RESEARCH & DEVELOPMENT

DETERMINING RECYCLED ASPHALT BINDER LIMITS CONTRIBUTED BY WASTE MATERIALS

N. PAUL KHOSLA, PhD
SRIKANTH SREE RAMOJU
NIVAS PRABU
DEPARTMENT OF CIVIL, CONSTRUCTION, AND ENVIRONMENTAL ENGINEERING
NORTH CAROLINA STATE UNIVERSITY

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by

N. Paul Khosla
Srikanth Sree Ramoju
and
Nivas Prabu

in Cooperation with

North Carolina Department of Transportation

Department of Civil Engineering
North Carolina State University

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16. Abstract

Reclaimed asphalt pavement (RAP) and reclaimed asphalt shingles (RAS) hold significant value with regard to the recycled binder and the recycled aggregate both of which can be incorporated into hot mix asphalt (HMA). Research on incorporating RAP and RAS into HMA has been conducted extensively and the methodology is to adjust the virgin aggregate gradation and amount of virgin binder to accommodate the portion of aggregate and binder contributed by waste materials. Specifications for recycled materials in HMA are based on the percentage weight of recycled materials by weight of total mix in HMA. However, limiting the percentage of recycled materials by total weight of the mix does not necessarily provide sufficient information on properties of blended binder.

In this research study, rheological testing was initially conducted on blended binders (RAP/RAS with virgin binder) using a dynamic shear rheometer and the results were compared to the properties of virgin binders. Limits on the amount of recycled binder in the blended binder were determined from blending charts to meet current Superpave specifications. These limits were used as the guideline for the Superpave mixture design procedure. Virgin mixtures and recycled mixtures were designed based on the recycled binder limits determined from the blending charts and each of these mixtures was tested on the asphalt mixture performance tester (AMPT) for measuring the dynamic modulus. The dynamic modulus was then used to estimate the fatigue and rutting life of each of the mixtures using a model pavement section in the AASHTOware Pavement M-E Design and was compared to the fatigue and rutting life of virgin HMA mixtures. Limits on the amounts of recycled binders were calculated based on the fatigue and rutting life of different mixtures and were then compared to the limits established from the blending charts. The lower of the two limits was selected for recommending a set of specifications for incorporating waste materials in HMA to the NCDOT.

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EXECUTIVE SUMMARY

Recycling of asphalt pavements and shingles is crucial to relaxing the growing demand for paving materials including both asphalt binder and aggregates. The idea of recycling asphalt pavements and shingles has been in practice for more than a couple of decades. Reclaimed Asphalt Pavement (RAP) and Reclaimed Asphalt Shingles (RAS) hold significant value with regard to the recycled binder and the recycled aggregate both of which can be incorporated into Hot Mix Asphalt (HMA). Since the binder in the RAP and RAS has aged considerably during its service life, incorporating RAP and RAS into HMA is accompanied with some undesirable effects and it is often required to change the grade of the virgin binder being used in HMA to compensate for the stiff recycled binder. Significant research has been conducted on the incorporation of RAP & RAS into HMA and the results have been documented. The most common methodology included making adjustments in the virgin aggregate gradation and amount of virgin binder to accommodate the portion of aggregate and binder contributed by the waste materials (RAP & RAS). Many states have adopted specifications for recycled materials in HMA based on the percentage weight of recycled materials by weight of total mix in HMA. However, limiting the percentage of recycled materials by total weight of the mix does not necessarily provide sufficient information on properties of the blended binder. These properties are crucial to performance of the pavements in the areas of fatigue cracking, rutting and thermal cracking as distresses.

Therefore, in this research rheological study was initially conducted on blended binders (RAP or RAS and Virgin binder) using a Dynamic Shear Rheometer (DSR) and the results were

compared to the properties of virgin binders. From the obtained results, blending charts were plotted and limits on the amount of recycled binder in the blended binder determined in accordance with the current Superpave specifications. These limits were used as a guideline for the Superpave mixture design procedure and each of the mixtures thus developed was tested on the AMPT (Asphalt Mixture Performance Tester) for measuring the dynamic modulus. The dynamic modulus was then used to estimate the fatigue and rutting life of each mix using a model pavement section in the AASHTOware Pavement M-E Design and was compared to that of the virgin HMA mixture. Limits on the amount of recycled binder were calculated based on the fatigue and rutting life of different mixtures and were then compared to the limits established from the blending charts. The lower of the two limits was selected for recommending a set of specifications for incorporating waste materials in HMA to the NCDOT.

