates for each blended binder were tested. The average G*/sinδ values of the three replicates at different test temperatures obtained upon testing the RTFO aged blended binders are shown in Table 4.4.

Table 4.4 G*/sinδ Values of RTFO Aged RAP-Virgin Blended Binders

Blended Binder	Average G*/sinδ (kPa) at Test Temperature		
	64 ˚C	70 ˚C	76 ˚C
PG 58-28 + 25% RAP	9.22	4.49	2.23
PG 58-28 + 40% RAP	14.54	6.98	3.41
PG 64-22 + 25% RAP	9.44	4.21	1.94
PG 64-22 + 40% RAP	20.9	8.94	4.08
PG 70-22 + 25% RAP	15.47	7.2	3.52
PG 70-22 + 40% RAP	25.79	11.87	5.76
100% RAP	146.57	63.69	29.83

Similar to the unaged blended binders, blending charts for RTFO aged blended binders with varying percentages of RAP binder at different testing temperatures were developed to determine the minimum limits of recycled binder for S9.5C and S9.5D mixes. Figures 4.3 and 4.4 show the blending charts for RTFO aged RAP-Virgin binders. These blending charts were used to determine the minimum amount of RAP binder required to be added to the virgin binders to obtain a high temperature grade of 70 ˚C and 76 ˚C for the resulting blended binder. This was achieved by determining the minimum percentage of RAP binder required to be added to a virgin binder to satisfy the condition G*/sinδ ≥ 2.2 kPa at each temperature.

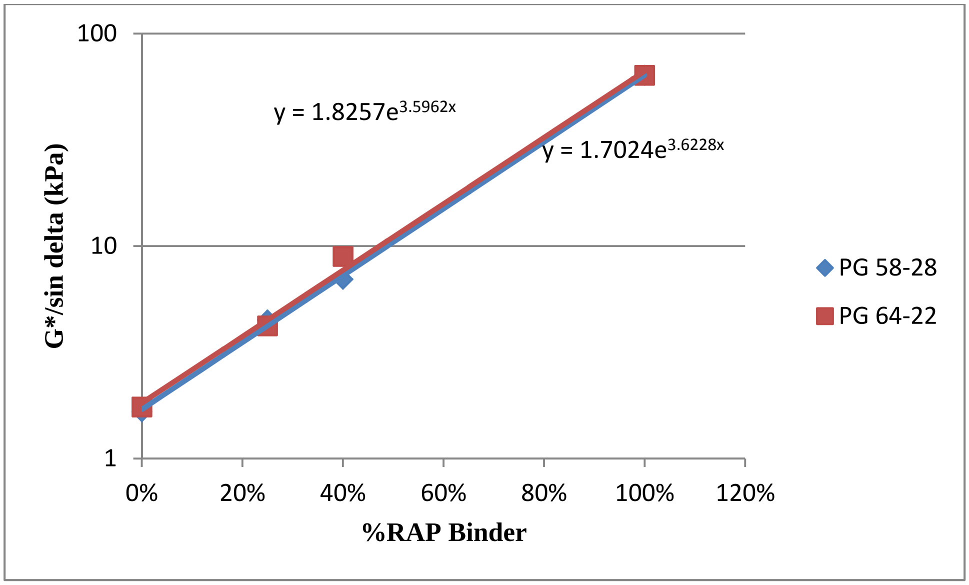


Figure 4.3 Blending Chart for RTFO Aged RAP-Virgin Blended Binders at 70 ˚C

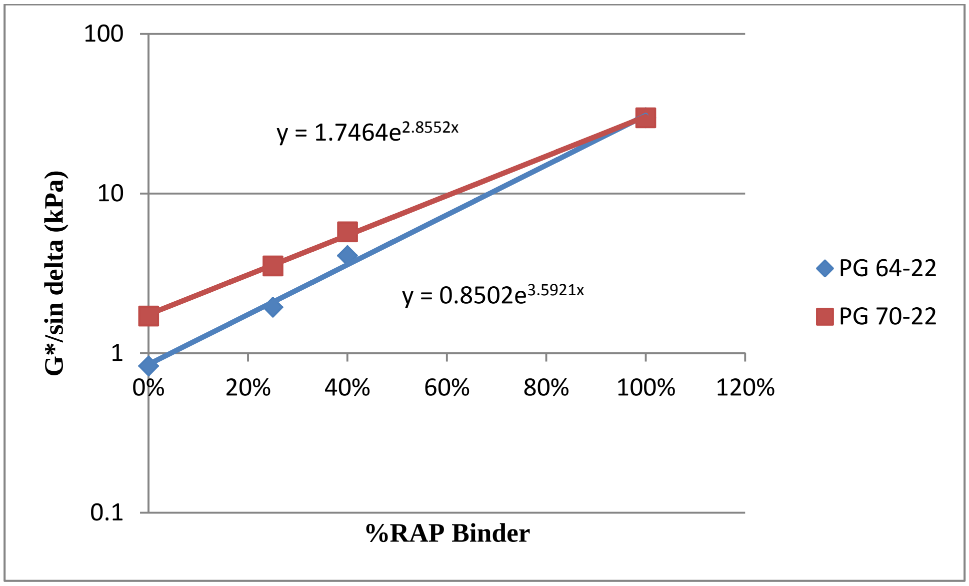


Figure 4.4 Blending Chart for RTFO Aged RAP-Virgin Blended Binders at 76 ˚C

The minimum limits of RAP binder required for each virgin binder are shown in Table 4.5. When PG 58-28 binder was blended with a minimum of 7% RAP binder the high temperature grade shifted from 58 ˚C to 70 ˚C. For PG 64-22 based blends, it can be observed that with a minimum of 5% RAP binder the high temperature grade of the blended binder shifted from 64 ˚C to 70 ˚C. It can also be noted that for a PG 64-22 virgin binder, a minimum of 27% RAP binder had to be added to have a high temperature grade of 76 ˚C. Similarly, for PG 70-22 virgin binder there is no need to add recycled binder to obtain high temperature grade of 70 ˚C. However, on blending the virgin binder PG 70-22 with a minimum of 8% RAP binder, the high temperature grade of the blended binder has shifted from 70 ˚C to 76 ˚C.

Table 4.5 Minimum Percentage of RAP Binder to Satisfy G*/sinδ = 2.20 kPa for RTFO Aged Blended Binders

Virgin Binder	Minimum %RAP Binder	
	70˚C	76˚C
PG 58-28	7%	27%
PG 64-22	5%	27%
PG 70-22	-	8%

The RTFO aged samples were subjected to long term aging using the pressure aging vessel (PAV) according to AASHTO R28, “Standard Practice for Accelerated Aging of Asphalt Binder Using a Pressurized Aging Vessel (PAV)”. In this test, thin film of RTFO aged asphalt samples are placed in a pressure vessel at a temperature of 100 ˚C for 20 hours under a pressure of 2070 kPa. This process simulates several years of exposure to the environment. PAV aged blended binder samples were then tested on the DSR to determine the rheological properties at different intermediate temperatures. Three replicates for each blended binder were tested. The average G*sinδ values of the three replicates at different test temperatures obtained upon testing the PAV aged blended binders are shown in Table 4.6. It can be observed that the stiffness of the blended binder increased with an increase in the proportion of RAP binder. This trend is similar to the one observed with unaged and RTFO aged blended binders. Increase in G*sinδ values indicates that the fatigue resistance of the asphalt blends may be affected by the addition of RAP binder.

Table 4.6 G*sinδ Values of PAV Aged RAP-Virgin Blended Binders

Blended Binder	Average G*sinδ (kPa) at Test Temperature			
	31˚C	28˚C	25˚C	22˚C
PG 58-28 + 25% RAP	-	2424	3373	4847
PG 58-28 + 40% RAP	-	3304	4495	6338
PG 64-22 + 25% RAP	2793	3752	5263	7373
PG 64-22 + 40% RAP	3824	4974	6793	9278
PG 70-22 + 25% RAP	2758	3974	5731	8183
PG 70-22 + 40% RAP	3537	4979	6987	9706

Similar to the unaged and RTFO blended binders, blending charts for PAV aged blended binders with varying percentages of RAP binder at different testing temperatures were developed to determine the maximum limits of RAP binder for S9.5C and S9.5D mixes. Figures 4.5 and 4.6 show the blending charts for PAV aged RAP-virgin blended binders.

These blending charts were used to determine the maximum amount of RAP binder that can be added to the virgin binders to obtain an intermediate temperature grade of 28 ˚C and 31 ˚C for the resulting blended binder. This was achieved by determining the maximum percentage of recycled binder required to be added to a virgin binder to satisfy the condition G*sinδ ≤ 5000 kPa at each temperature.

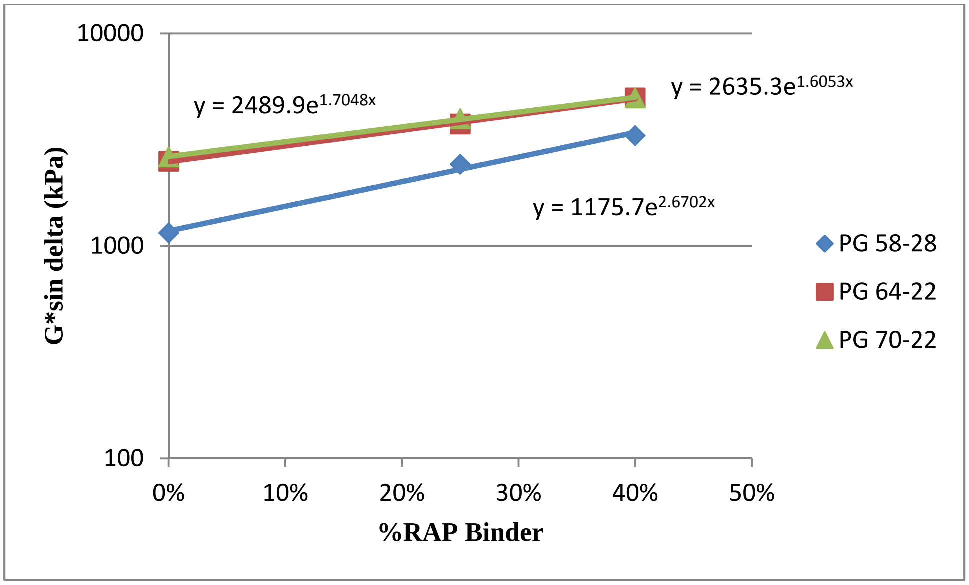


Figure 4.5 Blending Chart for PAV Aged RAP-Virgin Blended Binders at 28 ˚C

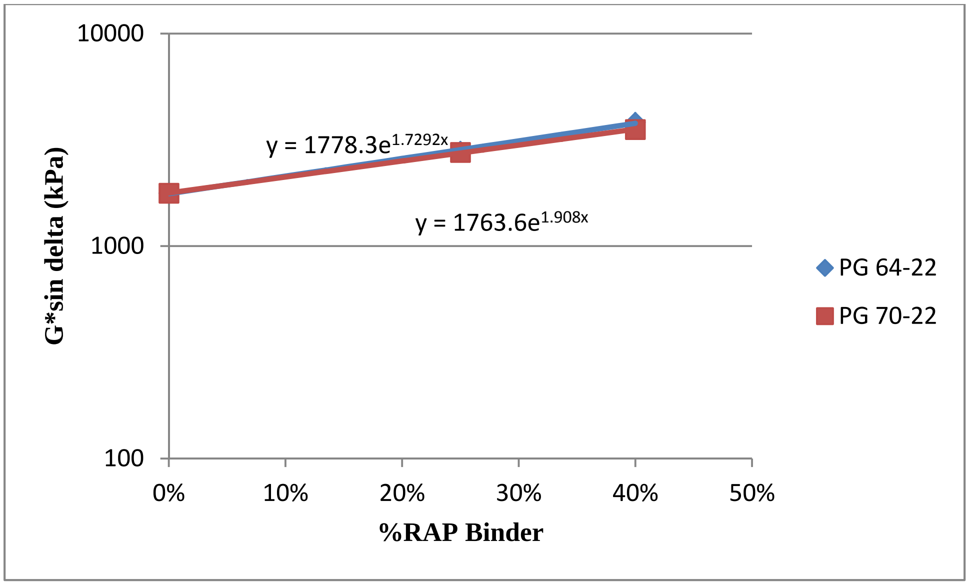


Figure 4.6 Blending Chart for PAV Aged RAP-Virgin Blended Binders at 31 ˚C

The maximum limits of RAP binder required for each virgin binder are shown in Table 4.7. For PG 70-22 based blends, the maximum limits for RAP binder to satisfy G*Sinδ ≤ 5000 kPa criteria at 28 ˚C and 31˚C are approximately 40% and 60%, respectively. Similarly, for PG 64-22 based blends the maximum RAP binder limits to satisfy G*Sinδ ≤ 5000 kPa criteria at 28˚C and 31˚C are about 40% and 55%, respectively. It can be noted that there is not much difference between PG 70-22 and PG 64-22 binders with respect to maximum limit of RAP binder. The maximum RAP binder limit for PG 58-28 binder is 54% at 28˚C.

Table 4.7 Maximum Percentage of RAP Binder to Satisfy G*sinδ = 5000 kPa for PAV Aged Blended Binders

Virgin Binder	Maximum %RAP Binder	
	28˚C	31˚C
PG 58-28	54%	-
PG 64-22	41%	55%
PG 70-22	40%	60%

4.2 PRAS Binder Limits

Asphalt binder from post-consumer recycled asphalt shingles (PRAS) was extracted according to AASHTO T319, "Quantitative Extraction and Recovery of Asphalt Binder from Hot Mix Asphalt". Virgin binders were blended with varying percentages of extracted PRAS binder as shown in Table 4.8. The percentage represents the proportion of extracted binder by weight of total blended binder. Mixing of virgin and PRAS binders was done using a mechanical blender and a hot plate.

Table 4.8 PRAS-Virgin Binder Blend Matrix

Virgin Binder	% PRAS Binder
PG 58-28	10%, 25%
PG 64-22	10%, 25%
PG 70-22	10%, 25%

The unaged PRAS-virgin blended binders were tested on the dynamic shear rheometer (DSR) to determine the complex shear modulus (G*) and phase angle (δ) at different high test temperatures. Three replicates for each blended binder were tested. The average G*/sinδ values of the three replicates at different test temperatures obtained upon testing the unaged blended binders is shown in Table 4.9. PRAS extracted binders could not be tested on DSR as the critical high temperature of RAS binders is beyond the capacity of the laboratory DSR. It can be observed that the G*/sinδ values increased with an increase in the proportion of PRAS binder at a given temperature, which indicates better resistance of the resulting binder blends to rutting**.** This is as expected because PRAS binder is much stiffer as it is air blown asphalt which has undergone additional aging during its service life on roof tops.

Table 4.9 G*/sinδ Values of Unaged PRAS-Virgin Blended Binders

Blended Binder	Average G*/sinδ (kPa) at Test Temperature		
	64 ˚C	70 ˚C	76 ˚C
PG 58-28 + 10% PRAS	4.22	2.08	1.02
PG 58-28 + 25% PRAS	12.24	6.08	3.08
PG 64-22 + 10% PRAS	3.39	1.56	0.75
PG 64-22 + 25% PRAS	22.9	10.35	4.87
PG 70-22 + 10% PRAS	5.67	2.61	1.33
PG 70-22 + 25% PRAS	25.44	12.24	6.17

Blending charts were developed based on test parameters obtained from the DSR to determine the limits for allowable PRAS binder that can be added to a virgin binder to meet the required Superpave binder specifications to satisfy PG 70-22 and PG 76-22 criteria. Blending charts for unaged blended binders with varying percentages of PRAS binder at different testing temperatures are shown in Figures 4.7 and 4.8. These blending charts were used to determine the minimum amount of PRAS binder required to be added to the virgin binders to obtain a blended binder with a high temperature grade of 70 ˚C and 76 ˚C. This was achieved by determining the minimum percentage of PRAS binder required to be added to a virgin binder to satisfy the condition G*/sinδ ≥ 1 kPa at each temperature.

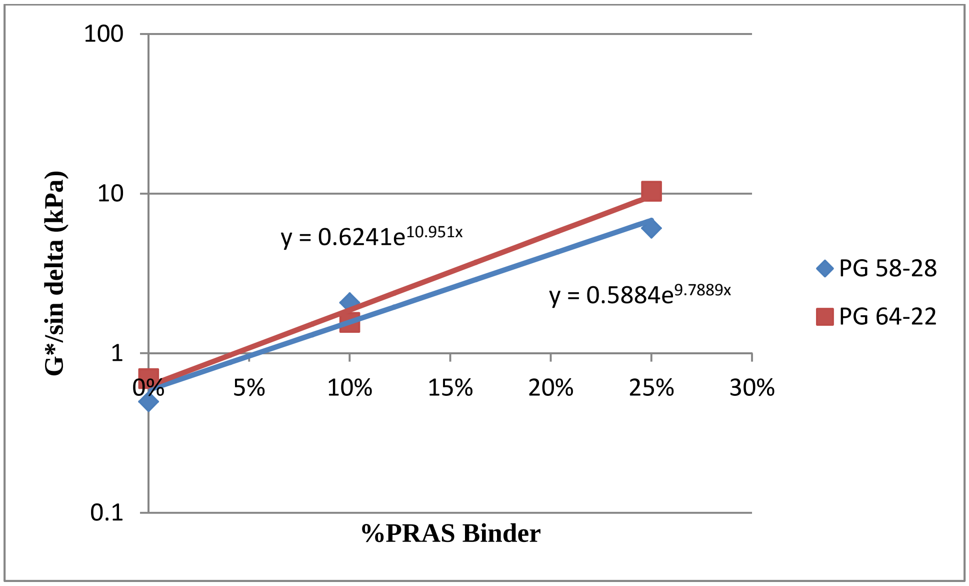


Figure 4.7 Blending Chart for Unaged PRAS-Virgin Blended Binders at 70 ˚C

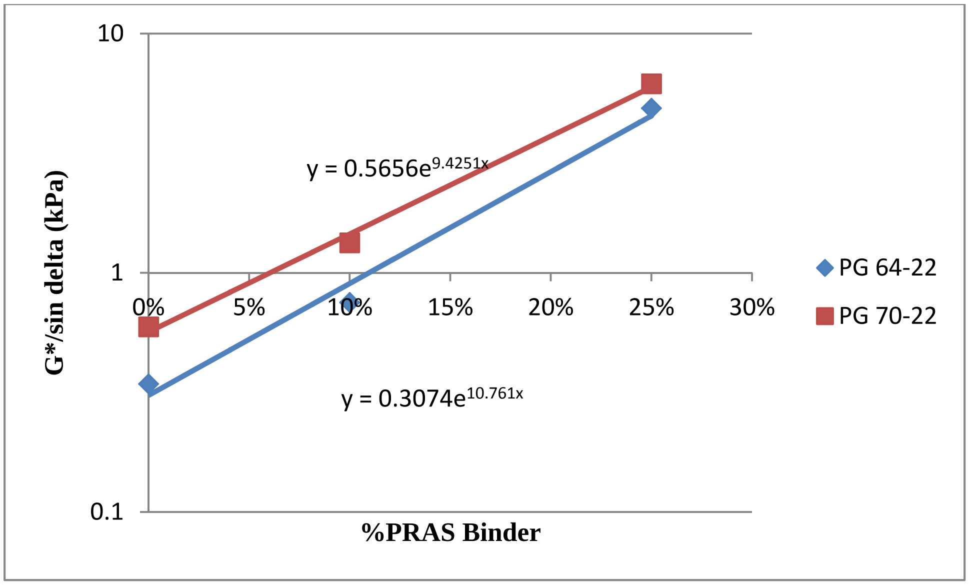


Figure 4.8 Blending Chart for Unaged PRAS-Virgin Blended Binders at 76 ˚C

The minimum limits of PRAS binder required for each virgin binder are shown in Table 4.10. PG 58-28 binder when blended with a minimum of 5% PRAS binder the high temperature grade shifted from 58 ˚C to 70 ˚C. For PG 64-22 based blends, it can be observed that with a minimum of 4% PRAS binder the high temperature grade of the blended binder has shifted from 64 ˚C to 70 ˚C. It can also be noted that for a PG 64-22 virgin binder, a minimum of 11% PRAS binder had to be added to obtain a high temperature grade of 76 ˚C. Similarly, for PG 70-22 virgin binder there is no need to add PRAS binder to obtain high temperature grade of 70 ˚C. However, on blending the virgin binder PG 70-22 with a minimum of 6% PRAS binder the high temperature grade of the blended binder has increased from 70 ˚C to 76 ˚C.

Table 4.10 Minimum Percentage of PRAS Binder to Satisfy G*/sinδ = 1.0 kPa for Unaged Blended Binders

Virgin Binder	Minimum %PRAS Binder	
	70˚C	76˚C
PG 58-28	5%	12%
PG 64-22	4%	11%
PG 70-22	-	6%

Similar to RAP blends, all the PRAS-virgin blended binders were subjected to short term aging using the rolling thin film oven (RTFO) to simulate aging during construction. RTFO aged blended binder samples were then tested on the DSR to determine complex modulus (G*) and phase angle (δ) at different temperatures. Three replicates for each blended binder were tested. The average G*/sinδ values of the three replicates at different test temperatures obtained upon testing the RTFO aged blended binders are shown in Table 4.11.

Table 4.11 G*/sinδ Values of RTFO Aged PRAS-Virgin Blended Binders

Blended Binder	Average G*/sinδ (kPa) at Test Temperature		
	64 ˚C	70 ˚C	76 ˚C
PG 58-28 + 10% PRAS	8.72	4.32	2.18
PG 58-28 + 25% PRAS	32.68	16.41	8.55
PG 64-22 + 10% PRAS	17.78	7.79	3.6
PG 64-22 + 25% PRAS	-	23.47	10.86
PG 70-22 + 10% PRAS	-	7.49	3.72
PG 70-22 + 25% PRAS	-	-	14.88

Similar to the unaged blended binders, blending charts for RTFO aged blended binders with varying percentages of PRAS binder at different testing temperatures were developed to determine the minimum limits of recycled binder for S9.5C and S9.5D mixes. Figures 4.9 and 4.10 show blending charts for RTFO aged PRAS-virgin binders. These blending charts were used to determine the minimum amount of PRAS binder required to be added to the virgin binders to obtain a high temperature grade of 70 ˚C and 76 ˚C for the resulting blended binder. This was achieved by determining the minimum percentage of PRAS binder required to be added to a virgin binder to satisfy the condition G*/sinδ ≥ 2.2 kPa at each temperature.

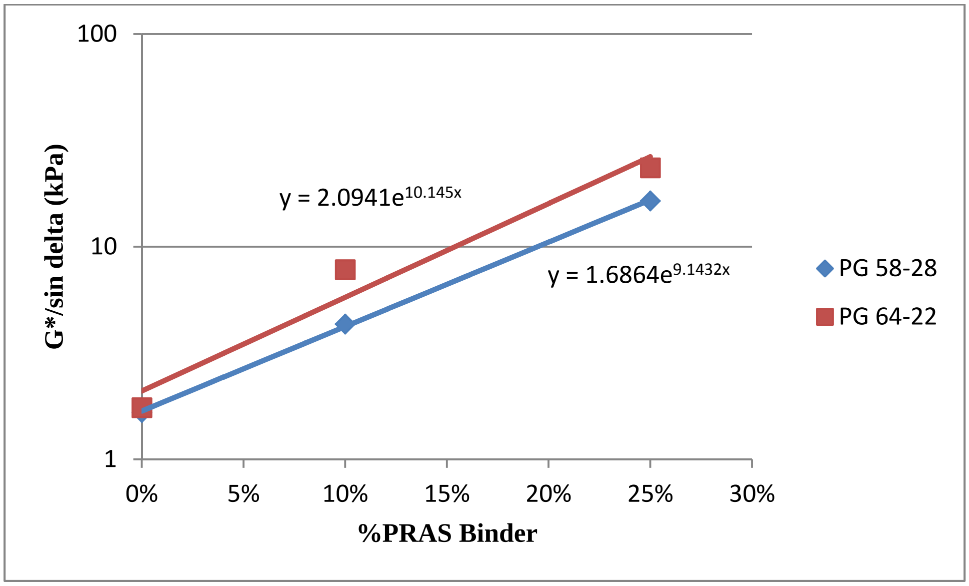


Figure 4.9 Blending Chart for RTFO Aged PRAS-Virgin Blended Binders at 70 ˚C

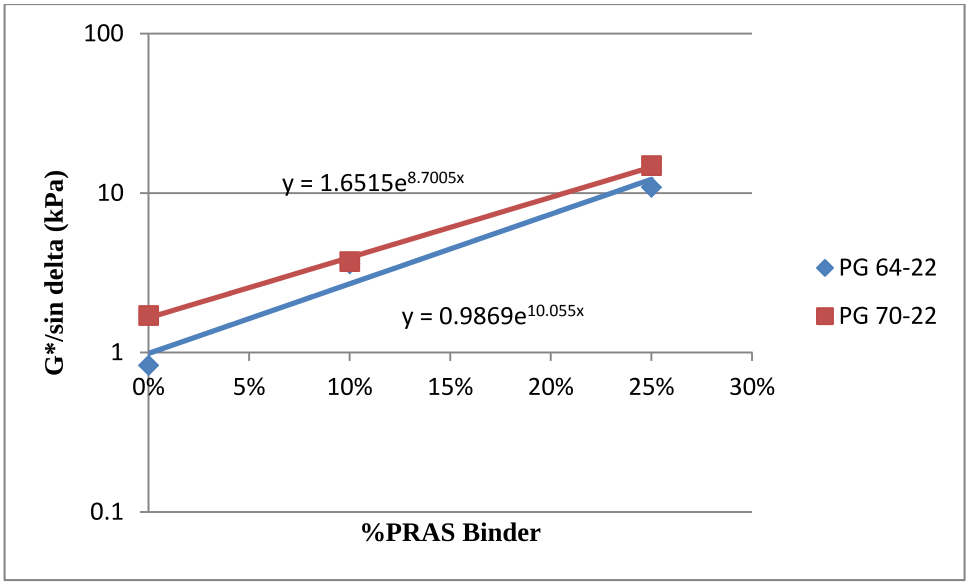


Figure 4.10 Blending Chart for RTFO Aged PRAS-Virgin Blended Binders at 76 ˚C

The minimum limits of PRAS binder required for each virgin binder are shown in Table 4.12 PG 58-28 binder when blended with a minimum of 3% PRAS binder the high temperature grade shifted from 58 ˚C to 70 ˚C. For PG 64-22 based blends, it can be observed that with a minimum of 1% PRAS binder the high temperature grade of the blended binder has shifted from 64 ˚C to 70 ˚C. It can also be noted that for a PG 64-22 virgin binder to qualify for a high temperature grade of 76 ˚C a minimum of 8% PRAS binder had to be added. Similarly, on blending the virgin binder PG 70-22 with a minimum of 3% PRAS binder, the high temperature grade of the blended binder has increased from 70 ˚C to 76 ˚C.

Table 4.12 Minimum Percentage of PRAS Binder to Satisfy G*/sinδ = 2.20 kPa for RTFO Aged Blended Binders

Virgin Binder	Minimum %PRAS Binder	
	70 ˚C	76 ˚C
PG 58-28	3%	10%
PG 64-22	1%	8%
PG 70-22	-	3%

The RTFO aged PRAS-Virgin binder samples were subjected to long term aging using the pressure aging vessel (PAV). PAV aged blended binder samples were then tested on the DSR to determine the rheological properties, complex modulus (G*) and phase angle (δ) at different intermediate temperatures. Three replicates for each blended binder were tested. The average G*sinδ values of the three replicates at different test temperatures obtained upon testing the PAV aged blended binders are shown in Table 4.13. It can be observed that the stiffness of the blended binder increased with an increase in the proportion of PRAS binder. This trend is similar to the one observed with unaged and RTFO aged blended binders. Increase in G*sinδ values indicates that the fatigue resistance of the asphalt blends may be affected by the addition of PRAS binder.

Table 4.13 G*sinδ Values of PAV Aged PRAS-Virgin Blended Binders

Blended Binder	Average G*sinδ (kPa) at Test Temperature			
	31 ˚C	28 ˚C	25 ˚C	22 ˚C
PG 58-28 + 10% PRAS	-	1912	2666	3833
PG 58-28 + 25% PRAS	-	3481	4578	6233
PG 64-22 + 10% PRAS	2791	3724	5171	7159
PG 64-22 + 25% PRAS	4246	5233	6862	9015
PG 70-22 + 10% PRAS	2306	3316	4792	6883
PG 70-22 + 25% PRAS	4499	6048	8147	10903

Similar to the unaged and RTFO blended binders, blending charts for PAV aged blended binders with varying percentages of PRAS binder at different testing temperatures were developed to determine the maximum limits of PRAS binder for S9.5C and S9.5D mixes. Figures 4.11 and 4.12 show the blending charts for PAV aged blends. These blending charts were used to determine the maximum amount of PRAS binder that can be added to the virgin binders to obtain an intermediate temperature grade of 28 ˚C and 31 ˚C for the resulting blended binder. This was achieved by determining the maximum percentage of PRAS binder required to be added to a virgin binder to satisfy the condition G*sinδ ≤ 5000 kPa at each temperature.

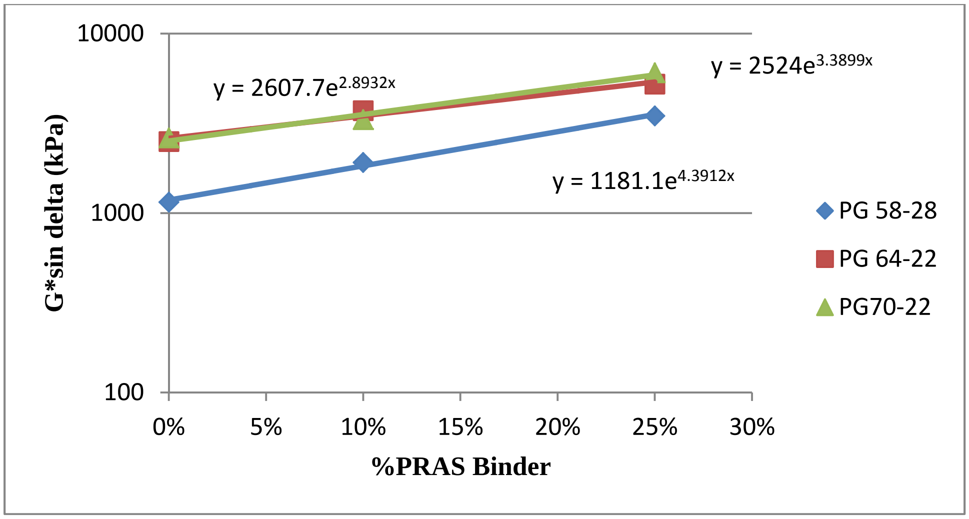


Figure 4.11 Blending Chart for PAV Aged PRAS-Virgin Blended Binders at 28 ˚C

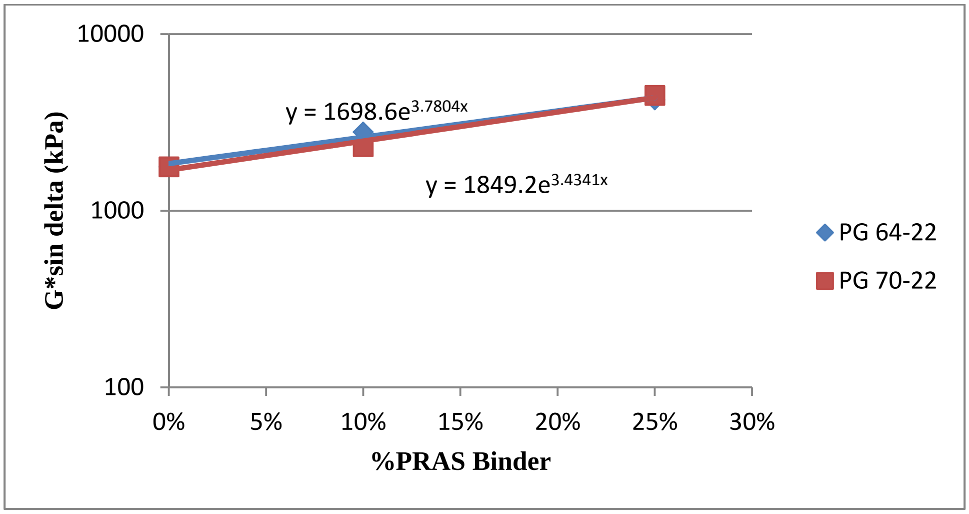


Figure 4.12 Blending Chart for PAV Aged PRAS-Virgin Blended Binders at 31 ˚C

The maximum limits of PRAS binder required for each virgin binder are shown in Table 4.14. For PG 70-22 based blends, the maximum limits for PRAS binder to satisfy G*sinδ ≤ 5000 kPa criteria at 28˚C and 31˚C are approximately 20% and 30%, respectively. Similarly, for PG 64-22 blends the maximum PRAS binder limits to satisfy G*sinδ ≤ 5000 kPa criteria at 28˚C and 31˚C are about 23% and 29%, respectively. It can be noted that there is not much difference between PG 70-22 and PG 64-22 binders with respect to maximum limit of PRAS binder. The maximum PRAS binder limit for PG 58-28 binder was 33% at 28˚C.

Table 4.14 Maximum Percentage of PRAS Binder to Satisfy G*sinδ = 5000 kPa for PAV Aged Blended Binders

Virgin Binder	Maximum %PRAS Binder	
	28 ˚C	31 ˚C
PG 58-28	33%	-
PG 64-22	23%	29%
PG 70-22	20%	29%

4.3 MRAS Binder Limits

Asphalt binder from manufacturer waste recycled asphalt shingles (MRAS) was extracted according to AASHTO T319 “Quantitative Extraction and Recovery of Asphalt Binder from Hot Mix Asphalt”. Virgin binders were blended with varying percentages of extracted MRAS binder as shown in Table 4.15. The percentage represents the proportion of extracted binder by weight of total blended binder. Mixing of virgin and MRAS binders was done using a mechanical blender and hot plate.

Table 4.15 MRAS-Virgin Binder Blend Matrix

Virgin Binder	% MRAS Binder
PG 58-28	10%, 20%
PG 64-22	10%, 20%
PG 70-22	10%, 20%

The unaged MRAS-virgin blended binders were tested on the dynamic shear rheometer (DSR) to determine the complex shear modulus (G*) and phase angle (δ) at different high test temperatures. Three replicates for each blended binder were tested. The average G*/sinδ values of the three replicates at different test temperatures obtained upon testing the unaged blended binders is shown in Table 4.16. MRAS extracted binders could not be tested on DSR as the critical high temperature of MRAS binders was beyond the capacity of the laboratory DSR. It can be observed that the G*/sinδ values increased with an increase in the proportion of MRAS binder at a given temperature, which indicates better resistance of the resulting binder blends to rutting**.**

Table 4.16 G*/sinδ Values of Unaged MRAS-Virgin Blended Binders

Blended Binder	Average G*/sinδ (kPa) at Test Temperature		
	64 ˚C	70 ˚C	76 ˚C
PG 58-28 + 10% MRAS	1.39	0.7	0.34
PG 58-28 + 20% MRAS	1.75	0.89	0.44
PG 64-22 + 10% MRAS	1.91	0.88	0.44
PG 64-22 + 20% MRAS	2.45	1.13	0.57
PG 70-22 + 10% MRAS	-	1.58	0.8
PG 70-22 + 20% MRAS	-	2.12	1.09

Blending charts were developed based on test parameters obtained from the DSR to determine the limits for allowable MRAS binder that can be added to a virgin binder to meet the required Superpave binder specifications to satisfy PG 70-22 and PG 76-22 criteria. Blending charts for unaged blended binders with varying percentages of MRAS binder at different testing temperatures are shown in Figures 4.13 and 4.14. These blending charts were used to determine the minimum amount of MRAS binder required to be added to the virgin binders to result in a blended binder with a high temperature grade of 70 ˚C and 76 ˚C. This was achieved by determining the minimum percentage of MRAS binder required to be added to a virgin binder to satisfy the condition G*/sinδ ≥ 1 kPa at each temperature.

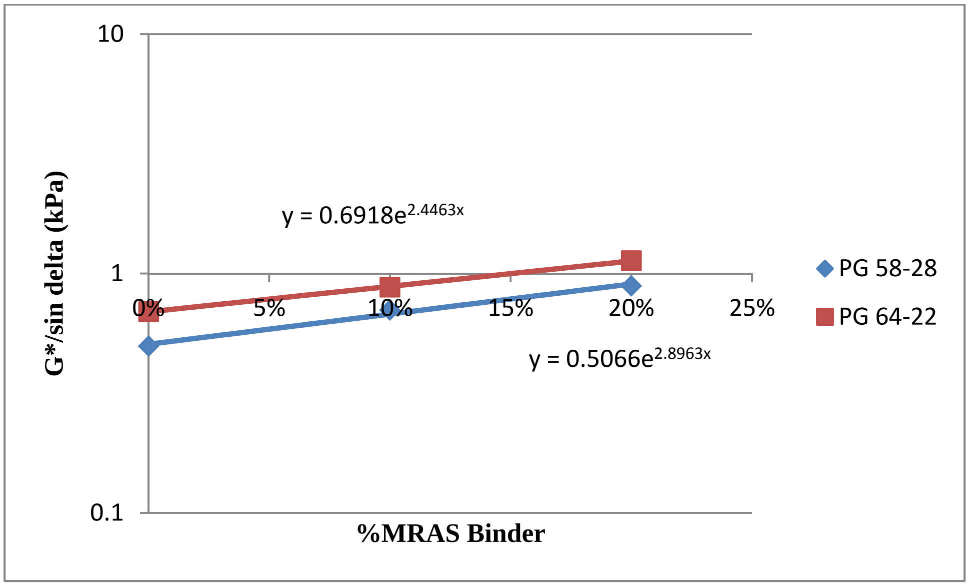


Figure 4.13 Blending Chart for Unaged MRAS-Virgin Blended Binders at 70 ˚C

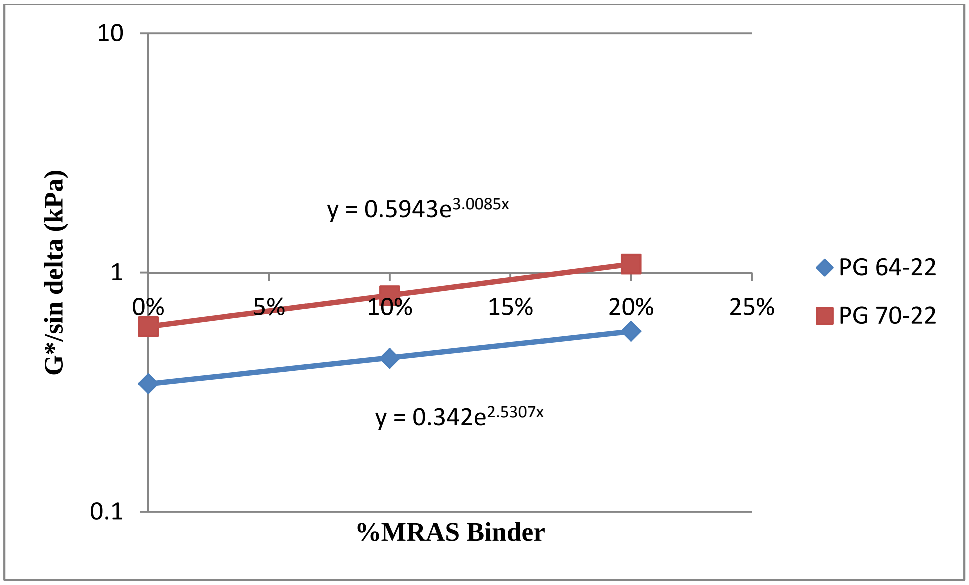


Figure 4.14 Blending Chart for Unaged MRAS-Virgin Blended Binders at 76 ˚C

The minimum limits of MRAS binder required for each virgin binder are shown in Table 4.17. When PG 58-28 binder was blended with a minimum of 24% MRAS binder the high temperature grade shifted from 58 ˚C to 70 ˚C. For PG 64-22 based blends, it can be observed that with a minimum of 15% MRAS binder, the high temperature grade of the blended binder has shifted from 64 ˚C to 70 ˚C. It can also be noted that for PG 64-22 virgin binder, a minimum of 42% MRAS binder had to be added to obtain a high temperature grade of 76 ˚C. Similarly, on blending the virgin binder PG 70-22 with a minimum of 17% MRAS binder the high temperature grade of the blended binder has shifted from 70 ˚C to 76 ˚C.

Table 4.17 Minimum Percentage of MRAS Binder to Satisfy G*/sinδ = 1.0 kPa for Unaged Blended Binders

Virgin Binder	Minimum %MRAS Binder	
	70 ˚C	76 ˚C
PG 58-28	24%	53%
PG 64-22	15%	42%
PG 70-22	-	17%

Similar to RAP and PRAS blends, all the MRAS-virgin binder blends were subjected to short term aging using the rolling thin film oven (RTFO) test, to simulate aging during construction. RTFO aged blended binder samples were then tested on the DSR to determine the rheological properties, complex modulus (G*) and phase angle (δ) at different temperatures. Three replicates for each blended binder were tested. The average G*/sinδ of three replicates at different test temperatures obtained upon testing the RTFO aged blended binders are shown in Table 4.18.

Table 4.18 G*/sinδ Values of RTFO Aged MRAS-Virgin Blended Binders

Blended Binder	Average G*/sinδ (kPa) at Test Temperature		
	64 ˚C	70 ˚C	76 ˚C
PG 58-28 + 10% MRAS	4.41	2.2	1.06
PG 58-28 + 20% MRAS	7.86	3.91	1.9
PG 64-22 + 10% MRAS	7.61	3.33	1.56
PG 64-22 + 20% MRAS	12.11	5.38	2.54
PG 70-22 + 10% MRAS	10.69	5.14	2.54
PG 70-22 + 20% MRAS	15.97	8.05	3.99

Similar to the unaged blended binders, blending charts for RTFO aged blended binders with varying percentages of MRAS binder at different testing temperatures were developed to determine the minimum limits of recycled binder for S9.5C and S9.5D mixes. Figures 4.15 and 4.16 show blending charts for RTFO aged MRAS-Virgin binders. These blending charts were used to determine the minimum amount of MRAS binder required to be added to the virgin binders to obtain a high temperature grade of 70 ˚C and 76 ˚C for the resulting blended binder. This was achieved by determining the minimum percentage of MRAS binder required to be added to a virgin binder to satisfy the condition G*/sinδ ≥ 2.2 kPa at each temperature.