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1. INTRODUCTION AND PROBLEM STATEMENT

As the demand for paving materials increases exponentially with limited availability, there is a need to study the various ways to incorporate recyclable waste materials in future pavements. Although the idea of making use of recyclable waste materials has been in practice for more than two decades now, there has been a constant effort to improve the efficiency of its usage. Significant progress has been made and various methods have been devised and documented to incorporate the waste materials into Hot Mix Asphalt (HMA). A large portion of the recyclable waste materials is a product of milling the aged and deteriorated pavements and this material is often termed as Recycled Asphalt Pavement (RAP). The North Carolina Department of Transportation also recognizes a second source of waste materials in shingles also called Recycled Asphalt Shingles (RAS). Recyclable Shingles are categorized into two types; MRAS (Manufacturer Waste Recycled Asphalt Shingles) & PRAS (Post-consumer Recycled Asphalt Shingles). MRAS are those waste shingles that do not make it to consumers' roofs and are mainly collected at the manufacturing site. Whereas PRAS are those set of waste shingles that are rendered useless and discarded from rooftops.

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 method involves, carefully extracting the binder from RAP or RAS and characterizing the extracted binder for its rheological properties and determining the gradation of the left over aggregate by sieve analysis. Once the properties of the waste materials have been determined, stockpiles of RAP and RAS are treated as any other aggregate stockpile in HMA mixture design. Adjustments are made in the virgin aggregate gradation and the total virgin asphalt binder content to accommodate the contribution by RAP, RAS or a combination of both. Performance tests are conducted on the mixes consisting of varying proportions of waste materials and the fatigue and rutting life of a simulated pavement structure is calculated based on the performance test data. Depending on the life cycle cost analysis of a similar pavement thus constructed, economically viable limits are established on the amount of waste materials that can be introduced into HMA pavements. 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 emphasize the percentage of allowable recyclable material based on the percent binder they contribute will allow for the optimal amount of recycled materials to be used since the binder content of the recycled material will be considered.

Use of RAP as a recyclable waste material is generally limited to 30% by weight of total mix due to fears of high variability and quality issues within RAP resulting in overall poor performance of the pavement in the long run. MRAS and PRAS are a product of shingles that contain very fine aggregate and the binder is usually air-blown oxidized binder that results in high stiffness. The presence of a very high proportion of mineral filler particles and very stiff binder makes it unreasonable to prepare HMA mixtures with large proportions of RAS. These two characteristics of RAS stand as the limiting factors for the inclusion of RAS in HMA mixtures and the usual limits are as low as 6-7% by weight of total mixture. Although the gradation of aggregates in MRAS and PRAS are relatively similar, the binder stiffness is significantly different as Post-Consumer Shingles are further aged during their service life whereas Manufacturer Waste Shingles are not. Therefore, a clear distinction between the two types of RAS is made through the entire course of this research study.

The goal of this study is to prepare a set of specifications for limiting the amount of recycled waste materials in HMA mixtures by placing an emphasis on the amount of total recycled binder contributed by the waste materials. This is achieved by first conducting a rheological study on the virgin and blended binders using the Dynamic Shear Rheometer (DSR) for plotting blending charts and determining the binder limits; secondly, using these binder limits to design HMA mixtures with varying proportions of waste materials and, finally testing these mixes on the Asphalt Mixture Performance Tester (AMPT) to determine the dynamic modulus and estimating the life cycle costs of test pavements constructed from each different mixture.

2. LITERATURE REVIEW

This chapter provides an overview of the various studies that have been conducted with an objective to understand the effect of incorporating RAP and RAS into HMA mixtures. Since both RAP and RAS have a great potential of being recycled in the pavement industry and thus eliminating the need to be disposed of in landfill sites, a substantial amount of work has been done in this area.