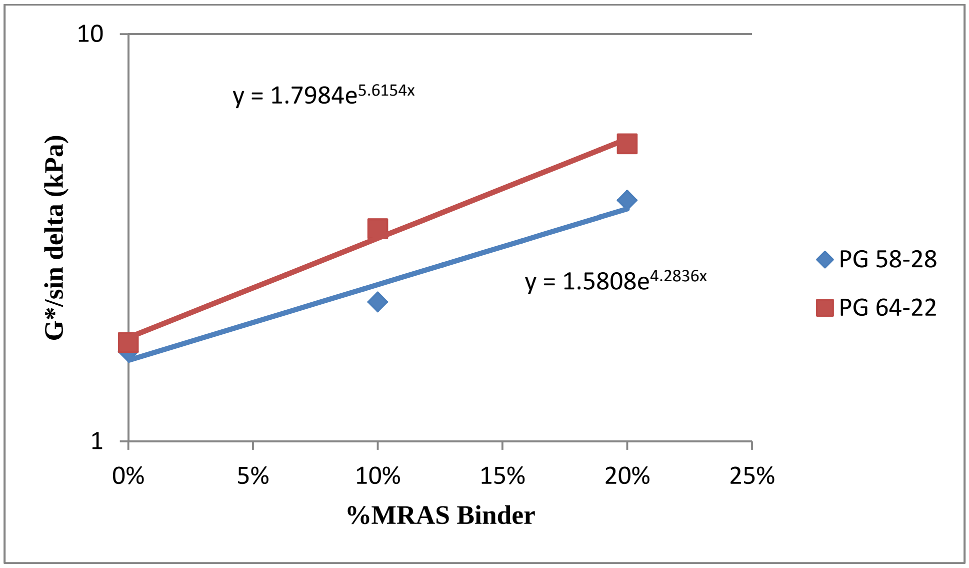


Figure 4.15 Blending Chart for RTFO Aged MRAS-Virgin Blended Binders at 70 ˚C

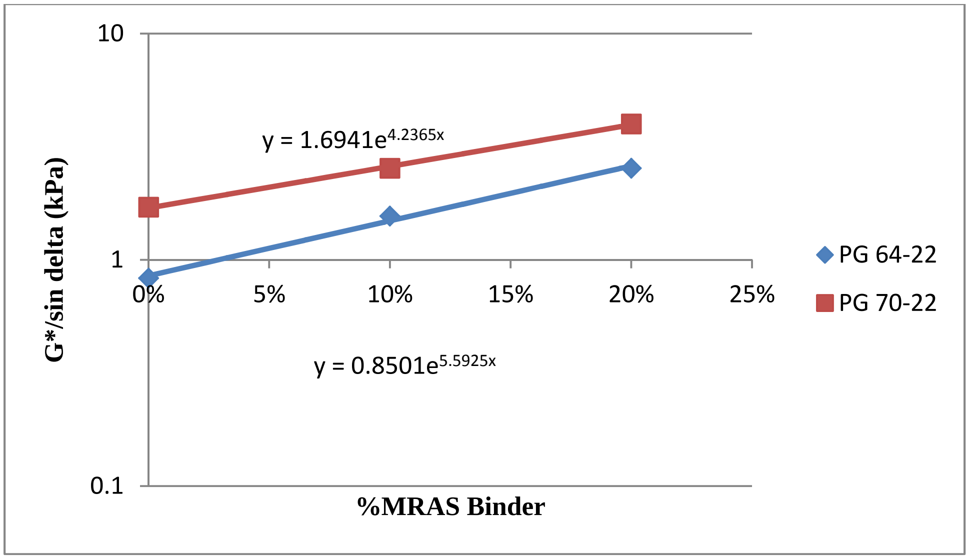


Figure 4.16 Blending Chart for RTFO Aged MRAS-Virgin Blended Binders at 76 ˚C

The minimum limits of MRAS binder required for each virgin binder are shown in Table 4.19. When PG 58-28 binder was blended with a minimum of 8% MRAS binder the high temperature grade shifted from 58 ˚C to 70 ˚C. For PG 64-22 based blends, it can be observed that with a minimum of 4% MRAS binder the high temperature grade of the blended binder has shifted from 64 ˚C to 70 ˚C. It can also be noted that for a PG 64-22 virgin binder, a minimum of 17% MRAS binder had to be added to have a high temperature grade of 76 ˚C. Similarly, for PG 70-22 virgin binder there is no need to add recycled binder to obtain high temperature grade of 70 ˚C. However, on blending the virgin binder PG 70-22 with a minimum of 6% MRAS binder, the high temperature grade of the blended binder has shifted from 70 ˚C to 76 ˚C.

Table 4.19 Minimum Percentage of MRAS Binder to Satisfy G*/sinδ = 2.20 kPa for RTFO Aged Blended Binders

Virgin Binder	Minimum %MRAS Binder	
	70 ˚C	76 ˚C
PG 58-28	8%	25%
PG 64-22	4%	17%
PG 70-22	-	6%

The RTFO aged MRAS-virgin binder samples were subjected to long term aging using the pressure aging vessel (PAV). PAV aged blended binder samples were then tested on the DSR to determine the rheological properties at different intermediate temperatures. Three replicates for each blended binder were tested. The average G*sinδ values of the three replicates at different test temperatures obtained upon testing the PAV aged blended binders are shown in Table 4.20. It can be observed that the stiffness of the blended binder increased with an increase in the proportion of MRAS binder. This trend is similar to the one observed with unaged and RTFO aged blended binders. Increase in G*sinδ values indicates that the fatigue resistance of the asphalt blends may be affected by the addition of MRAS binder.

Table 4.20 G*sinδ Values of PAV Aged MRAS-Virgin Blended Binders

Blended Binder	Average G*sinδ (kPa) at Test Temperature			
	31 ˚C	28 ˚C	25 ˚C	22 ˚C
PG 58-28 + 10% MRAS	-	1369	1953	2858
PG 58-28 + 20% MRAS	-	1791	2481	3537
PG 64-22 + 10% MRAS	2106	2875	4068	5734
PG 64-22 + 20% MRAS	2309	3063	4241	5893
PG 70-22 + 10% MRAS	1887	2741	3995	5799
PG 70-22 + 20% MRAS	2102	2982	4247	6003

Similar to the unaged and RTFO blended binders, blending charts for PAV aged blended binders with varying percentages of MRAS binder at different testing temperatures were developed to determine the maximum limits of MRAS binder for S9.5C and S9.5D mixes. Figures 4.17 and 4.18 show blending charts for PAV aged blends. These blending charts were used to determine the maximum amount of MRAS binder that can be added to the virgin binders to obtain an intermediate temperature grade of 28 ˚C and 31 ˚C for the resulting blended binder. This was achieved by determining the percentage of MRAS binder required to be added to a virgin binder to satisfy the condition G*sinδ ≤ 5000 kPa at each temperature.

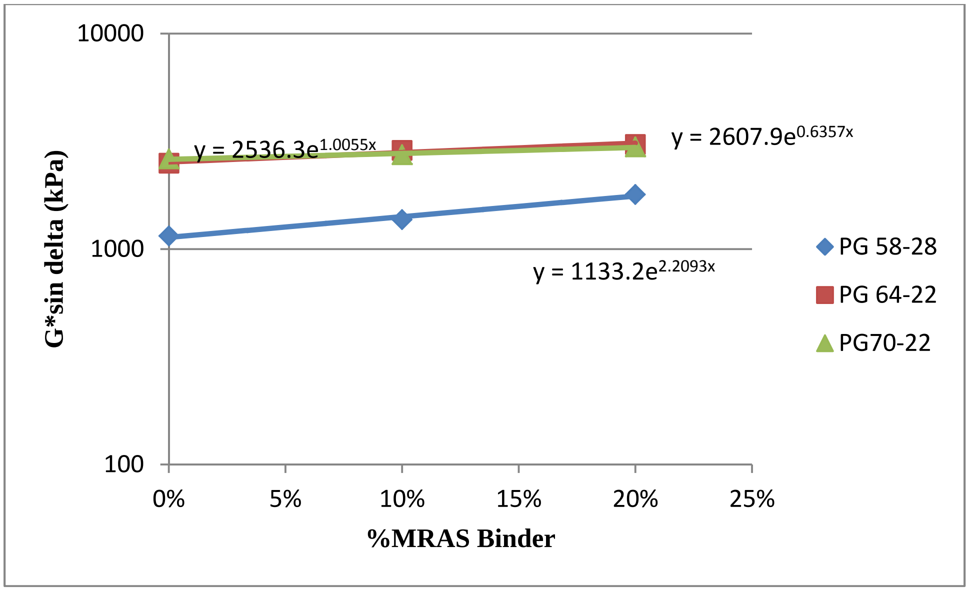


Figure 4.17 Blending Chart for PAV Aged MRAS-Virgin Blended Binders at 28 ˚C

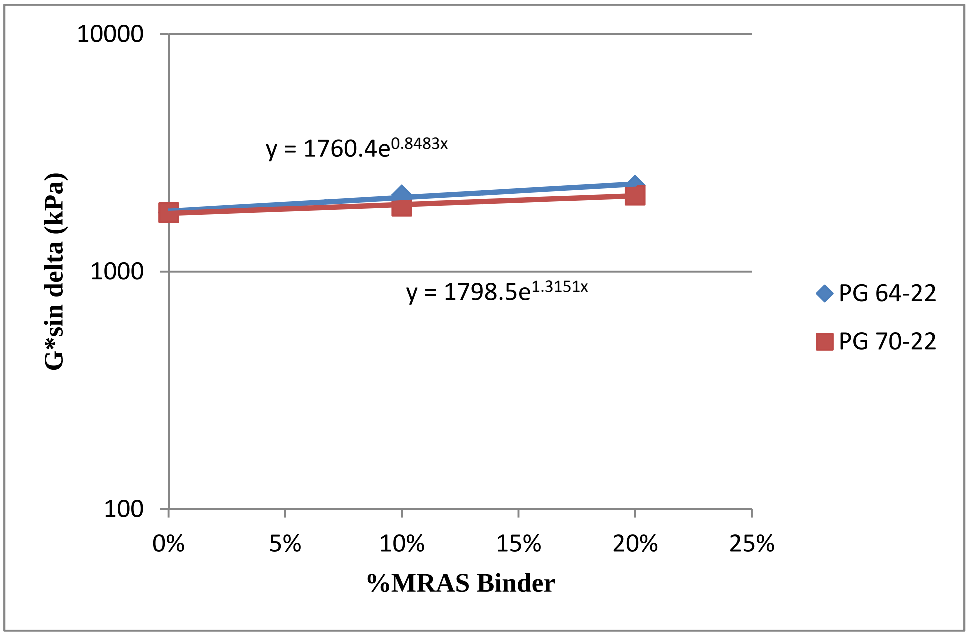


Figure 4.18 Blending Chart for PAV Aged MRAS-Virgin Blended Binders at 31 ˚C

The maximum limits of MRAS binder required for each virgin binder are shown in Table 4.21. For PG 70-22 binder based blends, no maximum limit could be established based on the regression to satisfy G*sinδ ≤ 5000 kPa criteria at 28 ˚C and 31 ˚C. For PG 64-22 binder based blends the maximum MRAS binder limits to satisfy G*sinδ ≤ 5000 kPa criteria at 28 ˚C and 31 ˚C were about 68% and 78%, respectively. The maximum MRAS binder limit for PG 58-28 binder was 67% at 28 ˚C.

Table 4.21 Maximum Percentage of MRAS Binder to Satisfy G*sinδ = 5000 kPa for PAV Aged Blended Binders

Virgin Binder	Maximum %MRAS Binder	
	28 ˚C	31 ˚C
PG 58-28	67%	-
PG 64-22	68%	78%
PG 70-22	NL**	NL**

** No maximum limit could be established based on the regression.

4.4 MRAS-RAP Binder Limits

Virgin binders were blended with both RAP and MRAS binders in different proportions as shown in Table 4.22. The percentage represents the proportion of recycled binder by weight of total blended binder. The blend proportions were chosen based on the individual recycled binder limits. Mixing of virgin, RAP and MRAS binders was done using a mechanical blender and hot plate. The unaged MRAS-RAP-virgin blended binders were tested on the dynamic shear rheometer (DSR) to determine the complex shear modulus (G*) and phase angle (δ) at different test temperatures. Three replicates for each blended binder were tested.

The average G*/sinδ values of three replicates at different test temperatures obtained upon testing the unaged blended binders are shown in Table 4.23.

Table 4.22 MRAS-RAP-Virgin Binder Blend Matrix

Virgin Binder	% RAP Binder	%MRAS Binder
PG 58-28	10%	10%
	10%	20%
	20%	10%
	20%	20%
PG 64-22	10%	10%
	10%	20%
	20%	10%
	20%	20%

Table 4.23 G*/sinδ Values of Unaged MRAS-RAP-Virgin Blended Binders

Blended Binder	Average G*/sinδ (kPa) at Test Temperature			
	58 ˚C	64 ˚C	70 ˚C	76 ˚C
PG 58-28 + 10M +10R	4.588	2.116	1.002	-
PG 58-28 + 10M + 20R	7.329	3.482	1.66	0.821
PG 58-28 + 20M + 10R	8.774	4.124	1.963	0.964
PG 58-28 + 20M + 20R	11.289	5.35	2.583	1.279
PG 64-22 + 10M + 10R	-	4.368	2.112	1.046
PG 64-22 + 10M + 20R	-	6.035	2.92	1.445
PG 64-22 + 20M + 10R	-	6.74	3.331	1.677
PG 64-22 + 20M + 20R	-	9.282	4.597	2.301

Note: M-%MRAS binder, R-%RAP binder

Regression analysis was conducted and equations were developed based on test parameters obtained from the DSR to determine the limits for allowable MRAS and RAP binder that can be added to a virgin binder to meet the required Superpave binder specifications to satisfy PG 70-22 and PG 76-22 criteria. The regression equation/function selection criteria were set based on the coefficient of determination of overall models and p-values of the estimated parameters. The multiple linear regressions with/without interaction variables and nonlinear regression equations such as log transformations were considered during the selection. The following equations (1) and (2) represent regression models for PG 58-28 binder based unaged blends at 70 ˚C and 76 ˚C, respectively. Equations (3) and (4) represent regression models for PG 64-22 binder based unaged blends at 70 ˚C and 76 ˚C, respectively. These regression equations were used to determine the minimum amount of MRAS and RAP binder is required to be added to the virgin binders to obtain a high temperature grade of 70 ˚C and 76 ˚C for the resulting blended binder. This was achieved by determining the minimum percentage of MRAS and RAP binder required to be added to a virgin binder to satisfy the condition $G^*/\sin\delta \geq 1$ kPa at each temperature. The minimum limits of MRAS-RAP binder combinations required for each virgin binder are shown in Table 4.24.

$$\ln(G^*/\sin\delta) = -0.727+5.059(\%MRAS)+3.395(\%RAP) \quad (1)$$

$$\ln(G^*/\sin\delta) = -1.387+4.903(\%MRAS)+3.280(\%RAP) \quad (2)$$

$$\ln(G^*/\sin\delta) = -0.312+5.437(\%MRAS)+4.122(\%RAP) \quad (3)$$

$$\ln(G^*/\sin\delta) = -1.020+5.564(\%MRAS)+4.079(\%RAP) \quad (4)$$

Table 4.24 Minimum Percentages of MRAS and RAP Binder to Satisfy G*/sinδ = 1.0 kPa for Unaged Blended Binders

Virgin Binder	Minimum %Recycled Binder at 70 ˚C		Minimum %Recycled Binder at 76 ˚C	
	MRAS	RAP	MRAS	RAP
PG 58-28	10%	7%	10%	27%
	15%	0%	20%	12%
	8%	10%	22%	10%
	0%	20%	15%	20%
PG 64-22	5%	0%	10%	10%
	0%	8%	4%	20%

MRAS-RAP-virgin binder blends were subjected to short term aging using the rolling thin film oven (RTFO) test. RTFO aged blended binder samples were then tested on the DSR to determine the rheological properties, complex modulus (G*) and phase angle (δ) at different temperatures. Three replicates for each blended binder were tested. The average G*/sinδ values of the three replicates at different test temperatures obtained upon testing the RTFO aged blended binders are shown in Table 4.25.

Table 4.25 G*/sinδ Values of RTFO Aged MRAS-RAP-Virgin Blended Binders

Blended Binder	Average G*/sinδ (kPa) at Test Temperature			
	58˚C	64˚C	70˚C	76˚C
PG 58-28 + 10M + 10R	10.363	4.835	2.277	1.115
PG 58-28 + 10M + 20R	14.969	6.903	3.251	1.579
PG 58-28 + 20M + 10R	-	9.695	4.645	2.272
PG 58-28 + 20M + 20R	-	13.314	6.417	3.122
PG 64-22 + 10M +10R	-	9.261	4.354	2.105
PG 64-22 + 10M + 20R	-	14.72	6.938	3.346
PG 64-22 + 20M + 10R	-	15.227	7.298	3.545
PG 64-22 + 20M + 20R	-	24.648	11.926	5.775

Note: M-%MRAS binder, R-%RAP binder

Regression analysis was conducted and equations were developed based on test parameters obtained from the DSR to determine the limits for allowable MRAS and RAP binder that can be added to a virgin binder to meet the required Superpave binder specifications to satisfy PG 70-22 and PG 76-22 criteria. The following equations (5) and (6) represent regression models for PG 58-28 binder based RTFO aged blends at 70 ˚C and 76 ˚C, respectively. Equations (7) and (8) represent regression models for PG 64-22 binder based RTFO aged blends at 70 ˚C and 76 ˚C, respectively. These regression equations were used to determine the minimum amount of MRAS and RAP binder required to be added to the virgin binders to obtain a high temperature grade of 70 ˚C and 76 ˚C for the resulting blended binder in RTFO aged conditions. This was achieved by determining the percentage of MRAS and RAP binder required to be added to a virgin binder satisfy the condition G*/sinδ ≥ 2.2 kPa at each temperature. The minimum limits of MRAS-RAP binder combinations required for each virgin binder are shown in Table 4.26.

$$\ln(G^*/\sin\delta) = -0.205+6.964(\%MRAS)+3.397(\%RAP) \quad (5)$$

$$\ln(G^*/\sin\delta) = -0.913+6.967(\%MRAS)+3.329(\%RAP) \quad (6)$$

$$\ln(G^*/\sin\delta) = 0.542+5.024(\%MRAS)+4.518(\%RAP) \quad (7)$$

$$\ln(G^*/\sin\delta) = -0.201+5.115(\%MRAS)+4.535(\%RAP) \quad (8)$$

Table 4.26 Minimum Percentages of MRAS and RAP Binder to Satisfy G*/sinδ = 2.20 kPa for RTFO Aged Blended Binders

Virgin Binder	Minimum %Recycled Binder at 70 ˚C		Minimum %Recycled Binder at 76 ˚C	
	MRAS	RAP	MRAS	RAP
PG 58-28	5%	20%	10%	30%
	10%	10%	15%	20%
	15%	0%	20%	10%
PG 64-22	5%	0%	10%	10%
	0%	6%	20%	0%

The RTFO aged MRAS-RAP-virgin binder samples were subjected to long term aging using the pressure aging vessel (PAV). PAV aged blended binder samples were then tested on DSR to determine complex modulus (G*) and phase angle (δ) at different intermediate temperatures. Three replicates for each blended binder were tested. The average G*sinδ values of three replicates at different test temperatures obtained upon testing the PAV aged blended binders are shown in Table 4.27.

Table 4.27 G*sinδ Values of PAV Aged MRAS-RAP-Virgin Blended Binders

Blended Binder	Average G*sinδ (kPa) at Test Temperature			
	31˚C	28˚C	25˚C	22˚C
PG 58-28 + 10M +10R	956.45	1408.25	2063.61	3018.21
PG 58-28 + 10M + 20R	1339.51	1939.96	2785.95	3989.21
PG 58-28 + 20M + 10R	1307.09	1853.95	2622.85	3683.57
PG 58-28 + 20M + 20R	1666.89	2422.28	3418.00	4742.43
PG 64-22 + 10M +10R	1735.53	2524.7	3664.18	5234.14
PG 64-22 + 10M + 20R	2285.45	3217.69	4510.94	6238.66
PG 64-22 + 20M + 10R	2129.72	2972.09	4142.83	5667.48
PG 64-22 + 20M + 20R	2602.11	3581.08	4889.96	6446.35

Note: M-%MRAS binder, R-%RAP binder

Regression analysis was conducted and equations were developed based on test parameters obtained from the DSR to determine the limits for allowable MRAS and RAP binder that can be added to a virgin binder to meet the required Superpave binder specifications to satisfy PG 70-22 and PG 76-22 criteria. The following equations (9) and (10) represent regression models for PG 58-28 binder based PAV aged blends at 28 ˚C and 31 ˚C, respectively. Equations (11) and (12) represent regression models for PG 64-22 binder based PAV aged blends at 28 ˚C and 31 ˚C, respectively. These regression equations were used to determine the minimum amount of MRAS and RAP binder required to be added to the virgin binders to obtain an intermediate temperature grade of 28 ˚C and 31 ˚C for the resulting blended binder. This was achieved by determining the percentage of MRAS and RAP binder required to be added to a virgin binder to satisfy the condition G*sinδ ≤ 5000 kPa at each temperature. The maximum limits of MRAS-RAP binder combinations required for each virgin binder are shown in Table 4.28.

$$\ln(G^*\sin\delta) = 6.722+2.481(\%MRAS)+2.934(\%RAP) \quad (9)$$

$$\ln(G^*\sin\delta) = 6.350+2.578(\%MRAS)+2.823(\%RAP) \quad (10)$$

$$\ln(G^*\sin\delta) = 7.498+1.351(\%MRAS)+2.145(\%RAP) \quad (11)$$

$$\ln(G^*\sin\delta) = 7.073+1.672(\%MRAS)+2.378(\%RAP) \quad (12)$$

Table 4.28 Maximum Percentage of MRAS and RAP Binder to Satisfy G*sinδ = 5000 kPa for PAV Aged Blended Binders

Virgin Binder	Maximum %Recycled Binder at 28 ˚C		Maximum %Recycled Binder at 31 ˚C	
	MRAS	RAP	MRAS	RAP
PG 58-28	10%	53%	10%	68%
	20%	44%	20%	59%
	30%	36%	30%	49%
	40%	30%	40%	40%
	50%	20%	50%	31%
	60%	10%	60%	22%
	70%	2%	70%	13%
PG 64-22	10%	41%	10%	54%
	20%	35%	20%	47%
	30%	29%	30%	40%
	40%	22%	40%	33%
	50%	16%	50%	26%
	60%	10%	60%	19%

4.5 PRAS-RAP Binder Limits

Virgin binders were blended with both RAP and PRAS binders at different proportions as shown in Table 4.29. The percentage represents the proportion of extracted binder by weight of total blended binder. The blend proportions were selected based on the individual recycled binder limits. Mixing of virgin, RAP and PRAS binders was done using a mechanical blender and hot plate. The unaged PRAS-RAP-virgin blended binders were tested on the dynamic shear rheometer (DSR) to determine the complex shear modulus (G*) and phase angle (δ) at different high test temperatures. Three replicates for each blended binder were tested. The average G*/sinδ values of three replicates at different test temperatures obtained upon testing the unaged blended binders are shown in Table 4.30.

Table 4.29 PRAS-RAP-Virgin Binder Blend Matrix

Virgin Binder	% RAP Binder	%PRAS Binder
PG 58-28	10%	10%
	10%	20%
	20%	10%
	20%	20%
PG 64-22	10%	10%
	10%	20%
	20%	10%
	20%	20%

Table 4.30 G*/sinδ Values of Unaged PRAS-RAP-Virgin Blended Binders

Blended Binder	Average G*/sinδ (kPa) at Test Temperature			
	58 ˚C	64 ˚C	70 ˚C	76 ˚C
PG 58-28 + 10P +10R	8.8	4	1.88	0.93
PG 58-28 + 10P+ 20R	14.58	6.62	3.11	1.5
PG 58-28 + 20P + 10R	26.47	12.39	1.963	0.964
PG 58-28 + 20P + 20R	38.63	17.97	8.56	4.15
PG 64-22 + 10P + 10R	-	5.34	2.43	1.16
PG 64-22 + 10P + 20R	-	7.32	3.32	1.57
PG 64-22 + 20P + 10R	-	17.20	8.03	3.78
PG 64-22 + 20P + 20R	-	25.94	12.09	5.71

Note: P-%PRAS binder, R-%RAP binder

Regression analysis was conducted and equations were developed based on test parameters obtained from the DSR to determine the limits for allowable PRAS and RAP binder that can be added to a virgin binder to meet the required Superpave binder specifications of a PG 70-22 and PG 76-22 binder. The following equations (13) and (14) represent regression models for PG 58-28 binder based unaged blends at 70 ˚C and 76 ˚C, respectively. Equations (15) and (16) represent regression models for PG 64-22 binder based unaged blends at 70 ˚C and 76 ˚C, respectively. These regression equations were used to determine the minimum amount of PRAS and RAP binder is required to be added to the virgin binders to result in a blended binder with a high temperature grade of 70 ˚C and 76 ˚C. This was achieved by determining the percentage of PRAS and RAP binder required to be added to a virgin binder to satisfy the condition $G^*/\sin\delta \geq 1$ kPa at each temperature. The minimum limits of PRAS-RAP binder combinations required for each virgin binder are shown in Table 4.31.

$$\ln(G^*/\sin\delta) = -0.720+10.348(\%PRAS)+3.972(\%RAP) \tag{13}$$

$$\ln(G^*/\sin\delta) = -1.382+10.192(\%PRAS)+3.750(\%RAP) \tag{14}$$

$$\ln(G^*/\sin\delta) = -0.433+11.461(\%PRAS)+2.647(\%RAP) \tag{15}$$

$$\ln(G^*/\sin\delta) = -1.143+11.328(\%PRAS)+2.541(\%RAP) \tag{16}$$

Table 4.31 Minimum Percentages of PRAS and RAP Binder to Satisfy $G^*/\sin\delta = 1.0$ kPa for Unaged Blended Binders

Virgin Binder	Minimum %Recycled Binder at 70 ˚C		Minimum %Recycled Binder at 76 ˚C	
	PRAS	RAP	PRAS	RAP
PG 58-28	5%	5%	10%	10%
	3%	10%	6%	20%
	1%	15%	3%	30%
PG 64-22	1%	10%	8%	10%
	2%	6%	6%	20%

PRAS-RAP-virgin binder blends were subjected to short term aging using the rolling thin film oven (RTFO) test. RTFO aged blended binder samples were then 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 at different temperatures. Three replicates for each blended binder were tested. The average G*/sinδ values of three replicates at different test temperatures obtained upon testing the RTFO aged blended binders are shown in Table 4.32.

Table 4.32 G*/sinδ Values of RTFO Aged PRAS-RAP-Virgin Blended Binders

Blended Binder	Average G*/sinδ (kPa) at Test Temperature			
	58 ˚C	64 ˚C	70 ˚C	76 ˚C
PG 58-28 + 10P +10R	13.59	6.25	2.95	1.44
PG 58-28 + 10P+ 20R	26.3	12.16	5.69	2.75
PG 58-28 + 20P + 10R	-	26.19	12.57	6.07
PG 58-28 + 20P + 20R	-	36.82	17.97	8.74
PG 64-22 + 10P +10R	-	13.37	6.06	2.83
PG 64-22 + 10P + 20R	-	19.16	8.77	4.08
PG 64-22 + 20P + 10R	-	32.41	15.16	7.19
PG 64-22 + 20P + 20R	-	49.91	24.26	11.3

Note: P-%PRAS binder, R-%RAP binder

Regression analysis was conducted and equations were developed based on test parameters obtained from the DSR to determine the limits for allowable PRAS and RAP binder that can be added to a virgin binder to meet the required Superpave binder specifications of a PG 70-22 and PG 76-22 binder. The following equations (17) and (18) represent regression models for PG 58-28 binder based RTFO aged blends at 70 ˚C and 76 ˚C, respectively. Equations (19) and (20) represent regression models for PG 64-22 binder based RTFO aged blends at 70 ˚C and 76 ˚C, respectively. These regression equations were used to determine the minimum amount of PRAS and RAP binder required to be added to the virgin binders to obtain a high temperature grade of 70 ˚C and 76 ˚C for the resulting blended binder. This was achieved by determining the percentage of PRAS and RAP binder required to be added to a virgin binder to satisfy the condition G*/sinδ $\geq$ 2.2 kPa at each temperature. The minimum limits of PRAS-RAP binder combinations required for each virgin binder are shown in Table 4.33.

$$\ln(G^*/\sin\delta) = 0.307+9.911(\%PRAS)+2.139(\%RAP) \quad (17)$$

$$\ln(G^*/\sin\delta) = -0.381+9.808(\%PRAS)+2.010(\%RAP) \quad (18)$$

$$\ln(G^*/\sin\delta) = 0.530+9.231(\%PRAS)+3.752(\%RAP) \quad (19)$$

$$\ln(G^*/\sin\delta) = -0.218+9.288(\%PRAS)+3.622(\%RAP) \quad (20)$$

Table 4.33 Minimum Percentages of PRAS and RAP Binder to Satisfy G*/sinδ = 2.2 kPa for RTFO Blended Binders

Virgin Binder	Minimum %Recycled Binder at 70 ˚C		Minimum %Recycled Binder at 76 ˚C	
	PRAS	RAP	PRAS	RAP
PG 58-28	3%	10%	10%	10%
	2%	15%	8%	20%
	1%	20%	6%	30%
PG 64-22	1%	4%	7%	10%
	0%	8%	3%	20%

The RTFO aged PRAS-RAP-Virgin binder samples were subjected to long term aging using the pressure aging vessel (PAV). PAV aged blended binder samples were then tested on the DSR to determine complex modulus (G*) and phase angle (δ) at different intermediate temperatures. Three replicates for each blended binder were tested. The average G*sinδ values of three replicates at different test temperatures obtained upon testing the PAV aged blended binders is shown in Table 4.34.

Table 4.34 G*sinδ Values of PAV Aged PRAS-RAP-Virgin Blended Binders

Blended Binder	Average G*sinδ (kPa) at Test Temperature			
	31 ˚C	28 ˚C	25 ˚C	22 ˚C
PG 58-28 + 10P +10R	1212.9	1777.93	2589.22	3755.21
PG 58-28 + 10P+ 20R	1765.3	2528.3	3537.58	4946.31
PG 58-28 + 20P + 10R	2244.03	3135.53	4337.35	5917.97
PG 58-28 + 20P + 20R	2717.93	3719.6	5037.9	-
PG 64-22 + 10P +10R	2541.76	3574.19	5066.02	-
PG 64-22 + 10P + 20R	3718.26	5164.1	-	-
PG 64-22 + 20P + 10R	4448.54	6032.85	-	-
PG 64-22 + 20P + 20R	5050.6	-	-	-

Note: P-%PRAS binder, R-%RAP binder

Regression analysis was conducted and equations were developed based on test parameters obtained from the DSR to determine the limits for allowable PRAS and RAP binder that can be added to a virgin binder to meet the required Superpave binder specifications of a PG 70-22 and PG 76-22 binder. The following equations (21) and (22) represent regression models for PG 58-28 binder based PAV aged blends at 28 ˚C and 31 ˚C, respectively. Equations (23) and (24) represent regression models for PG 64-22 binder based PAV aged blends at 28 ˚C and 31 ˚C, respectively. These regression equations were used to determine the maximum amount of PRAS and RAP binder that can be added to the virgin binders to obtain an intermediate temperature grade of 28 ˚C and 31 ˚C for the resulting blended binder. This was achieved by determining the percentage of PRAS and RAP binder required to be added to a virgin binder to satisfy the condition G*sinδ ≤ 5000 kPa at each temperature. The maximum limits of PRAS-RAP binder combinations required for each virgin binder are shown in Table 4.35.

$$\ln(G^*\sin\delta) = 7.003+4.093(\%PRAS) +1.941(\%RAP) \quad (21)$$

$$\ln(G^*\sin\delta) = 6.340+5.234(\%PRAS) +2.834(\%RAP) \quad (22)$$

$$\ln(G^*\sin\delta) = 7.781+3.448(\%PRAS) +1.893(\%RAP) \quad (23)$$

$$\ln(G^*\sin\delta) = 7.217+4.330(\%PRAS) +2.537(\%RAP) \quad (24)$$

Table 4.35 Maximum Percentage of PRAS and RAP Binder to Satisfy G*sinδ = 5000 kPa for PAV Aged Blended Binders

Virgin Binder	Maximum %Recycled Binder at 28 ˚C		Maximum %Recycled Binder at 31 ˚C	
	PRAS	RAP	PRAS	RAP
PG 58-28	10%	57%	10%	58%
	20%	36%	20%	40%
	30%	15%	30%	21%
	36%	2%	40%	3%
PG 64-22	10%	21%	10%	34%
	20%	2%	20%	17%

4.6 Summary of Binder Testing Results

The allowable recycled binder limits for virgin binders were determined to satisfy the performance grade (PG) specifications for S9.5C and S9.D mixes, which use a virgin binder grade of PG 70-22 and PG 76-22, respectively. The minimum recycled binder percentages obtained from unaged and RTFO binder testing were compared and the larger of the two values were used to establish the minimum limits for recycled binder that can be added to the virgin binder to satisfy the high temperature grades of 70 ˚C and 76 ˚C. The recycled binder percentages obtained from PAV binder testing was used as the maximum limits for recycled binder that can be added to the virgin binder to satisfy the intermediate temperature grade of 28 ˚C and 31 ˚C. Tables 4.36 and 4.37 show the allowable recycled binder limits, rounded to nearest 5% based on the binder testing and blending chart results. The percentages represent proportion of recycled binder by weight of total binder in the asphalt mixture. These limits were used as guidelines for designing the recycled mixtures and these designed mixtures were tested for performance using Asphalt Mixture Performance Tester (AMPT).

Table 4.36 Minimum and Maximum Percentages of Recycled Binder to Satisfy PG 70-22 (9.5C Mixes) Specifications

Virgin Binder	Rec. Binder	Minimum %	Maximum %
PG 58-28	RAP	20%	55%
	MRAS	25%	70%
	PRAS	5%	35%
PG 64-22	RAP	10%	40%
	MRAS	15%	70%
	PRAS	5%	25%
PG 70-22	RAP	-	40%
	MRAS	-	-
	PRAS	-	20%

Table 4.37 Minimum and Maximum Percentages of Recycled Binder to Satisfy PG 76-22 (9.5D Mixes) Specifications

Virgin Binder	Rec. Binder	Minimum %	Maximum %
PG 64-22	RAP	40%	55%
	MRAS	40%	75%
	PRAS	10%	30%
PG 70-22	RAP	30%	60%
	MRAS	20%	-
	PRAS	5%	30%

CHAPTER 5 - SUPERPAVE MIX DESIGN

This chapter describes the Superpave mix designs developed in the laboratory for S9.5C and S9.5D virgin mixtures and recycled mixtures incorporating recycled asphalt pavement (RAP) and recycled asphalt shingles (RAS). The amount of recycled material allowed in a mixture was limited based on the percent recycled binder in the mix. The NCDOT Superpave mix design procedure was followed for the laboratory mix design.

5.1 Virgin Mixtures

Virgin Mixtures S9.5C and S9.5D, which use a virgin binder grade of PG 70-22 and PG 76-22, respectively were designed first as control mixtures. These control mixtures served as baselines to compare the mixtures developed by incorporating recycled material. Mixing and compaction temperature ranges for PG 70-22 asphalt binder were determined in the laboratory by rotational viscometer following ASTM D 4402/4402M-12. For asphalt binder PG 76-22, mixing and compaction temperatures were recommended by NuStar (manufacturer) for their modified binders, as temperature/viscosity charts do not apply for modified binders. Table 5.1 shows the mixing and compaction temperature ranges for both PG 70-22 and PG 76-22 binders.

Table 5.1 Mixing and Compaction Temperature Ranges

	PG 70-22 (S9.5C)	PG 76-22 (S9.5D)
Laboratory Mixing Temperature	325˚ F - 335 ˚F	315 ˚F - 325 ˚F
Laboratory Compaction Temperature	305 ˚F - 315 ˚F	305 ˚F - 315 ˚F

Different trial aggregate blends were mixed with various asphalt contents for both S9.5C and S9.5D mixes. Mixing was done by a mechanical mixer. After mixing, loose asphalt mixture was conditioned for two hours in a forced-draft oven maintained at compaction temperature. Test specimens were then compacted at these temperatures with a Superpave gyratory compactor (SGC). The gyratory compaction levels for the given mix type are shown in the Table 5.2

Table 5.2 Gyratory Compaction Levels

Mix Type	Design ESALs Millions	Gyratory Compaction Levels	
		N_{ini}	N_{des}
S9.5C	3-30	7	75
S9.5D	>30	8	100

Bulk specific gravity (G_{mb}) of compacted test specimens was determined according to AASHTO T 331, "Standard Method of Test for Bulk Specific Gravity and Density of Comapcted Hot Mix Asphalt (HMA) using Automatic Vacuum Sealing Method". Maximum theoretical specific gravity (G_{mm}) of loose mix was measured according to AASHTO T209-05, "Standard Method of Theoretical Maximum Specific Gravity and Density of Hot Mix

Asphalt (HMA)". Superpave gyratory compaction data was analyzed, and the volumetric properties were calculated for each trial blend and asphalt contents.

The design aggregate blends and optimum asphalt contents were selected based on the NCDOT Superpave mix design criteria. The design aggregate blend gradations are shown in Table 5.3. Figure 5.1 shows the FHWA 0.45 power chart for the design aggregate blend gradations. Design asphalt content was chosen for each mixture to have percent air voids at Ndes, as close to 4±0.5% as possible. The optimum asphalt content determined for virgin mixtures S9.5C and S9.5D was 6.1%. Table 5.4 shows the Superpave mixture volumetric properties and design asphalt content of the virgin mixtures developed in the laboratory.

Table 5.3 Single-Point Aggregate Blend Gradations

	% Passing	
Sieve Size, mm	S9.5 C	S9.5 D
12.5	100	100
9.5	96	96
4.75	67	69
2.36	50	53
1.18	40	42
0.6	28	30
0.3	17	18
0.15	9	9
0.075	5.99	6.06

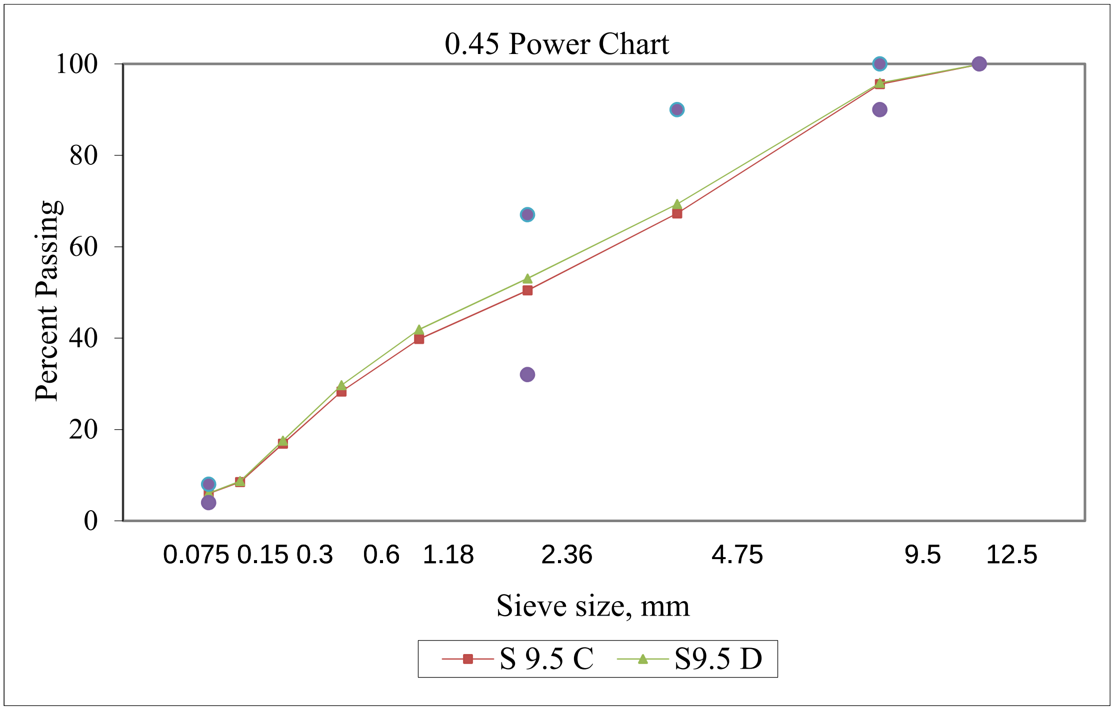


Figure 5.1 Aggregate Blend Gradations

Table 5.4 Volumetric Properties of Designed Virgin Mixtures

Mix Type	Asphalt Binder	Asphalt Content %	% Air Voids @ Ndes	%VMA	%VFA	Dust to Binder Ratio	%Gmm @ Nini
S9.5C	PG 70-22	6.1	4.3	17.2	74.4	1.06	89.0
		NCDOT Spec	*4±0.5*	*Min. 15.5*	*65-78*	*0.6-1.4*	*≤90.5*
S9.5D	PG 76-22	6.1	4.2	17.1	75.4	1.07	89.1
		NCDOT Spec	*4±0.5*	*Min. 15.5*	*65-78*	*0.6-1.4*	*≤90.0*

5.2 RAP Mixtures

Eleven RAP mixes were designed in the laboratory with varying proportions of RAP to meet the requirements of S9.5C and S9.5D mixtures. The amount of RAP material allowed in a mixture was limited by the percent of binder that the RAP binder would replace in the mixture. Virgin binder grades PG 58-28, PG 64-22 and PG 70-22 were used for S9.5C mixes, PG 64-22 and PG 70-22 were used for S9.5D mixes containing RAP. Different percentages of RAP binder replacement corresponding to the virgin asphalt binder used for S9.5C and S9.5D mixes are shown in Table 5.5. These percentages were chosen from the binder test results.

Table 5.5 Percent RAP Binder by Weight of Total Binder

Virgin Asphalt Binder	% RAP Binder Replacement by Weight of Total Binder	
	S9.5C	S9.5D
PG 58-28	25%, 40%	-
PG 64-22	12%, 25%, 40%	40%
PG 70-22	12%, 25%, 40%	30%, 40%

RAP was treated as a separate aggregate stockpile and sampling techniques were used to batch the required amount of RAP for each SGC specimen according to AASHTO T248, “Reducing Samples of Aggregate to Testing Size”. RAP was fractionated into coarse and fine fractions using #4 or 4.75mm sieve for mixtures containing more than 30% of RAP by weight of total mix. The aggregate design structure of the mixtures incorporating RAP was kept as close as possible to the baseline or control mixture gradation. The selected percentages of individual aggregates in aggregate blends are shown in Tables 5.6.

Table 5.6 Percentages of Individual Aggregates in Combined Blend for RAP mixes

Aggregate Type	Percent in Combined Gradation				
	S9.5C			S9.5D	
RAP	15	29	45	35	45
# 78M	43	38	33	34	30
WS	13	10	7	10	8
MS	27	21	15	21	17
Pond fines	3	2	0	1	0
Binder Replacement, %	12	25	40	30	40

RAP was preheated at 60 ˚C for 12 hours and then heated at the same target mixing temperature as that of virgin aggregates, but with a timeframe of two hours prior to mixing [25]. Mixing and Compaction temperatures corresponding to the virgin binder of the mix type were used. Mixing was done by a mechanical mixer. After mixing, loose asphalt mixture was conditioned for two hours in a forced-draft oven maintained at compaction temperature. Test specimens were then compacted at these temperatures with a Superpave gyratory compactor (SGC). Bulk specific gravity (G_{mb}) of compacted test specimens and maximum theoretical specific gravity (G_{mm}) of loose mix was measured. Superpave gyratory compaction data was analyzed, and the volumetric properties were calculated for all the mixes. Table 5.8 shows the Superpave mixture volumetric properties and design asphalt content of RAP mix designs developed in the laboratory. Design asphalt content was chosen for each mixture to have percent air voids @ Ndes, within in the specification range of

4±0.5%. There was a decrease in total asphalt content with an increase in RAP content. This presents an economical benefit since asphalt cement is the expensive part of hot-mix asphalt. The mix design data illustrates that volumetric properties of all mixes incorporating RAP met the requirements specified by NCDOT. The data shows a slight decrease in percent VMA and VFA with increasing RAP content. This could be due to the extent of blending between old and virgin asphalt binder, since the aggregate design structure is similar to virgin mixtures.