The research conducted by Beth Visintine “An Investigation of Various Percentages of Reclaimed Asphalt Pavement on the Performance of Asphalt Pavements” focused on determining the effects of RAP on the pavement performance (1). The PG grades of asphalt binders blended with various percentages of binders recovered from RAP were analyzed by conducting Superpave binder tests. Performance tests on mixes were later conducted to analyze the performance of the pavement mixes fabricated with binders blended with RAP and the data obtained from these tests were used to perform economic analysis to determine the economic impact of using higher percentages of RAP in pavements.

Two sources of RAP were selected with varying RAP aggregate gradations and binder contents, so that the results of this project could be applied for a much wider scope of RAP properties. RAP material properties such as binder content, aggregate gradation, aggregate specific gravity and binder rheology were determined by Superpave testing for both sources of RAP. Virgin binders were selected such that they closely resembled the binder that was practically used in design of pavements in North Carolina. Superpave tests were conducted on virgin binders to verify the PG grades and rheological properties of the selected binders. Aggregate sources with a maximum nominal size of 9.5mm and 19.0mm were selected from Westgate and Pineville, respectively. Properties of the virgin aggregates such as their specific gravities and gradations were determined for further design.

Virgin binders were blended with varying proportions of binders recovered from RAP and they were subjected to Superpave tests to determine their rheological properties such as shear modulus (G*) and phase angle (δ). Blending charts were developed using these rheological properties to determine the limits of RAP binder that can be used in the pavement mixtures. The blended binders were subjected to rolling thin film oven (RTFO) aging and pressure aging vessel (PAV) aging to simulate aging due to mixing, construction process and aging of pavement during its service life in the field, respectively. Similar binder tests were conducted on these aged binder samples and blend charts were generated.

The blending charts were used to determine the minimum and maximum limits of RAP to be blended with the virgin binders using the specifications $G^*/\sin\delta \geq 1.0$ kPa, $G^*/\sin\delta \geq 2.2$ kPa and $G^*\sin\delta \leq 5000$ kPa for each of the original aged, RTFO aged and PAV aged binder samples, respectively. These conditions were used to determine the high and intermediate temperature characteristics of the binders.

Similarly, Superpave Bending Beam Rheometer (BBR) tests were conducted to determine the low temperature characteristics of the binders. Blending charts were developed for all the binder mixes to determine the maximum limits of RAP. From the limits established through these binder tests the following conclusion as shown in Table 2-1 was reached with respect to the allowable percentages of RAP to satisfy all PG 64-22 specifications.

Table 2-1. Minimum and Maximum Percentage of RAP Binder Required to Satisfy all PG 64-22 Specifications (1)

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

These limits were used accordingly in the mix design process by choosing the suitable trial gradation and asphalt binder content for each mixes. The design aggregate and design binder content were chosen by ensuring that the volumetric properties of the mixes satisfied the Superpave volumetric criteria as specified by NCDOT.

The Frequency Sweep Test at Constant Height (FSTCH) was conducted at varying frequencies at 20°C to calculate the complex modulus and phase angle which were later used to perform comparative studies between virgin mixtures and mixtures blended with varying proportions of RAP. The complex modulus values were used to predict the pavement's fatigue life. The fatigue life of pavements constructed using mixtures with different proportions of RAP were subsequently compared to perform economic analysis. The Repeated Simple Shear Test at Constant Height (RSSTCH) was used to measure the plastic strains of the test specimens which were later used to evaluate the rutting resistance characteristics of the pavement.

The results from FSTCH and RSSTCH tests were used to carry out performance analysis based on models developed by Strategic Highway Research Program (SHRP) and Asphalt Institute (AI). Fatigue and rutting life cycles of the pavements were determined using these models. The results showed an increasing trend in fatigue life performance with increase in the percentage of RAP in the blended mix. This is expected as RAP is stiffer and contributes to increased stiffness resulting in smaller strains and thus increasing fatigue life cycles.

Similarly, rutting analysis was conducted using both SHRP and AI models. The results showed an increasing trend in life cycle of the pavement with respect to rutting with increase in RAP percentage which is expected as the stiff RAP contributes to reduced shear plastic strains providing resistance to rutting.