Table 5.7 Volumetric Properties of Designed RAP Mixtures

Mix Type	Virgin Binder	% RAP Binder Replacement	% TAC	% VAC	% Air Voids @ Ndes	% VMA	% VFA	Dust to Binder Ratio	% Gmm @ Nini
9.5C	PG 58-28	25	5.8	4.35	4.2	16.5	74.7	1.09	89.2
		40	5.6	3.36	4.3	16.4	72.4	1.12	89.0
	PG 64-22	12	6.1	5.37	3.8	16.7	77.4	1.04	89.6
		25	5.8	4.35	4.2	16.4	74.3	1.1	89.2
		40	5.6	3.36	4.4	16.7	73.5	1.09	88.7
	PG 70-22	12	6.1	5.37	4	16.8	76.4	1.05	89.5
		25	5.8	4.35	4.2	16.4	74.3	1.1	89.2
		40	5.6	3.36	4.4	16.2	73.2	1.12	89
	NCDOT Spec.				*4±0.5*	*Min. 15.5*	*65-78*	*0.6-1.4*	*≤90.5*
9.5D	PG 64-22	40	5.6	3.36	3.9	16.1	75.9	1.1	89.5
	PG 70-22	30	5.7	3.99	3.8	16.4	76.5	1.09	89.6
		40	5.6	3.36	3.8	16.1	76.7	1.09	89.6
	NCDOT Spec.				*4±0.5*	*Min. 15.5*	*65-78*	*0.6-1.4*	*≤90.0*

Note: TAC-Total Asphalt Content; VAC-Virgin Asphalt Content

5.3 PRAS Mixtures

Six PRAS mixes were designed in the laboratory with varying proportions of PRAS to meet the requirements of S9.5C and S9.5D mixtures. The amount of PRAS allowed in a mixture was limited by the percent of binder that the PRAS binder would replace in the mixture. Virgin binder grades PG 58-28, PG 64-22 and PG 70-22 were used for S9.5C mixes and, PG 64-22 and PG 70-22 were used for S9.5D mixes containing PRAS. Different percentages of PRAS binder replacement corresponding to the virgin asphalt binder used for S9.5C and S9.5D mixes are shown in Table 5.9. These percentages were chosen from the binder test results.

Table 5.8 Percent PRAS Binder by Weight of Total Binder

Virgin Asphalt Binder	% PRAS Binder Replacement by Weight of Total Binder	
	S9.5C	S9.5D
PG 58-28	15%, 30%	-
PG 64-22	10%	15%
PG 70-22	10%	15%

PRAS was treated as a separate aggregate stockpile and was blended with virgin aggregates to have a final aggregate design structure as close as possible to the baseline or control mixture gradation. Initially PRAS was handled similar to that of RAP and it was preheated at 60 ˚C for 12 hours and then heated at the same target mixing temperature as that of virgin aggregates, but with a timeframe of two hours prior to mixing. This mixing procedure resulted in stiffer mixes which affected the compactability and it was not possible to keep the percent air voids at Ndes close to 4.0% and meet Superpave volumetric criteria even by increasing the asphalt content. Table 5.11 shows the results for percent air voids at Ndes using this mixing procedure.

Table 5.9 Percent Air Voids at Ndes for PRAS Mixes (Trial Mixing)

Mix Type	Virgin Binder	%PRAS Binder Replacement	% Total Asphalt Content	% Air Voids @ Ndes
9.5C	PG 64-22	20	6.3	4.9
	PG 70-22	10	6.3	5

Then, mixing procedure was changed and PRAS was preheated separately at a lower temperature of 110 ˚C [26]. The virgin aggregates were heated at a higher temperature such that when mixed with recycled materials the resulting mix is within the required mixing temperature range. Mixing and compaction temperatures corresponding to the virgin binder of the mix type were used. Mixing was done by a mechanical mixer. After mixing, loose asphalt mixture was conditioned for two hours in a forced-draft oven maintained at compaction temperature. Test specimens were then compacted at these temperatures with a Superpave gyratory compactor (SGC).

Bulk specific gravity (G_{mb}) of compacted test specimens and maximum theoretical specific gravity (G_{mm}) of loose mix was measured. Superpave gyratory compaction data was analyzed, and the volumetric properties were calculated for all the mixes. Table 5.12 shows the Superpave mixture volumetric properties and design asphalt content of PRAS mixtures developed in the laboratory. Design asphalt content was chosen for each mixture such that percent air voids at Ndes is in the range of 4±0.5%. There was a slight increase in total asphalt content for PRAS mixes. This could be because of the increase in stiffness of mix due to PRAS binder or it could be due to inadequate blending of PRAS binder with virgin binder because it was not a paving grade binder originally. PRAS binder replacement was limited to 10% in S9.5C mixes and to 15% in S9.5D mixes with virgin binders PG 64-22 and PG 70-22. This shows that the virgin binder that is added must effectively act as the rejuvenator for the PRAS. The mix design data illustrates that volumetric properties of all mixes incorporating PRAS met the requirements specified by NCDOT.

Table 5.10 Volumetric Properties of Designed PRAS Mixtures

Mix Type	Virgin Binder	% PRAS Binder Replacement	% TAC	% VAC	% Air Voids @ Ndes	% VMA	% VFA	Dust to Binder Ratio	% Gmm @ Nini
9.5C	PG 58-28	15	6.2	5.27	3.6	16.7	78.4	1.05	90
		30	6.2	4.34	4.1	17.3	76.5	1.05	89.4
	PG 64-22	10	6.2	5.58	3.9	17.4	77.5	1	89.9
		20	6.2	4.96	5.2				
	PG 70-22	10	6.2	5.58	3.9	17.3	77.4	1.01	89.7
		20	6.3	5.04	4.9				
	NCDOT Spec.				*4±0.5*	*Min. 15.5*	*65-78*	*0.6-1.4*	*≤90.5*
9.5D	PG 64-22	15	6.1	5.18	3.7	17.3	78.3	1.01	89.4
	PG 70-22	15	6.1	5.18	4.1	17	76	1.05	89.3
	NCDOT Spec.				*4±0.5*	*Min. 15.5*	*65-78*	*0.6-1.4*	*≤90.0*

Note: TAC-Total Asphalt Content; VAC-Virgin Asphalt Content

5.4 MRAS Mixtures

Seven MRAS mixes were designed in the laboratory with varying proportions of MRAS to meet the requirements of S9.5C and S9.5D mixtures. The amount of MRAS allowed in a mixture was limited by the percent of binder that the MRAS binder would replace in the mixture. Virgin binder grades PG 58-28, PG 64-22 and PG 70-22 were used for 9.5C mixes and, PG 64-22 and PG 70-22 were used for S9.5D mixes containing MRAS. Different percentages of MRAS binder replacement corresponding to the virgin asphalt binder used for S9.5C and S9.5D mixes are shown in Table 5.13. These percentages were selected from the binder test results.

Table 5.11 Percent MRAS Binder by Weight of Total Binder

Virgin Asphalt Binder	% MRAS Binder Replacement by Weight of Total Binder	
	S9.5C	S9.5D
PG 58-28	25%, 50%	-
PG 64-22	15%, 50%	50%
PG 70-22	15%	20%

MRAS was treated as a separate aggregate stockpile and was blended with virgin aggregates to have a final aggregate design structure as close as possible to the baseline or control mixture gradation. Initially MRAS was also handled similar to that of RAP and it was preheated at 60 ˚C for 12 hours and then heated at the same target mixing temperature as that of virgin aggregates, but with a timeframe of two hours prior to mixing. This mixing procedure resulted in stiffer mixes which affected the compactability and it was not possible to keep the percent air voids at Ndes close to 4.0% and meet Superpave volumetric criteria even by increasing the asphalt content. Table 5.15 shows the results for percent air voids at Ndes using this mixing procedure.

Table 5.12 Percent Air Voids at Ndes for MRAS Mixes (Trial Mixing)

Mix Type	Virgin Binder	%MRAS Binder Replacement	Total Asphalt Content %	% Air Voids @ Ndes
9.5C	PG 58-28	25	6.1	5.7
		50	6.1	5.3

Then, mixing procedure was changed and PRAS was preheated separately at a lower temperature of 110 ˚C [26]. The virgin aggregates were heated at a higher temperature such that when mixed with recycled materials the resulting mix is within the required mixing temperature range. Mixing and compaction temperatures corresponding to the virgin binder of the mix type were used. Mixing was done by a mechanical mixer. After mixing, loose asphalt mixture was conditioned for two hours in a forced-draft oven maintained at compaction temperature. Test specimens were then compacted at these temperatures with a Superpave gyratory compactor (SGC).

Bulk specific gravity (G_{mb}) of compacted test specimens and maximum theoretical specific gravity (G_{mm}) of loose mix was measured. Superpave gyratory compaction data was analyzed, and the volumetric properties were calculated for all the mixes. Table 5.16 shows the Superpave mixture volumetric properties and design asphalt content of MRAS mixtures developed in the laboratory. Design asphalt content was chosen for each mixture such that percent air voids at Ndes is in the range of 4±0.5%. There was a decrease in total asphalt content with increase in MRAS content, this shows that there is a difference between MRAS and PRAS binders. MRAS binder could blend with virgin binders more effectively when compared to that of PRAS binders. PRAS binder is much stiffer because it comes from in-service roofing shingles that have experienced several years of aging. The mix design data illustrates that volumetric properties of all mixes incorporating MRAS met the requirements specified by NCDOT.

Table 5.13 Volumetric Properties of Designed MRAS Mixtures

Mix Type	Virgin Binder	% MRAS Binder Replacement	% TAC	% VAC	% Air Voids @ Ndes	% VMA	% VFA	Dust to Binder Ratio	% Gmm @ Nini
9.5C	PG 58-28	25	5.8	4.35	3.8	16.1	76.5	1.12	89.7
		50	5.7	2.85	4.1	16	74.6	1.18	89
	PG 64-22	15	6.1	5.18	3.8	16.8	78	1.04	89.8
		50	5.7	2.85	4.5	16.6	72.7	1.14	88.4
	PG 70-22	15	6.1	5.18	3.6	16.5	78	1.05	89.9
	NCDOT Spec.				*4±0.5*	*Min. 15.5*	*65-78*	*0.6-1.4*	*≤90.5*
9.5D	PG 64-22	50	5.7	2.85	4.2	16.8	75.2	1.06	88.8
	PG 70-22	20	5.8	4.64	3.7	16.5	77.5	1.15	89.6
	NCDOT Spec.				*4±0.5*	*Min. 15.5*	*65-78*	*0.6-1.4*	*≤90.0*

Note: TAC-Total Asphalt Content; VAC-Virgin Asphalt Content

CHAPTER 6 - DYNAMIC MODULUS TEST

Dynamic modulus tests were conducted on all the designed mixtures to determine changes in the mixture stiffness due to the incorporation of recycled material. Dynamic modulus is the primary material input for asphalt concrete layer characterization in the AASHTOWare® Pavement ME Design (DARWin-ME) Pavement Design and Analysis Software or other mechanistic empirical structural design procedures.

The complex modulus (E*) is defined as the complex number that relates stress to strain for a linear viscoelastic material subjected to sinusoidal loading. The absolute value or magnitude of the complex modulus is referred to as the dynamic modulus (|E*|). Asphalt Mixture Performance Tester (AMPT) device shown in Figure 6.1 was used to conduct the dynamic modulus tests in the laboratory. Dynamic modulus testing was performed according to AASHTO TP 79- 09, “Standard Method of Test for Determining the Dynamic Modulus and Flow Number for Hot Mix Asphalt (HMA) Using the Asphalt Mixture Performance Tester (AMPT)". The AMPT is a servo-hydraulic testing device capable of applying cyclic, stress-controlled loading on asphalt concrete specimen at multiple temperatures and loading frequencies. Both the applied stress and the resulting strain are continuously recorded during testing. AMPT device measures two material properties of asphalt concrete specimen: dynamic modulus (|E*|) and phase angle (Φ). The dynamic modulus is defined as the peak stress divided by the peak strain and is a measure of the overall stiffness of the mixture at a particular temperature and loading frequency. Phase angle is the lag between peak stress and peak strain.

$$|E^*| = \sigma_0/\varepsilon_0$$

$|E^*|$ = dynamic modulus, psi;

σ_0 = peak-to-peak stress amplitude, psi; and

ε_0 = peak-to-peak strain amplitude, inches/inch

$$\Phi = 2\pi f \Delta t$$

Φ = phase angle, radians;

f = frequency, Hz; and

Δt = time lag between stress and strain , seconds

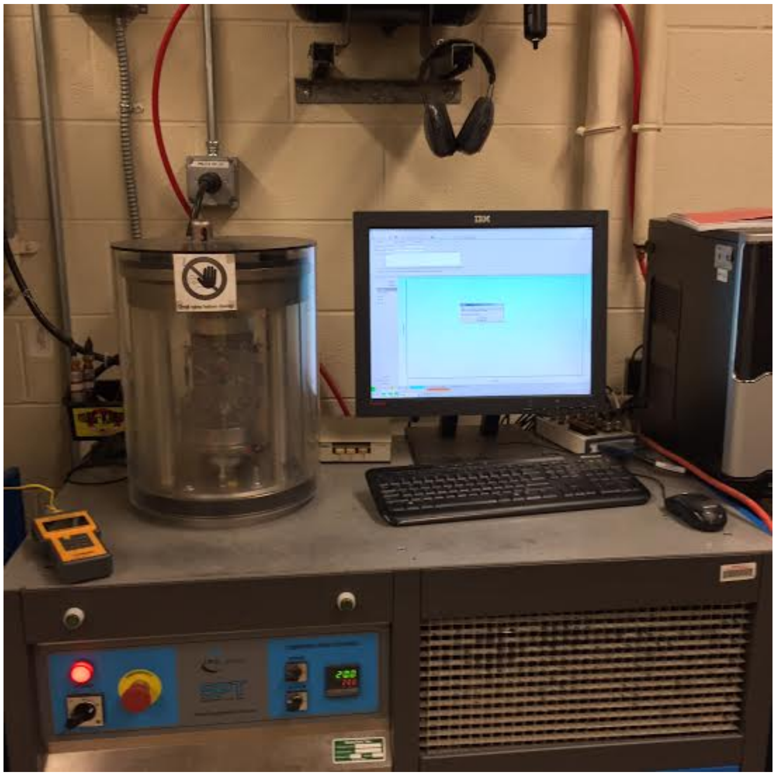


Figure 6.1 AMPT Device

The dynamic modulus test specimens were fabricated to dimensions of 100 mm (4 in.) diameter and 150 mm (6 in.) height with 4±0.5 percent air voids. Each mixture was short-term aged for four hours at the respective compaction temperature, based on the type of mix. Asphalt concrete specimens of each mixture were compacted in the Superpave gyratory compactor to a height of 178 mm and diameter of 150 mm with 7±1% air voids. These specimens were later cored and cut to the required dimensions for testing. The AMPT applies cyclic loading to load the specimen in a stress-controlled mode. Axial deformations were measured by placing three linear variable displacement transducers (LVDTs) along the vertical length of the specimen at 120 degree positions. Core and rod LVDTs were used for the AMPT testing. The LVDT's were attached to provide a gauge length of 70 mm using brackets and targets glued to the specimen. Latex membrane was placed at the top and bottom of the test specimen to reduce friction between the end of specimen and the loading plates. A typical set-up of the test specimen is shown in Figure 6.2.

The dynamic modulus tests were performed at three different temperatures of 4 ˚C, 20 ˚C and 40 ˚C and three frequencies of 0.1, 1 and 10 Hz to obtain the temperature- and rate-dependent behavior of the asphalt concrete. The dynamic modulus data was used to construct dynamic modulus master curve using time-temperature superposition principle, i.e., the same modulus value of a material can be obtained either at lower test temperatures and higher frequencies or at higher test temperatures but lower frequencies. The dynamic modulus master curves were generated for all the mixtures designed in the laboratory at a reference temperature of 70 ˚F according to AASHTO PP61-09, "Provisional Standard Practice for Developing Dynamic Modulus Master Curves for Hot Mix Asphalt (HMA) Using the Asphalt Mixture Performance Tester".

Figure 6.2 Typical Setup of Test Specimen

6.1 Dynamic Modulus Test Results of RAP Mixtures

Three replicate specimens for each of the RAP mixtures were tested using the AMPT device. Each specimen was tested at temperatures of 4 ˚C, 20 ˚C, and 40 ˚C and loading frequencies of 0.1, 1 and 10 Hz. Tables 6.1 and 6.2 show the dynamic modulus test results of 9.5C and 9.5D RAP mixes, respectively. The dynamic modulus values shown in the table are averages of the three replicates tested for each mixture. In general, dynamic modulus increased with increase in the percentage of recycled binder for a given virgin binder grade, showing an expected increase in stiffness. Dynamic modulus master curves were developed for each mixture at a reference temperature of 70 ˚F. Figures 6.3 through 6.6 show master curve comparisons for 9.5C and 9.5D RAP mixes with different percentages of RAP binder based on the virgin binder grade. The upper right portion of the graph represents material responses at high frequencies. The lower left portion of the graph represents material behavior at lower frequencies.

For 9.5C mix type, the mixtures with PG 64-22 and PG 70-22 binders incorporating 12% RAP binder had similar stiffness to that of the virgin mix which used PG 70-22 binder at all temperatures and frequencies. PG 58-28 based mixture with 25% RAP binder had lower stiffness than that of virgin mix, while the mixtures with PG 64-22 and PG 70-22 binders with 25% RAP binder showed similar stiffness to each other and were stiffer than virgin mix at all frequencies. The mixture prepared with PG 58-28 binder and 40% RAP binder exhibited similar stiffness to that of the virgin mix for upper half of the frequency range and was stiffer than the virgin mix for lower half of the frequency range. This indicates that this mixture performs similar to that of virgin mixture at low and intermediate temperatures and performs better in terms of rutting at high temperatures. Mixtures with PG 64-22 and PG 70-22 binders incorporating 40% RAP binder also showed similar stiffness to each other and were significantly stiffer than the virgin mix.

For 9.5D mix type, mixtures with soft binders PG 64-22 and PG 70-22 incorporating RAP binder had much higher stiffness when compared to that of the virgin mix which uses PG 76-22; this could be because PG 76-22 was a polymer modified asphalt binder. Dynamic modulus testing showed that RAP mixtures prepared with PG 64-22 and PG 70-22 binders exhibited similar stiffness to each other. This indicated that use of softer PG 64-22 for these mixtures had little impact on the mixture stiffness.

Table 6.1 Dynamic Modulus Test Results for 9.5C RAP Mixes

Mix	Test Temp ˚C	Dynamic Modulus (MPa)		
		0.1 Hz	1 Hz	10 Hz
Virgin Mix PG 70-22	4	9656	13587	17757
	20	2584	4847	7982
	40	385	818	1874
PG 58-28 + 25%RAP	4	7835	11964	17149
	20	2131	3946	6603
	40	435	911	1853
PG 58-28 + 40%RAP	4	10063	14778	19530
	20	3766	6330	9465
	40	616	1354	2737
PG 64-22 + 12%RAP	4	8916	12630	16689
	20	2582	4644	7703
	40	422	860	1943
PG 64-22 + 25%RAP	4	10877	14810	18949
	20	3591	6102	9334
	40	684	1321	2757
PG 64-22 + 40%RAP	4	12227	16163	20297
	20	4406	6947	10011
	40	856	1643	3189

Table 6.1 Continued

Mix	Test Temp ˚C	Dynamic Modulus (MPa)		
		0.1 Hz	1 Hz	10 Hz
PG 70-22 + 12%RAP	4	9560	12973	17402
	20	3007	5254	8228
	40	457	1013	2287
PG 70-22 + 25%RAP	4	11924	15606	19382
	20	4003	6561	9567
	40	774	1566	3215
PG 70-22 + 40%RAP	4	12732	16330	20432
	20	4650	7457	11004
	40	912	1826	3730

Table 6.2 Dynamic Modulus Test Results for 9.5D RAP Mixes

Mix	Test Temp ˚C	Dynamic Modulus (MPa)		
		0.1 Hz	1 Hz	10 Hz
Virgin Mix PG 76-22	4	8686	12756	17350
	20	2501	4516	7239
	40	411	765	1740
PG 64-22 + 40%RAP	4	12025	15648	19270
	20	4096	6757	10079
	40	844	1609	3202
PG 70-22 + 30%RAP	4	11446	15041	18698
	20	3975	6608	10014
	40	801	1616	3269
PG 70-22 + 40%RAP	4	12857	16485	20167
	20	4727	7517	10882
	40	940	1906	3756

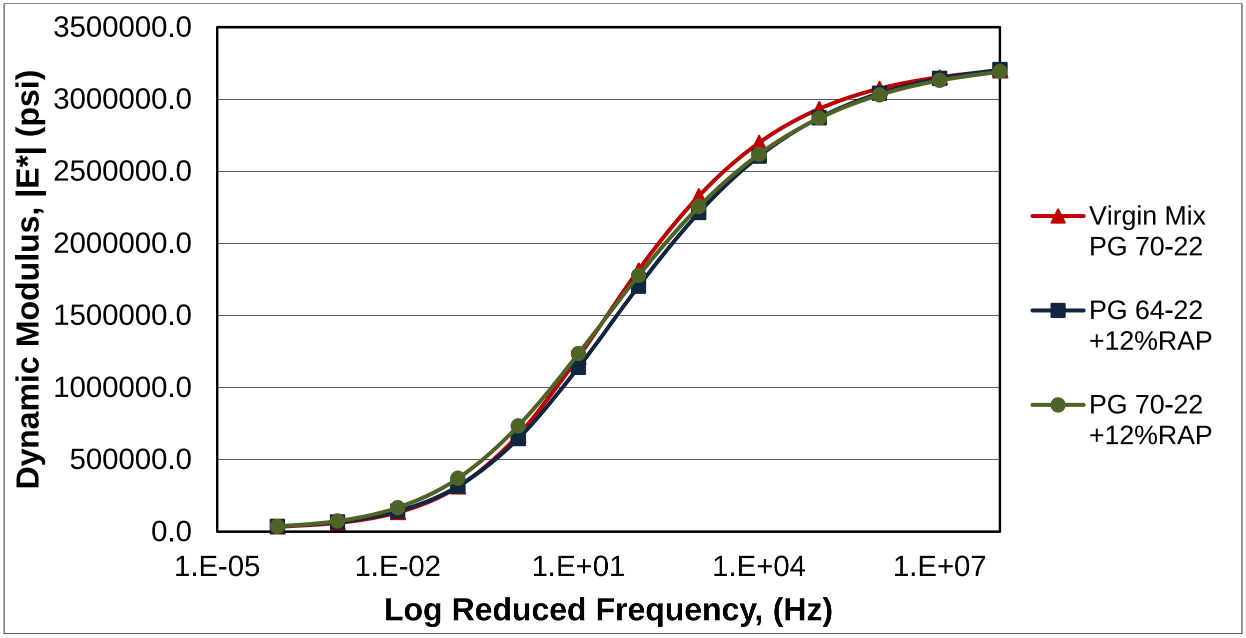


Figure 6.3 Dynamic Modulus Master Curves for 9.5C Mixes with 12% RAP Binder (Reference Temperature 70˚ F)

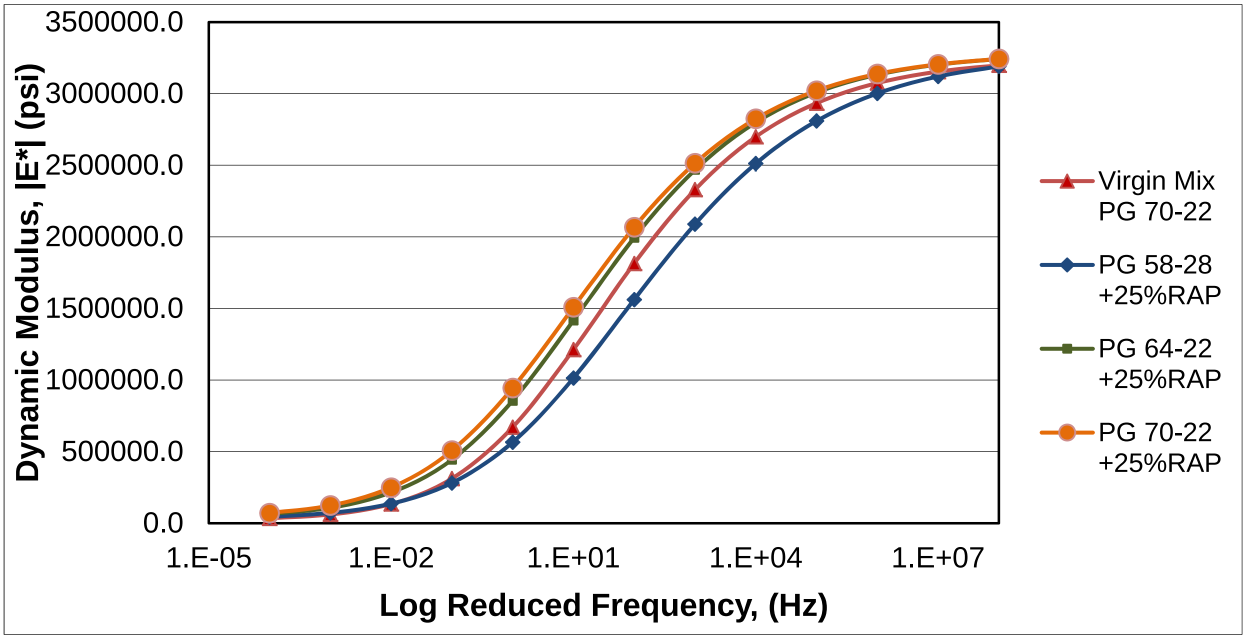


Figure 6.4 Dynamic Modulus Master Curves for 9.5C Mixes with 25% RAP Binder (Reference Temperature 70˚ F)

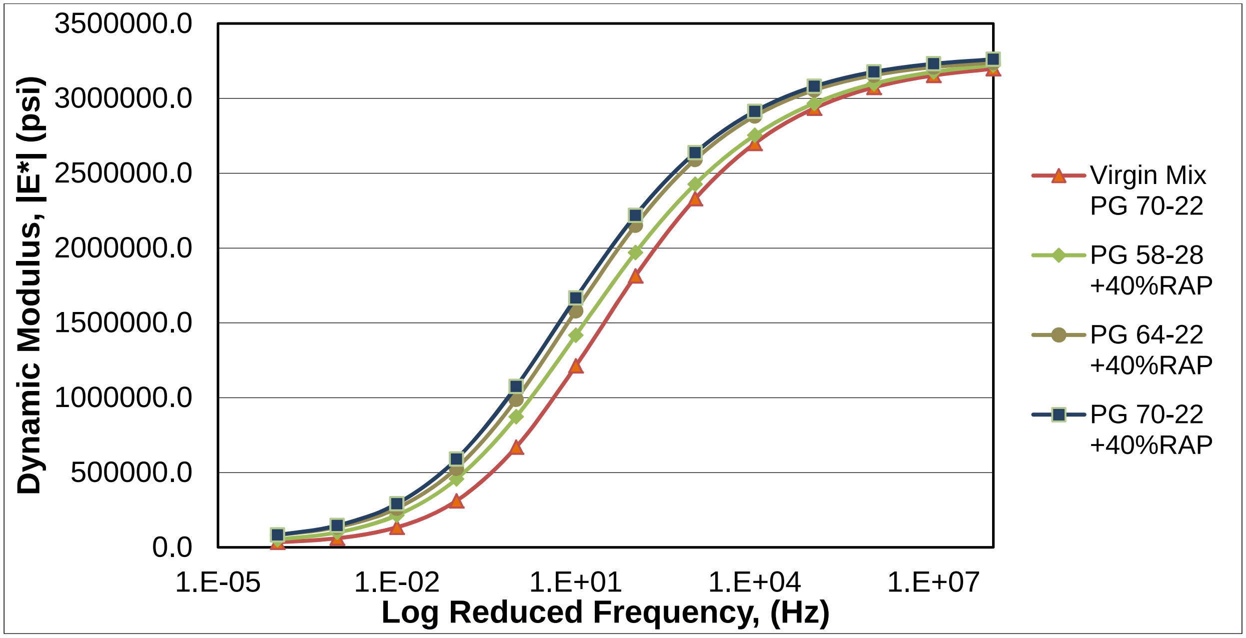


Figure 6.5 Dynamic Modulus Master Curves for 9.5C Mixes with 40% RAP Binder (Reference Temperature 70˚ F)

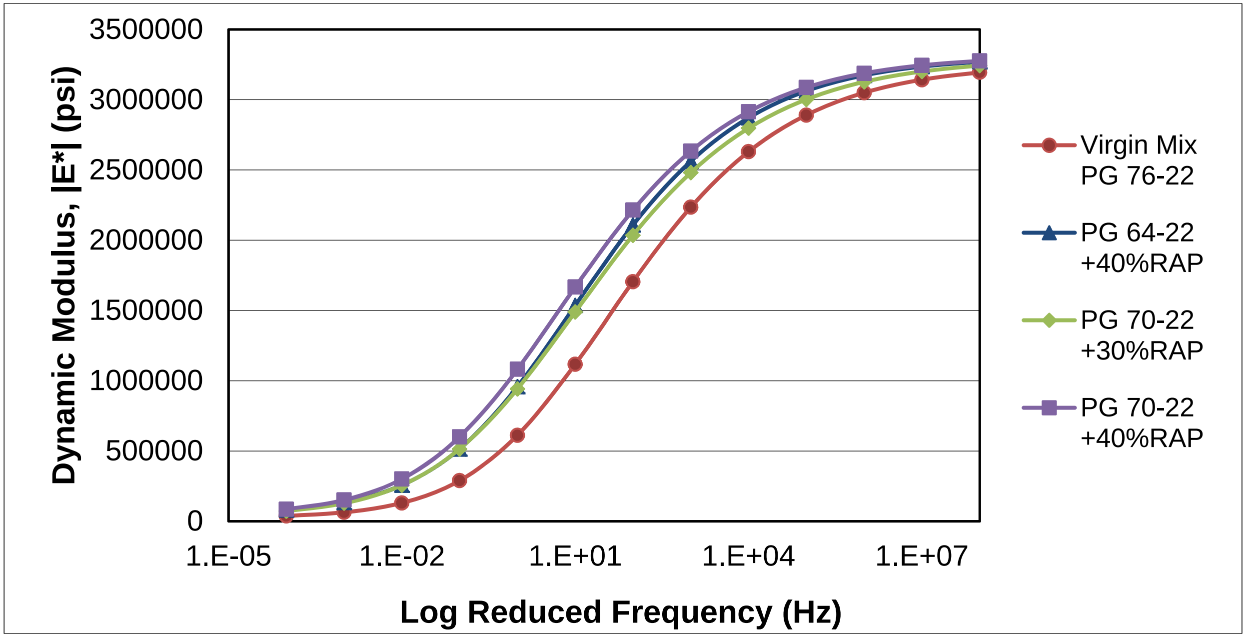


Figure 6.6 Dynamic Modulus Master Curves for 9.5D RAP Mixes (Reference Temperature 70˚ F)

6.1.1 Ranking of RAP Mixtures

Dynamic modulus test data of each RAP mixture at different temperatures provides an indication of mixture stiffness and its performance. At high temperatures, the stiffness provides an indication of the rutting performance of the mixture. At intermediate temperatures, the stiffness is an indicator of the fatigue performance of the mixture. At low temperatures, stiffness gives an indication of thermal cracking [27, 28]. Dynamic modulus values averaged over three test frequencies were used to calculate the modular ratio between the different RAP mixes and that of the virgin (control) mix for a given temperature [27, 28]. The modular ratio was calculated using the following equation:

$$\text{M.R.} = E^*_{\text{RAP mix}}/E^*_{\text{virgin mix}}$$

Where

M.R. = Modular ratio

$E^*_{\text{RAP mix}}$ = Average dynamic modulus of a RAP mix for a given temperature

$E^*_{\text{virgin mix}}$ = Average dynamic modulus of a virgin (control) mix for a given temperature

Tables 6.3 through 6.4 show the modular ratios and rankings of the 9.5C and 9.5D RAP mixtures at three different temperatures. At high temperatures, stiffer asphalt mixture is preferred to minimize rutting. Therefore the mixture with highest modular ratio was ranked best at 40 ˚C. However at low temperatures, stiffer mixtures are more prone to thermal cracking. Therefore at 4 ˚C, mixtures with lower modular ratio are ranked higher. Several fatigue performance prediction models such as the Asphalt Institute model, Shell model as well as the M-E Design Guide model predicts fatigue life of asphalt concrete to be inversely proportional to the stiffness of the mix, i.e. number of cycles to fatigue failure $N_f \alpha (1/E)$. The less stiff mixes were assumed to have better resistance to fatigue cracking at intermediate temperatures. Therefore mixtures with lower modular ratio are ranked better at 20 ˚C.

For 9.5C RAP mixes, PG 70-22 and PG 64-22 binder based mixtures with 40% RAP binder rank better at high temperatures indicating better rutting performance with addition of aged binder. Conversely, at intermediate and low temperatures PG 58-28 binder with 25% RAP binder and PG 64-22 with 12% RAP binder are ranked better indicating better resistance to cracking. Overall, mixtures with PG 64-22 and PG 70-22 binders with up to 25% RAP binder and PG 58-28 based mixture with 25% to 40% RAP binder have modular ratios comparable to the virgin (control) mix at all temperatures indicating equivalent or better performance in terms of both rutting and cracking. For 9.5D RAP mixes, mixtures with PG 64-22 and PG 70-22 binders incorporating RAP binder had much higher modular ratios when compared to the control mix; because the virgin (control) mix used PG 76-22 binder which was a polymer modified asphalt binder.

Table 6.3 Modular Ratios and Rankings of 9.5C RAP Mixes

(a) Test Temperature 40 ˚C

Mix	Test Temp ˚C	Average Dynamic Modulus (MPa)	Modular Ratio	Ranking at 40 ˚C
PG 70-22 + 40%RAP	40	2156	2.10	1
PG 64-22 + 40%RAP	40	1896	1.85	2
PG 70-22 + 25%RAP	40	1852	1.81	3
PG 64-22 + 25%RAP	40	1587	1.55	4
PG 58-28 + 40%RAP	40	1569	1.53	5
PG 70-22 + 12%RAP	40	1252	1.22	6
PG 64-22 + 12%RAP	40	1075	1.05	7
PG 58-28 + 25%RAP	40	1066	1.04	8
Virgin Mix PG 70-22	40	1025	1.00	9

(b) Test Temperature 20 ˚C

Mix	Test Temp ˚C	Average Dynamic Modulus (MPa)	Modular Ratio	Ranking at 20 ˚C
PG 58-28 + 25%RAP	20	4227	0.82	1
PG 64-22 + 12%RAP	20	4976	0.97	2
Virgin Mix PG 70-22	20	5138	1.00	3
PG 70-22 + 12%RAP	20	5496	1.07	4
PG 64-22 + 25%RAP	20	6342	1.23	5
PG 58-28 + 40%RAP	20	6520	1.27	6
PG 70-22 + 25%RAP	20	6710	1.31	7
PG 64-22 + 40%RAP	20	7121	1.39	8
PG 70-22 + 40%RAP	20	7704	1.50	9

(c) Test Temperature 4 ˚C

Mix	Test Temp ˚C	Average Dynamic Modulus (MPa)	Modular Ratio	Ranking at 4 ˚C
PG 58-28 + 25%RAP	4	12316	0.90	1
PG 64-22 + 12%RAP	4	12745	0.93	2
PG 70-22 + 12%RAP	4	13312	0.97	3
Virgin Mix PG 70-22	4	13667	1.00	4
PG 58-28 + 40%RAP	4	14790	1.08	5
PG 64-22 + 25%RAP	4	14878	1.09	6
PG 70-22 + 25%RAP	4	15637	1.14	7
PG 64-22 + 40%RAP	4	16229	1.19	8
PG 70-22 + 40%RAP	4	16498	1.21	9

Table 6.4 Modular Ratios and Rankings of 9.5D RAP Mixes

(a) Test Temperature 40 ˚C

Mix	Test Temp ˚C	Average Dynamic Modulus (MPa)	Modular Ratio	Ranking at 40 ˚C
PG 70-22 + 40%RAP	40	2201	2.26	1
PG 70-22 + 30%RAP	40	1895	1.95	2
PG 64-22 + 40%RAP	40	1885	1.94	3
Virgin Mix PG 76-22	40	972	1.00	4

(b) Test Temperature 20 ˚C

Mix	Test Temp ˚C	Average Dynamic Modulus (MPa)	Modular Ratio	Ranking at 20 ˚C
Virgin Mix PG 76-22	20	4752	1.00	1
PG 70-22 + 30%RAP	20	6866	1.44	2
PG 64-22 + 40%RAP	20	6977	1.47	3
PG 70-22 + 40%RAP	20	7709	1.62	4

(c) Test Temperature 4 ˚C

Mix	Test Temp ˚C	Average Dynamic Modulus (MPa)	Modular Ratio	Ranking at 4 ˚C
Virgin Mix PG 76-22	4	12931	1.00	1
PG 70-22 + 30%RAP	4	15062	1.16	2
PG 64-22 + 40%RAP	4	15648	1.21	3
PG 70-22 + 40%RAP	4	16503	1.28	4

6.2 Dynamic Modulus Test Results of PRAS Mixtures

Three replicate specimens for each of the PRAS mixture were tested using the AMPT device. Each specimen was tested at temperatures of 4, 20, and 40 ˚C and loading frequencies of 0.1, 1, and 10 Hz. Tables 6.5 and 6.6 show the dynamic modulus test results of 9.5C and 9.5D PRAS mixes, respectively. The dynamic modulus values shown in the table are averages of the three replicates tested for each mixture. Overall, there is an increase in dynamic modulus values with the addition of PRAS binder, indicating increased mixture stiffening. Dynamic modulus master curves were developed for each mixture tested at a reference temperature of 70 ˚F. Master curves for 9.5C and 9.5D PRAS mixes with different percentages of PRAS binder are shown in Figures 6.7 and 6.8.

For 9.5C mix type, the mixture with PG 64-22 binder incorporating 10% PRAS binder and the mixture with PG 58-28 binder and 30% PRAS binder had similar stiffness to that of the virgin mix which used PG 70-22 binder. PG 58-28 based mixture with 15% PRAS binder had lower stiffness than that of the virgin mix, while the mixture with PG 70-22 binder and 10% PRAS binder was significantly stiffer than the virgin mix. For 9.5D mix type, PG 70-22 based mixture incorporating 15% PRAS binder had much higher stiffness when compared to that of the virgin mix which used PG 76-22; this could be because PG 76-22 is a polymer modified asphalt binder. The mixture with PG 64-22 binder and 15% PRAS binder had similar stiffness to that of the virgin mix.

Table 6.5 Dynamic Modulus Test Results for 9.5C PRAS Mixes

Mix	Test Temp ˚C	Dynamic Modulus (MPa)		
		0.1 Hz	1 Hz	10 Hz
Virgin Mix PG 70-22	4	9656	13587	17757
	20	2584	4847	7982
	40	385	818	1874
PG 58-28 + 15%PRAS	4	8121	11668	15537
	20	2359	4277	7133
	40	420	869	2005
PG 58-28 + 30%PRAS	4	10609	13870	17281
	20	3814	6091	9044
	40	783.2	1507	2973
PG 64-22 + 10%PRAS	4	9366	13030	16902
	20	3288	5411	8557
	40	580	1175	2450
PG 70-22 + 10%PRAS	4	12165	15897	19791
	20	4214	6815	10130
	40	858.9	1628	3245

Table 6.6 Dynamic Modulus Test Results for 9.5D PRAS Mixes

Mix	Test Temp ˚C	Dynamic Modulus (MPa)		
		0.1 Hz	1 Hz	10 Hz
Virgin Mix PG 76-22	4	8686	12756	17350
	20	2501	4516	7239
	40	411	765	1740
PG 64-22 + 15%PRAS	4	10097	13452	16928
	20	3388	5611	8590
	40	618	1207	2550
PG 70-22 + 15%PRAS	4	12767	16311	19950
	20	4813	7602.5	11007.5
	40	875.7	1795	3600

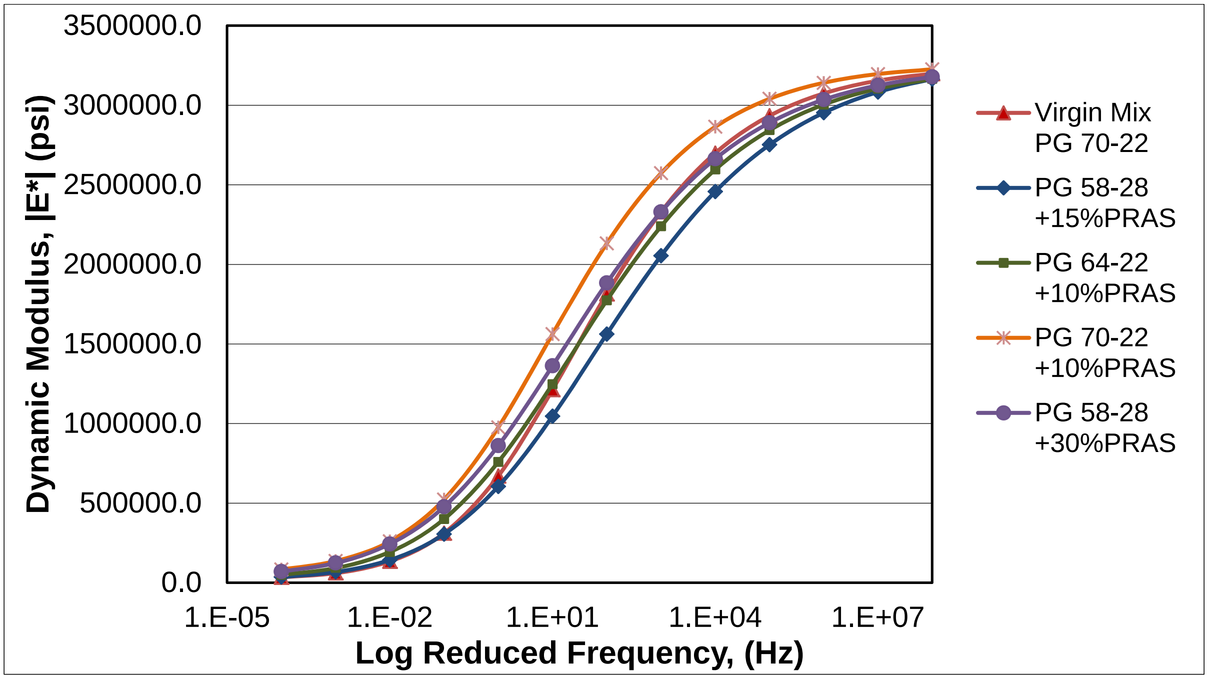


Figure 6.7 Dynamic Modulus Master Curves for 9.5C PRAS Mixes (Reference Temperature 70˚ F)