Based on the life cycles determined from the above models, life time economic analysis of the pavements constructed using various percentages of RAP was performed. The study concluded that total life time cost savings of around 26-28% and 35-37% can be achieved for pavements that were constructed using 30% and 40% RAP by weight of total mixture, respectively.

The study conducted by Soleymani, McDaniel and Rebecca on “Recommended Use of Reclaimed Asphalt Pavement in the Superpave Mix Design Method” initially focused on the binder extraction and recovery procedures of RAP in order to recommend an appropriate method for use in the Superpave system (2). Suitable virgin and RAP samples were chosen with a view of analyzing materials with different properties. Two virgin binders were chosen such that one was soft base asphalt that could be used in colder places and the other was a medium graded asphalt binder that could be used in warmer regions. Three RAP samples were selected from different regions with low, medium and high stiffness values, respectively. The critical temperatures for each of the virgin asphalt were determined by developing blend charts after performing rheological binder testing. The viscosities of the RAP samples were also determined using a rotational viscometer. The chosen virgin samples and RAP binders were subjected to short term and long term aging. Binder blends containing recycled binder contents ranging from 10% to 40% were prepared. Both 100% virgin binders and 100% binders extracted from RAP were also considered for binder testing.

A “black rock study” was also carried out to investigate the behavior of the RAP materials when mixed with the virgin aggregate and binder. The objective was to observe whether the

binder from RAP material actually blends with the virgin binder in a mix. In order to evaluate the significance of the blending of RAP with virgin binders, three concepts were studied in this project. They were black rock, actual practice and total blending. In the black rock concept no RAP binder was used in the mix. The actual practice samples had RAP aggregates containing recycled binder that were used in the mix. In the case of total blending, the RAP and virgin binders were blended before being used in the mix design procedure. These three concepts were compared using various performance testing procedures to determine whether actual blending of RAP and virgin binders take place and whether the blending effect is significant.
A binder effect study was performed to evaluate the effect of RAP content and it's stiffness on the property of the blend mix. This study also discussed the selection of virgin asphalt binder to achieve the target blended mix grade. The study concluded that RAP does not behave as a black rock since the black rock samples were found to provide performance test results that were completely different from the standard results obtained from mixtures containing RAP. Thus, the concept of blending charts was found to appropriately represent actual blending conditions.

Superpave tests were conducted on the selected levels of blend mixes. Frequency Sweep (FS), Simple Shear (SS) and Repeated Shear at Constant Height (RSCH) were conducted to characterize the mixtures at high and intermediate temperatures.

Frequency Sweep test was performed to determine the complex shear modulus (G*) and phase angle (δ) at a wide range of frequencies from 0.01 Hz to 10 Hz and at temperatures of 4°C, 20°C & 40°C. As expected, the stiffness values were found to increase with the increase in RAP content except in the samples prepared using black rock concept. This was due to the absence of RAP binder in the mix. Similarly, Simple Shear tests were conducted on the samples at 4°C, 20°C & 40°C by applying shear loads at 70 kPa/sec. The maximum shear deformation for each sample was measured. As expected, the shear deformation was found to reduce with increase in RAP content except in the case of black rock concept. Repeated Simple Shear tests yielded similar conclusions where the black rock samples showed higher shear strains at 40% RAP when compared with actual practice and total blending concepts.

The effect of aging on the three cases was studied by testing the samples at 4°C & 20°C using Frequency Sweep test and Simple Shear tests after subjecting them to long term aging. The results from these tests on long term aged samples followed a similar trend that was obtained from original aged samples where actual practice and total blending samples were indistinguishable while they were different from black rock samples. All these results indicate that the RAP blends effectively with the virgin binders and it has a significant effect on the performance tests of the mixtures, which would indicate significant effects on the performance of the pavements.

Table 2-2. Mixtures ETG Guidelines for RAP (2)

RAP Percentage	Recommended Virgin Asphalt Binder
Less than 15%	No change in binder selection
15-25%	Select virgin binder one grade softer than the normal
Greater than 25%	Follow blending chart recommendations

The Table 2-2 “Mixtures ETG Guidelines for RAP” concludes that there exists a threshold level of RAP below which its binding effect is negligible. It indicates that the level is in the interim of 10% to 20% depending on the stiffness of the RAP. These findings validate the three concepts for the usage of RAP in a HMA mix as recommended by the Mixture Expert Task Group.