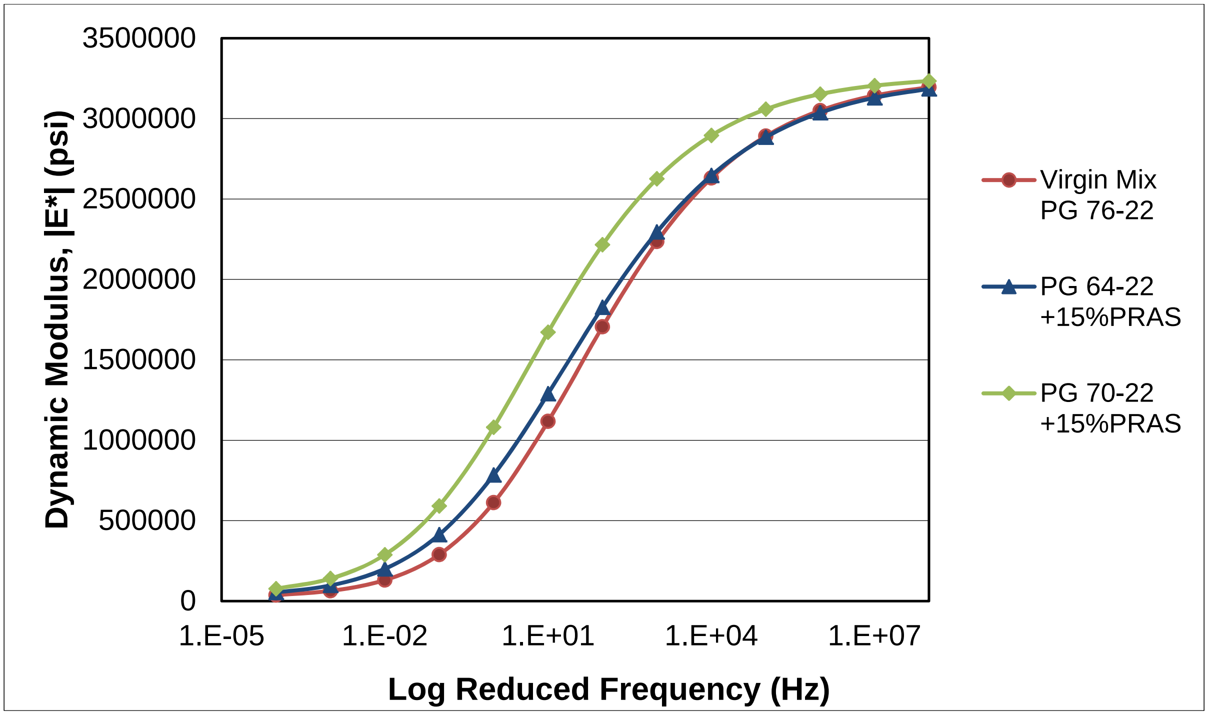


Figure 6.8 Dynamic Modulus Master Curves for 9.5D PRAS Mixes (Reference Temperature 70˚ F)

6.2.1 Ranking of PRAS Mixtures

Similar to RAP mixes, dynamic modulus values averaged over three test frequencies were used to calculate the modular ratio between the different PRAS mixes and that of the virgin (control) mix for a given temperature. Tables 6.7 through 6.8 show the modular ratios and rankings of the 9.5C and 9.5D PRAS mixtures at three different temperatures. At high temperatures, stiffer asphalt mixture is preferred to minimize rutting. Therefore the mixture with highest modular ratio was ranked best at 40 ˚C. However at low temperatures, stiffer mixtures are more prone to cracking. Therefore at 4 ˚C, mixtures with lower modular ratio are ranked higher. The less stiff mixes are assumed to have better resistance to fatigue cracking at intermediate temperatures. Therefore mixtures with lower modular ratio are ranked better at 20 ˚C.

For 9.5C PRAS mixes, PG 70-22 binder based mixture with 10% PRAS binder ranks better at high temperatures indicating better rutting performance. Conversely, at intermediate and low temperatures PG 58-28 binder with 15% PRAS binder and PG 64-22 with 10% PRAS binder are ranked better indicating better resistance to cracking. Overall, mixture with PG 64-22 binder incorporating 10% PRAS binder and PG 58-28 binder based mixture with 15% and 30% PRAS binder have modular ratios comparable to the virgin (control) mix at all temperatures indicating equivalent or better performance in terms of both rutting and cracking. For 9.5D PRAS mixes, PG 64-22 and PG 70-22 binder based mixtures incorporating PRAS binder had much higher modular ratios when compared to the control mix at high temperatures. Overall, mixture with PG 64-22 binder incorporating 15% PRAS binder was comparable to the virgin (control) mix at all temperatures indicating equivalent or better performance in terms of both rutting and cracking.

Table 6.7 Modular Ratios and Rankings of 9.5C PRAS Mixes

(a) Test Temperature 40 ˚C

Mix	Test Temp ˚C	Average Dynamic Modulus (MPa)	Modular Ratio	Ranking at 40 ˚C
PG 70-22 + 10%PRAS	40	1911	1.86	1
PG 58-28 + 30%PRAS	40	1754	1.71	2
PG 64-22 + 10%PRAS	40	1402	1.37	3
PG 58-28 + 15%PRAS	40	1098	1.07	4
Virgin Mix PG 70-22	40	1025	1.00	5

(b) Test Temperature 20 ˚C

Mix	Test Temp ˚C	Average Dynamic Modulus (MPa)	Modular Ratio	Ranking at 20 ˚C
PG 58-28 + 15%PRAS	20	4590	0.89	1
Virgin Mix PG 70-22	20	5138	1.00	2
PG 64-22 + 10%PRAS	20	5752	1.12	3
PG 58-28 + 30%PRAS	20	6316	1.23	4
PG 70-22 + 10%PRAS	20	7053	1.37	5

(c) Test Temperature 4 ˚C

Mix	Test Temp ˚C	Average Dynamic Modulus (MPa)	Modular Ratio	Ranking at 4 ˚C
PG 58-28 + 15%PRAS	4	11775	0.86	1
PG 64-22 + 10%PRAS	4	13099	0.96	2
Virgin Mix PG 70-22	4	13667	1.00	3
PG 58-28 + 30%PRAS	4	13920	1.02	4
PG 70-22 + 10%PRAS	4	15951	1.17	5

Table 6.8 Modular Ratios and Rankings of 9.5D PRAS Mixes

(a) Test Temperature 40 ˚C

Mix	Test Temp ˚C	Average Dynamic Modulus (MPa)	Modular Ratio	Ranking at 40 ˚C
PG 70-22 + 15%PRAS	40	2090	2.15	1
PG 64-22 + 15%PRAS	40	1458	1.50	2
Virgin Mix PG 76-22	40	972	1.00	3

(b) Test Temperature 20 ˚C

Mix	Test Temp ˚C	Average Dynamic Modulus (MPa)	Modular Ratio	Ranking at 20 ˚C
Virgin Mix PG 76-22	20	4752	1.00	1
PG 64-22 + 15%PRAS	20	5863	1.23	2
PG 70-22 + 15%PRAS	20	7808	1.64	3

(c) Test Temperature 4 ˚C

Mix	Test Temp ˚C	Average Dynamic Modulus (MPa)	Modular Ratio	Ranking at 4 ˚C
Virgin Mix PG 76-22	4	12931	1.00	1
PG 64-22 + 15%PRAS	4	13492	1.04	2
PG 70-22 + 15%PRAS	4	16343	1.26	3

6.3 Dynamic Modulus Test Results of MRAS Mixtures

Three replicate specimens for each of the MRAS mixture were tested using the AMPT device. Each specimen was tested at temperatures of 4˚C, 20˚C, and 40 ˚C and loading frequencies of 0.1, 1, and 10 Hz. Tables 6.9 and 6.10 show the dynamic modulus test results of 9.5C and 9.5D MRAS mixes, respectively. The dynamic modulus values shown in the table are averages of the three replicates tested for each mixture. In general, there is an increase in dynamic modulus values with the addition of MRAS binder, illustrating increased mixture stiffening. Dynamic modulus master curves were developed for each mixture at a reference temperature of 70 ˚F. Figure 6.9 through 6.11 show master curve comparisons for 9.5C and 9.5D MRAS mixes with different percentages of MRAS binder.

For 9.5C mix type, the mixture with PG 64-22 binder incorporating 15% MRAS binder and the mixture with PG 58-28 binder and 25% MRAS binder were softer than the virgin mix which used PG 70-22 binder at higher frequencies but the same mixes exhibited similar stiffness to that of virgin mix at lower frequencies. Mixture with PG 70-22 binder and 15% MRAS binder was stiffer than virgin mix at lower frequencies but exhibited similar stiffness to that of virgin mix at higher frequencies. Mixtures with PG 58-28 and PG 64-22 binder incorporating as high as 50% MRAS binder had similar or lower stiffness to that of virgin mix at high frequencies and had much higher stiffness than the virgin mix at lower frequency range. This illustrates that with an increase in MRAS binder percentage in the mixture, there is an increase in mixture modulus to a larger extent at lower loading frequencies/ high temperatures than at higher frequencies/ low temperatures; indicating an equivalent or better performance than virgin mixture.

For 9.5D mix type, the mixture with PG 70-22 binder incorporating 20% MRAS binder and the mixture with PG 64-22 binder and 50% MRAS showed similar stiffness to each other at all loading frequencies. The mixtures exhibited similar stiffness to that of the virgin mix which used PG 76-22 binder at upper half of the loading frequency range, and are significantly stiffer than virgin mix at lower half of the frequency range, indicating that addition of MRAS binder improves the mixture performance.

Table 6.9 Dynamic Modulus Test Results for 9.5C MRAS Mixes

Mix	Test Temp ˚C	Dynamic Modulus (MPa)		
		0.1 Hz	1 Hz	10 Hz
Virgin Mix PG 70-22	4	9656	13587	17757
	20	2584	4847	7982
	40	385	818	1874
PG 58-28 + 25%MRAS	4	7578	10993	14818
	20	2241	4003	6723
	40	441	842	1904
PG 64-22 + 15%MRAS	4	8575	12215	16131
	20	2438	4533	7533
	40	453	920	2046
PG 70-22 + 15%MRAS	4	10509	14137	17865
	20	3493	5918	9096
	40	662	1301	2705

Table 6.9 Continued

Mix	Test Temp ˚C	Dynamic Modulus (MPa)		
		0.1 Hz	1 Hz	10 Hz
PG 58-28 + 50%MRAS	4	9317	12234	15390
	20	3554	5533	8146
	40	861	1525	2818
PG 64-22 + 50%MRAS	4	10313	13648	17502
	20	4270	6385	8925
	40	987	1777	3196

Table 6.10 Dynamic Modulus Test Results for 9.5D MRAS Mixes

Mix	Test Temp ˚C	Dynamic Modulus (MPa)		
		0.1 Hz	1 Hz	10 Hz
Virgin Mix PG 76-22	4	8686	12756	17350
	20	2501	4516	7239
	40	411	765	1740
PG 70-22 + 20%MRAS	4	10518	13911	17458
	20	3665	6017	9138
	40	724	1417	2929
PG 64-22 + 50%MRAS	4	10118	13424	17328
	20	4035	6153	8798
	40	995	1759	3166

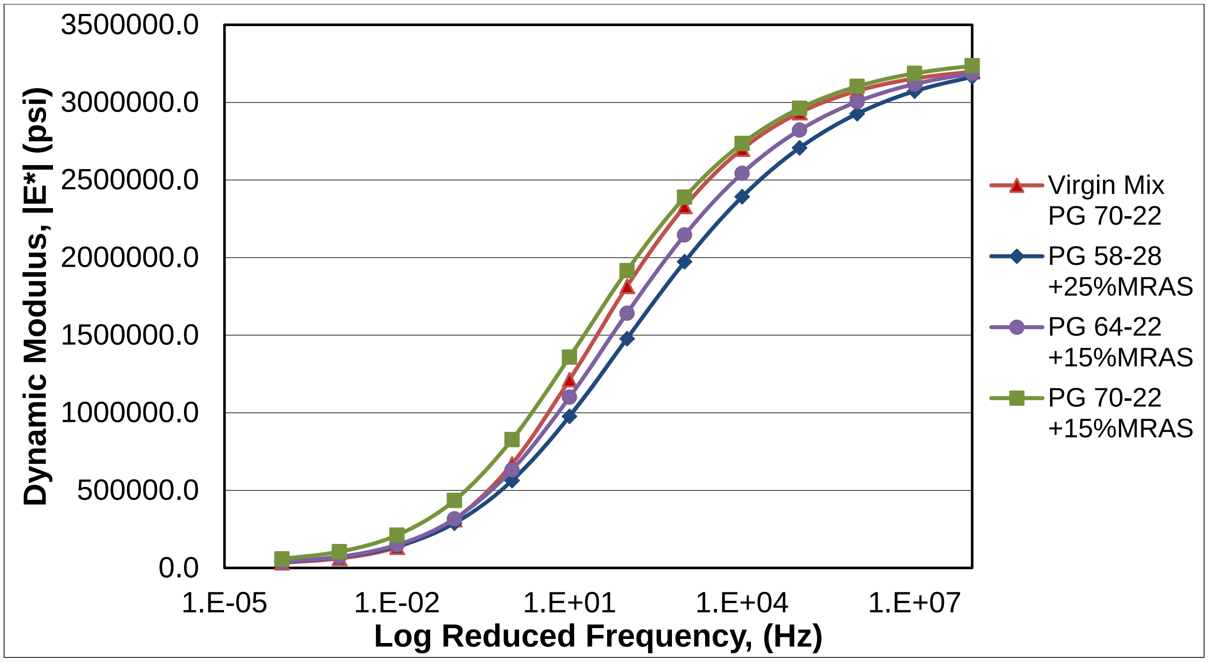


Figure 6.9 Dynamic Modulus Master Curves for 9.5C Mixes with less than 30% MRAS Binder (Reference Temperature 70˚ F)

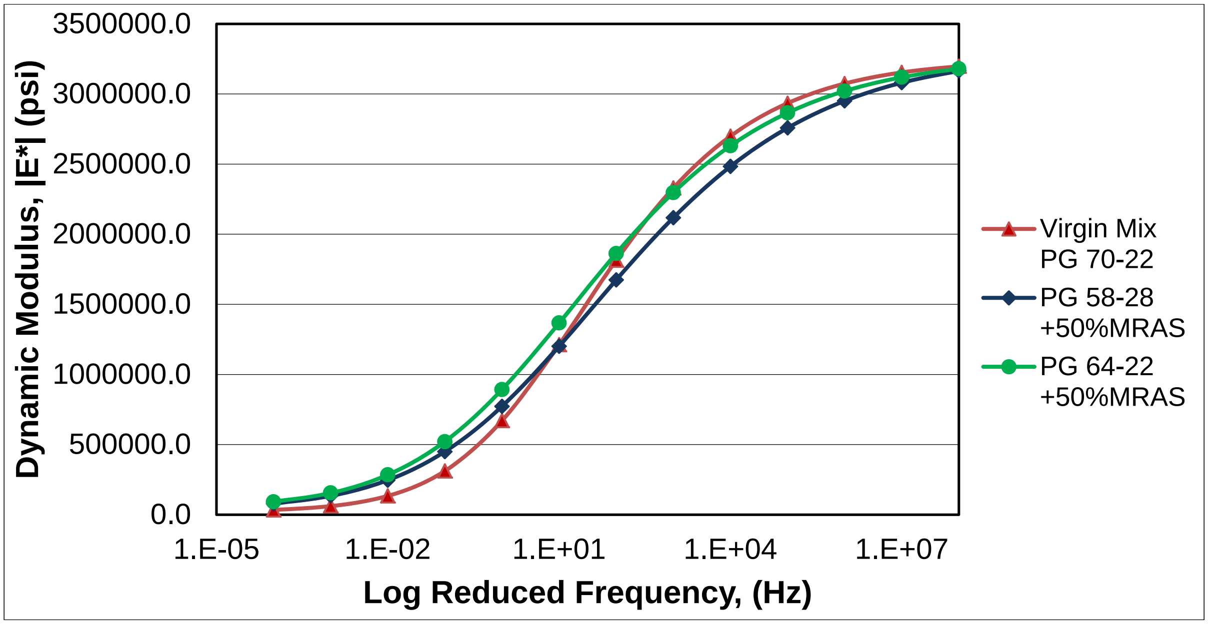


Figure 6.10 Dynamic Modulus Master Curves for 9.5C Mixes with 50% MRAS Binder (Reference Temperature 70˚ F)

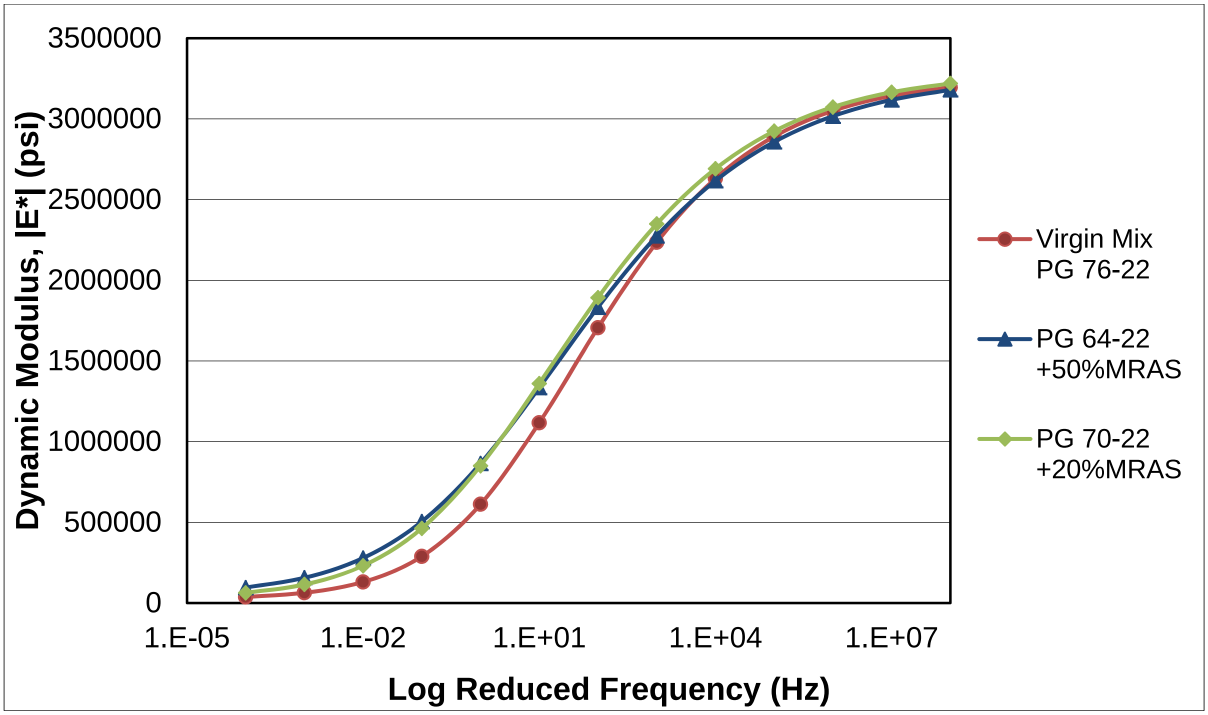


Figure 6.11 Dynamic Modulus Master Curves for 9.5D MRAS Mixes (Reference Temperature 70˚ F)

6.3.1 Ranking of MRAS Mixtures

Similar to RAP and PRAS mixes, dynamic modulus values averaged over three test frequencies were used to calculate the modular ratio between the different MRAS mixes and that of the virgin (control) mix for a given temperature. Tables 6.11 through 6.12 show the modular ratios and rankings of the 9.5C and 9.5D MRAS mixtures at three different temperatures. At high temperatures, stiffer asphalt mixture is preferred to minimize rutting. Therefore the mixture with highest modular ratio was ranked best at 40 ˚C. However at low temperatures, stiffer mixtures are more prone to cracking. Therefore at 4 ˚C, mixtures with lower modular ratio are ranked higher. The less stiff mixes are assumed to have better resistance to fatigue cracking at intermediate temperatures. Therefore mixtures with lower modular ratio are ranked better at 20 ˚C.

For 9.5C MRAS mixes, PG 64-22 and PG 58-28 binder based mixtures incorporating 50% MRAS binder rank better at high temperatures indicating better rutting performance. At intermediate temperatures, PG 64-22 and PG 58-28 binder based mixtures incorporating less than 30% MRAS binder rank better. However, modular ratios of the mixtures incorporating 50% MRAS binder and virgin mixtures is similar at 20 ˚C, and also the modular ratio of mixture with PG 70-22 and 15% MRAS binder is not too different from virgin mix, indicating no significant effect on fatigue performance. At low temperatures, PG 58-28 binder based mixtures are ranked well even with 50% MRAS binder. There is no significant difference in modular ratios between the MRAS mixtures and virgin mix at 4 ˚C. Overall, MRAS mixture modular ratios at all temperatures indicate equal or better performance to virgin mix in terms of both rutting and cracking.