The research work by Sondag, Chadbourn and Drescher, on “Investigation of Recycled Asphalt Pavement (RAP) Mixtures” had two main objectives (3). The first objective was to sample RAP stockpiles from around the state of Minnesota to characterize the typical properties of RAP gradation and its binder properties. The second objective was to develop a mix design methodology using the Superpave approach to proportion the materials in the mixtures containing RAP. RAP binder was extracted using solvent extraction method and ignition method on two RAP sources namely District 6 and District 8. The gradations of the retained aggregates were determined. Samples were compacted in the laboratory using Superpave gyratory compactor. Samples were prepared as shown in Table 2-3 with varying percentages of RAP from both the sources which were blended with virgin asphalt binders PG 58-28, PG 52-34, and PG 46-40. This matrix was designed to determine the amount of RAP and the grade of virgin asphalt binder which can be added to the mixtures in order to yield mixture properties that were considered acceptable for a mixture composed entirely of virgin materials.

Fine aggregate from Lakeland, Minnesota pit and coarse aggregate from the Granite Falls, Minnesota quarry and fine aggregates from Dresser, Wisconsin were blended and used for gradations for virgin mixtures. A control mixture was chosen from the various possible blends and it was ensured that all volumetric requirements were satisfied.

The RAP aggregates were blended with the virgin aggregates accordingly to achieve a gradation similar to the control mixture. It was possible to blend a maximum of 40% of District 6 RAP and virgin aggregate to produce a gradation similar to the control gradation while only a maximum of 30% District 8 RAP could be blended with control aggregate to achieve a gradation similar to the control gradation due to the large amount of fine aggregate in District 8 RAP.

Ignition oven and solvent extraction methods were used to extract asphalt from RAP and determine their binder contents. The PG grades of the recovered binders were also determined. The samples were tested for resilient modulus, complex modulus and moisture sensitivity. The moisture sensitivity tests were conducted to determine how durable or susceptible the mixtures were when they were exposed to moisture. The complex modulus test was conducted using the Indirect Tensile Test setup (IDT).

Table 2-3. Test Matrix for Materials (3)

RAP Content		**0%**			**15%**			**30%**			**40%**		
PG Grade		46 -40	52-34	58-28	46-40	52-34	58-28	46-40	52-34	58-28	46-40	52-34	58-28
RAP Source	District 6	X	X	X	X	X	X	X	X	X	X	X	X
	District 8				X	X	X	X	X	X			

Complex modulus test was performed by using the MTS 810 electro hydraulic test system. Complex modulus data collected at lower temperatures were found to have more variability than data collected from other temperatures. The asphalt binder grade was found to have a pronounced effect on the complex modulus values up to the 25°C test temperature. The effect was not nearly as pronounced at 32°C. The complex modulus was also found to increase with increase in RAP content. This phenomenon was observed at all test temperatures for all the mixtures. The increase in complex modulus of mixtures with increase in RAP content collected from District 6 is shown in the Figure 2.1.