For 9.5D MRAS mixes, PG 64-22 and PG 70-22 binder based mixtures incorporating MRAS binder had much higher modular ratios when compared to the control mix at high temperatures. At intermediate temperatures, virgin mix with PG 76-22 binder ranked highest. However, PG 64-22 binder based mixture with 50% MRAS binder and mixture with PG70-22 binder incorporating 20% MRAS had similar modular ratios. MRAS mixtures modular ratios were equal to that of virgin mix at 4 ˚C. Overall, MRAS mixture modular ratios at all temperatures indicated that performance of mixes improved with addition of MRAS.

Table 6.11 Modular Ratios and Rankings of 9.5C MRAS Mixes

(a) Test Temperature 40 ˚C

Mix	Test Temp ˚C	Average Dynamic Modulus (MPa)	Modular Ratio	Ranking at 40 ˚C
PG 64-22 + 50%MRAS	40	1987	1.94	1
PG 58-28 + 50%MRAS	40	1734	1.69	2
PG 70-22 + 15%MRAS	40	1556	1.52	3
PG 64-22 + 15%MRAS	40	1140	1.11	4
PG 58-28 + 25%MRAS	40	1062	1.04	5
Virgin Mix PG 70-22	40	1025	1.00	6

(b) Test Temperature 20 ˚C

Mix	Test Temp ˚C	Average Dynamic Modulus (MPa)	Modular Ratio	Ranking at 20 ˚C
PG 58-28 + 25%MRAS	20	4322	0.84	1
PG 64-22 + 15%MRAS	20	4835	0.94	2
Virgin Mix PG 70-22	20	5138	1.00	3
PG 58-28 + 50%MRAS	20	5744	1.12	4
PG 70-22 + 15%MRAS	20	6169	1.20	5
PG 64-22 + 50%MRAS	20	6527	1.27	6

(c) Test Temperature 4 ˚C

Mix	Test Temp ˚C	Average Dynamic Modulus (MPa)	Modular Ratio	Ranking at 4 ˚C
PG 58-28 + 25%MRAS	4	11130	0.81	1
PG 64-22 + 15%MRAS	4	12307	0.90	2
PG 58-28 + 50%MRAS	4	12313	0.90	3
Virgin Mix PG 70-22	4	13667	1.00	4
PG 64-22 + 50%MRAS	4	13821	1.01	5
PG 70-22 + 15%MRAS	4	14170	1.04	6

Table 6.12 Modular Ratios and Rankings of 9.5D MRAS Mixes

(a) Test Temperature 40 ˚C

Mix	Test Temp ˚C	Average Dynamic Modulus (MPa)	Modular Ratio	Ranking at 40 ˚C
PG 64-22 + 50%MRAS	40	1973	2.03	1
PG 70-22 + 20%MRAS	40	1690	1.74	2
Virgin Mix PG 76-22	40	972	1.00	3

(b) Test Temperature 20 ˚C

Mix	Test Temp ˚C	Average Dynamic Modulus (MPa)	Modular Ratio	Ranking at 20 ˚C
Virgin Mix PG 76-22	20	4752	1.00	1
PG 70-22 + 20%MRAS	20	6273	1.32	2
PG 64-22 + 50%MRAS	20	6329	1.33	3

(c) Test Temperature 4 ˚C

Mix	Test Temp ˚C	Average Dynamic Modulus (MPa)	Modular Ratio	Ranking at 4 ˚C
Virgin Mix PG 76-22	4	12931	1.00	1
PG 64-22 + 50%MRAS	4	13623	1.05	2
PG 70-22 + 20%MRAS	4	13962	1.08	3

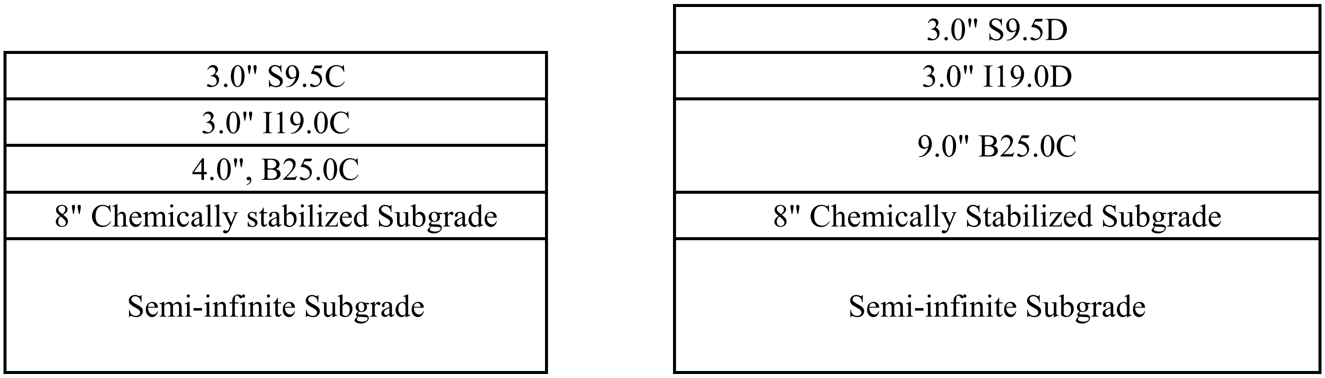
CHAPTER 7 - ASPHALT MIXTURE CHARACTERIZATION AND ECONOMIC ANALYSIS

7.1 MEPDG Analysis

AASHTOWare Pavement ME Design software (DARWin M-E), referred as MEPDG throughout this chapter was used to evaluate and predict the performance of surface mixtures incorporating recycled material with respect to fatigue cracking and rutting. The MEPDG software uses asphalt mixture and binder properties along with other inputs such as design reliability, climate, traffic loading and pavement layer structure and material properties to calculate the accumulated pavement damage over a specified design life. This allows the user to judge whether or not the input design thickness and/or materials met the expected performance during the design period.

The pavement sections used in the MEPDG analysis are shown in Figure 7.1. The pavement section layer properties are representative of typical pavement sections constructed to handle traffic levels corresponding to S9.5C and S9.5D mixes in North Carolina. The surface layer is the asphalt mixture designed in the laboratory and the corresponding mixture obtained from dynamic modulus test (|E*|) and binder properties obtained from dynamic shear rheometer test (G* and δ) were used as the Level 1 input parameters. The asphalt concrete base course layers are standard NCDOT designated mixtures with a nominal maximum aggregate size (NMAS) of 19 mm (I19.0C/ I19.0D) and 25 mm (B25.0C). Level 3 input parameters were used for base course layers based on NCDOT criteria. The model pavement sections were four lane highways with two lanes in design direction. An initial two-way

AADTT of 1200 and 1500 was assumed for 9.5C and 9.5D mixes, respectively, with a linear annual growth rate of 3% and operational speed of 60 mph. Climatic data for Raleigh-Durham station was used and analysis was conducted for 20 year design life.



(a) (b)

Figure 7.1 Pavement Section Used in MEPDG Analysis for (a) 9.5C Mixes (b) 9.5D Mixes

Failure criteria were defined as 25% of total pavement area cracked for fatigue cracking and 0.75 inches for total pavement rutting. The pavement performance was analyzed for all the designed recycled mixtures as surface layer. The results of MEPDG analyses for different mixtures are shown in Tables 7.1 and 7.2. None of the pavements reached the failure limit for any distress. It could be because the transfer functions are not explicitly calibrated to account for the effect of recycled material in asphalt mixtures. Fatigue cracking was not significant in the analyses, possibly due to a thick pavement test section. The models used in the prediction of fatigue and rutting calculate higher number of cycles to failure for stiffer mixes. The recycled mixtures had higher modulus values (stiffness) which resulted in increasing fatigue and rutting life.

Table 7.1 MEPDG Analysis Results for 9.5C Mixes

Surface Layer Mixture	Failure	Reliability Achieved
Virgin Mix PG 70-22	None	>98%
PG 58-28 + 25%RAP	None	>98%
PG 58-28 + 40%RAP	None	>98%
PG 64-22 + 12%RAP	None	>98%
PG 64-22 + 25%RAP	None	>98%
PG 64-22 + 40%RAP	None	>98%
PG 70-22 + 12%RAP	None	>98%
PG 70-22 + 25%RAP	None	>98%
PG 70-22 + 40%RAP	None	>98%
PG 58-28 + 15%PRAS	None	>98%
PG 58-28 + 30%PRAS	None	>98%
PG 64-22 + 10%PRAS	None	>98%
PG 70-22 + 10%PRAS	None	>98%
PG 58-28 + 25%MRAS	None	>98%
PG 64-22 + 15%MRAS	None	>98%
PG 70-22 + 15%MRAS	None	>98%
PG 58-28 + 50%MRAS	None	>98%
PG 64-22 + 50%MRAS	None	>98%

Table 7.2 MEPDG Analysis Results for 9.5DMixes

Surface Layer Mixture	Failure	Reliability Achieved
Virgin Mix PG 76-22	None	>98%
PG 64-22 + 40%RAP	None	>98%
PG 70-22 + 30%RAP	None	>98%
PG 70-22 + 40%RAP	None	>98%
PG 64-22 + 15%PRAS	None	>98%
PG 70-22 +1 5%PRAS	None	>98%
PG 70-22 + 20%MRAS	None	>98%
PG 64-22 + 50%MRAS	None	>98%

7.2 Economic Analysis

An economic analysis was performed as a basis for comparison between mixtures containing various amounts of recycled materials. It should be noted that economic analysis in this study is just a basic estimate for understanding differences in costs for using recycled mixtures over virgin mixtures. Since pavement performance analyses showed that none of the recycled mixtures failed for any kind of distresses during a 20 year design life, it eliminates the need for a life cycle cost analysis. The difference in only initial material costs for pavements constructed with designed recycled mixtures was calculated. Table 7.3 shows the assumptions used to calculate the cost of asphalt mixture.

Table 7.3 Assumptions Used for Asphalt Mixture Cost Estimates

Material	Cost Per Ton
Virgin Aggregates	$ 22
PG 76-22	$ 538
PG 70-22	$ 480
PG 64-22	$ 377
PG 58-28	$ 350
RAP	$ 15
RAS	$ 20

The cost of each of the recycled mixtures was calculated by assuming that recycled mixtures will have a reduction in cost equivalent to the amount virgin materials replaced by recycled materials in the mixture, but will incur an additional cost for recycled material. The percentages of recycled material by weight of mix were calculated using asphalt contents of 5% for RAP, 14.7% for MRAS and 18.6% for PRAS which were determined for the materials used in this study. These percentages vary for recycled materials containing different amounts of asphalt and should be calculated separately for each new material. Tables 7.4 and 7.5 show the cost savings for various recycled surface mixtures. Overall, the economic analysis indicates that incorporating recycled materials in surface mixtures results in material cost savings up to 40%. Mixtures incorporating RAP material resulted in 10% to 40% of cost savings. PRAS based mixtures cost savings were about 4% to 25%. Mixtures containing MRAS resulted in 8% to 35% cost savings. It can be noted that incorporating recycled materials up to allowable recycled binder limits for a given virgin binder grade could provide more flexibility in using higher amounts of recycled materials in asphalt pavements and will help reduce material costs. However, it is essential to note this is achieved only when asphalt pavement is designed properly with appropriate materials, proportions, adequate thickness and construction parameters.

Table 7.4 Material Cost Savings for 9.5C Mixes

Surface Layer Mixture	Total Asphalt Content	% Recycled binder by weight of Total Binder	% Recycled Material by Weight of Total Mix	Cost of Virgin Binder	Cost of Virgin Aggregates	Cost of Recycled Material	Total Cost ($/Ton)	% Savings
Virgin Mix PG 70-22	6.1	0	0	29.3	20.7	0.0	50	-
PG 58-28+25%RAP	5.8	25	29.00	15.2	14.7	4.4	34.2	32%
PG 58-28+40%RAP	5.6	40	45.00	11.7	11.4	6.8	29.8	40%
PG 64-22+12%RAP	6.1	12	15.00	20.2	17.5	2.3	39.9	20%
PG 64-22+25%RAP	5.8	25	29.00	16.4	14.7	4.4	35.4	29%
PG 64-22+40%RAP	5.6	40	45.00	12.6	11.4	6.8	30.7	39%
PG 70-22+12%RAP	6.1	12	15.00	25.7	17.5	2.3	45.5	9%
PG 70-22+25%RAP	5.8	25	29.00	20.9	14.7	4.4	39.9	20%
PG 70-22+40%RAP	5.6	40	45.00	16.1	11.4	6.8	34.2	32%
PG 58-28+15%PRAS	6.2	15	5.90	17.9	19.6	1.2	38.6	23%
PG 58-28+30%PRAS	6.2	30	8.70	16.0	19.1	1.7	36.9	26%
PG 64-22+10%PRAS	6.2	10	2.90	21.3	20.1	0.6	42.0	16%
PG 70-22+10%PRAS	6.2	10	2.90	27.2	20.1	0.6	47.9	4%
PG58-28+25%MRAS	5.8	25	9.00	15.7	19.0	1.8	36.5	27%
PG64-22+15%MRAS	6.1	15	5.70	19.8	19.6	1.1	40.6	19%
PG70-22+15%MRAS	6.1	15	5.70	25.3	19.6	1.1	46.0	8%
PG58-28+50%MRAS	5.7	50	17.70	10.8	17.4	3.5	31.8	36%
PG64-22+50%MRAS	5.7	50	17.70	11.7	17.4	3.5	32.6	35%

Table 7.5 Material Cost Savings for 9.5D Mixes

Surface Layer Mixture	Total Asphalt Content %	% Recycled binder by weight of Total Binder	% Recycled Material by Weight of Total Mix	Cost of Virgin Binder	Cost of Virgin Aggregates	Cost of Recycled Material	Total Cost ($/Ton)	% Savings
Virgin Mix PG 76-22	6.1	0	0	32.8	20.7	0.0	53.5	-
PG 64-22+40%RAP	5.6	40	45.0	12.6	11.4	6.8	30.7	42%
PG 70-22+30%RAP	5.7	30	35.0	19.0	13.4	5.3	37.6	29%
PG 70-22+40%RAP	5.6	40	45.0	16.1	11.4	6.8	34.2	35%
PG 64-22+15%PRAS	6.1	15	5.9	18.9	19.6	1.2	39.6	25%
PG 70-22+15%PRAS	6.1	15	5.9	24.0	19.6	1.2	44.8	15%
PG70-22+20%MRAS	5.8	20	7.2	22.8	19.4	1.4	43.6	18%
PG64-22+50%MRAS	5.7	50	17.7	11.7	17.4	3.5	32.6	38%

CHAPTER 8 - CONCLUSIONS AND RECOMMENDATIONS

8.1 Conclusions

The following conclusions can be drawn from this study:

- The dynamic shear rheometer test results indicate that stiffness of the blended binder increased with an increase in the proportion of recycled binder. Among all the blended binders, blends that contained PRAS binder had the highest stiffness. This is because PRAS binder is an air blown asphalt that has undergone additional aging during its service life on roof tops.
- Allowable recycled binder limits were determined using blending charts for three virgin binders: PG 58-28, PG 64-22 and PG 70-22 and recycled asphalt from RAP, MRAS and PRAS to satisfy the performance grade (PG) specifications for S9.5C and S9.5D mixes, which use virgin binder grades of PG 70-22 and PG 76-22, respectively. In order to meet the high and intermediate temperature criteria of PG 70-22 binder (S9.5C), PG 58-28 binder had to be blended with 20% to 55% RAP binder, or with 25% to 70% MRAS binder, or with 5% to 35% PRAS binder. PG 64-22 binder had to be blended with 10% to 40% RAP binder, or with 15% to 70% MRAS binder, or with 5% to 25% PRAS binder. PG 70-22 binder could be blended with up to 40% RAP binder or with 20% PRAS binder. In order to meet the high and intermediate temperature criteria of PG 76-22 binder (S9.5D), PG 64-22 binder had to be blended with 40% to 55% RAP binder, or with 40% to 75% MRAS binder, or with 10% to 30% PRAS binder. PG 70-22 binder had to be blended with 30% to 60%

RAP binder, or with 5% to 30% PRAS binder, or with a minimum of 20% MRAS binder.

- Multiple linear regression equations were developed to determine the allowable recycled binder limits for RAP-MRAS and RAP-PRAS binder combinations with PG 58-28 and PG 64-22 binders at high and intermediate temperatures. Different RAP-MRAS and RAP-PRAS combinations were obtained using these equations to satisfy the performance grade (PG) specifications for S9.5C and S9.5D mixes at high and intermediate temperatures. Reasonable optimized proportions of recycled binders could be selected after comparing individual recycled binder limits for a given virgin binder.
- The amount of recycled material that can be incorporated into a mix depends on the virgin binder grade used in the mix as well as the aggregate design structure. Recycled materials contain a high amount of material passing the 0.075 mm sieve. This higher amount of mineral aggregates is generally the limiting factor to the amount of recycled material that can be added to an asphalt mixture. RAP was limited to 40% by weight of binder for both S9.5C and S9.5D mixes. PRAS was limited to 30% by weight of binder with PG 58-28 binder for S9.5C mixes. The PRAS binder limits for PG 64-22 and PG 70-22 binders were 10% in S9.5C mixes and to 15% in S9.5D mixes. This shows that the virgin binder that is added must effectively act as the rejuvenator for the PRAS. MRAS binder limits were as high as 50% with PG 58-28 and PG 64-22 binders for S9.5C and S9.5D mixes, respectively. This indicates that

MRAS binders are softer and could blend with virgin binders more effectively in mixes when compared to that of PRAS binders.

- The mix design data illustrated that optimum asphalt content decreased as the amount of RAP and MRAS increased. This could be because the absorption of recycled material is less when compared to virgin aggregates. The increase in asphalt content for PRAS mixes could be due to the increase in stiffness of mix due to PRAS binder. It was concluded that PRAS is stiffer when compared to MRAS and it is necessary and important to differentiate MRAS from PRAS when used in asphalt mixes.
- There is a slight decrease in percent VMA and VFA with increasing recycled binder content in a mix. This could be due to the extent of blending between recycled and virgin asphalt binder, since the aggregate design structure was similar to virgin mixtures. Volumetric properties of all the mixes with recycled materials met the NCDOT requirements.
- Dynamic modulus data and master curves illustrate that stiffness of the mixtures increased with increase in percent recycled binder in a mix for a given virgin binder. Modular ratios indicate that for 9.5C RAP mixes, PG 70-22 and PG 64-22 binder based mixtures with 40% RAP binder rank better at high temperatures indicating better rutting performance with addition of recycled binder. Conversely, at intermediate and low temperatures PG 58-28 binder with 25% RAP binder and PG 64-22 with 12% RAP binder are ranked better, indicating better resistance to cracking. Overall, mixtures with PG 64-22 and PG 70-22 binders and up to 25% RAP binder and PG 58-28 based mixtures with 25% to 40% RAP binder are comparable or

similar to the virgin (control) mix at all temperatures indicating equivalent or better performance in terms of both rutting and cracking. For 9.5D RAP mixes, mixtures with PG 64-22 and PG 70-22 binders incorporating RAP binder had much higher modular ratios when compared to the control mix.

- Modular ratios indicate that for 9.5C PRAS mixes, the mixture with PG 64-22 binder incorporating 10% PRAS binder and the mixture with PG 58-28 binder and 15% and 30% PRAS binder are comparable to the virgin (control) mix at all temperatures. For 9.5D PRAS mixes, PG 64-22 based mixture incorporating 15% PRAS binder was comparable to the virgin (control) mix at all temperatures . For 9.5C and 9.5D MRAS mixes, all the designed mixtures including PG 64-22 and PG 58-28 binder based mixtures incorporating 50% MRAS binder are comparable or similar to the virgin mixtures in terms of rutting and cracking performance. Overall, performance of mixes improved with addition of MRAS.
- MEPDG analysis showed that none of the model pavements with designed recycled mixtures as surface layer reached the failure limit for any distress. The economic analysis indicates that incorporating recycled materials in surface mixtures results in material cost savings up to 40% for RAP mixes, 25% for PRAS mixes and 35% for MRAS mixes
- Incorporating recycled materials up to allowable recycled binder limits for a given virgin binder grade could give more flexibility in using higher amounts of recycled materials in asphalt pavements and will help reduce material costs and increase the longevity of the nation’s roadways when properly designed.

8.2 Recommendations

- This study assumes 100% blending of recycled and virgin binder but in reality, there is most likely only a partial blending between the RAS and virgin binders that occurs in the mixture during production and placement. Further research should be done to determine extent of blending and to maximize the amount of blending that occurs so that the pavement performs well over its design life.
- Additional studies should be conducted using various additives to rejuvenate the RAS binder so that mixtures can accommodate more recycled material and also perform well with respect to both rutting and fatigue cracking.
- Further investigation should be conducted to study variability due to source of recycled material on the allowable limits.
- Rheological properties of the blended binders at low temperatures were not considered in this study. Thermal cracking is one of the major distresses cracking which normally occurs when the temperature at the surface of the pavement drops sufficiently to produce thermally induced shrinkage stresses in excess of the tensile strength of the HMA layer. Thus, there is a need to evaluate the properties of blended binders at low temperatures in order to determine the acceptable limits of recycled material with respect to thermal cracking in asphalt mixes.

IMPLEMENTATION AND TECHNOLOGY TRANSFER PLAN

The products of this research are the allowable recycled binder limits for virgin binders to satisfy the performance grade (PG) specifications for S9.5C and S9.5D mixes in North Carolina. This study will enable design engineers the knowledge of the effects different recycled binder types have on surface mixes and to determine virgin binder grade to be used with different types and percentages of recycled binder.

The results and conclusions of this study could be used as a guide to change specifications to limit recycled materials based on the percent recycled binder they contribute to the total binder percentage instead of the percent by total weight of mixture**.** For the implementation of this product, there is no additional training needed as the research product is the allowable recycle binder limits for surface mixtures and testing procedure of which personnel are already trained for.

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