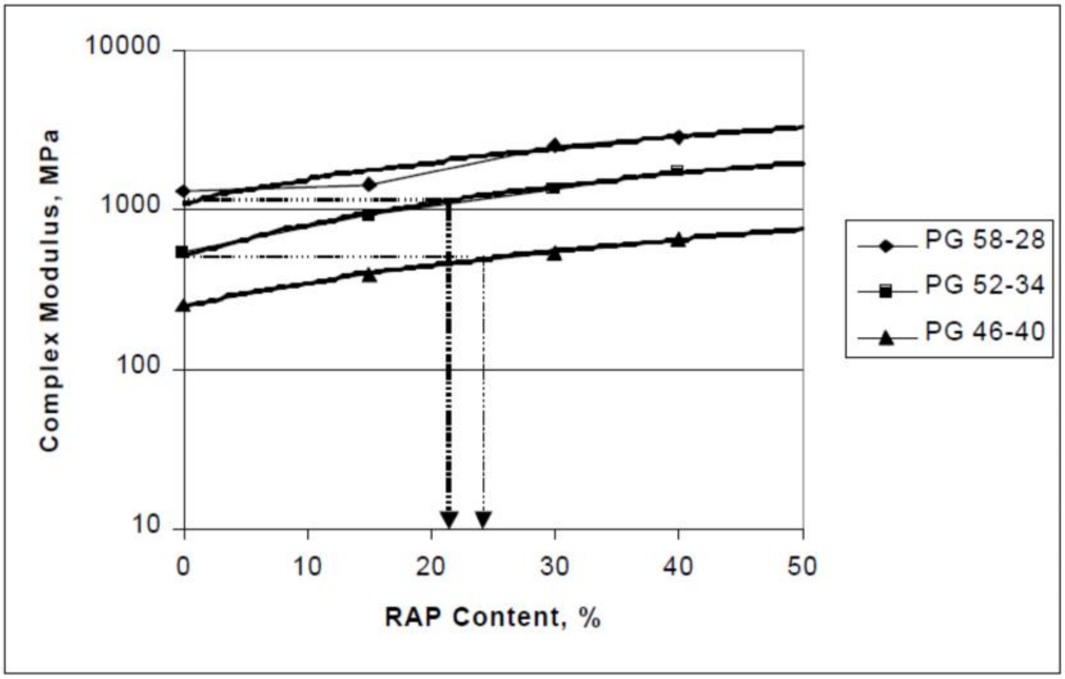

Figure 2.1. Change in Complex Modulus with RAP Content; District 6 RAP Mixtures, 25°C, 1.0 Hz (3)

From the figure it can be seen that the effects of the virgin binder and the RAP content have a significant impact on the complex modulus of the mixtures with RAP. This effect of RAP content was noticeable at the test temperature of 25ºC. As the temperature was increased to 32°C it became more difficult to distinguish between mixtures made of different asphalt binders. However, the increase in complex modulus with RAP content was well pronounced. The addition of 40% RAP content to the mixtures was found to triple the value of complex modulus when compared with that of the control mixtures. This phenomenon of increased stiffness of mixtures at high temperatures could be very helpful in avoiding rutting behavior of pavements. The complex modulus results were used to determine the amount of RAP required in each mixture to achieve equivalent results as observed in the original virgin mixtures.

Table 2-4. Recommended RAP Contents and Asphalt Binders (3)

Original asphalt grade	Asphalt grade with RAP	RAP Content with District 6 RAP	RAP Content with District 8 RAP
PG 58-28	PG 52-34	20%	10%
PG 58-28	PG 46-40	50%	35%
PG 52-34	PG 46-40	25%	15%

The project recommended that the complex modulus test should replace the resilient modulus test as the standard test for mixture evaluation as it provides more information about mixture properties. This project also showed that dynamic modulus test is an efficient way of determining the limits of RAP that can be used in a mix to achieve a target high temperature grade.

The project “Evaluation of Field Produced Hot Mix Asphalt (HMA) Mixtures with Fractionated Recycled Asphalt Pavement (FRAP)” was conducted by Vavrik, Carpenter, Gillen & Benhke. It aimed to determine whether the tollway design adopted by Rock Road companies and Rockford Blacktop at the Illinois Tollway involving high FRAP content in mixes would produce high quality HMA pavements (4).

Nine HMA mixes were plant produced and tested as a part of this research as shown in Table 2-5. Three mixtures were SMA mixtures with different coarse aggregate content and the same FRAP content to evaluate the use of fine portions and to determine if the material properties of the resulting mixture were consistent with other SMA mixes previously produced in Illinois. The base, binder and surface mixes were used to gauge their performance with increased FRAP percentage.

The previous IDOT specification involving higher percentage of RAP without fractionating caused a lot of inconsistencies in the mix properties. Hence in this project RAP was fractionated into two fractions, namely fine and coarse fractions. Mixtures were fabricated using these fractionated portions of RAP. The samples produced for each mix were subjected to dynamic modulus testing to verify whether materials with higher FRAP content will provide better consistency in test results when compared with tests carried out using previous specifications.. The samples were tested at -10°C, 4°C & 20°C at load frequencies ranging from 0.01 Hz to 25 Hz. The dynamic modulus testing was performed on samples with 4% and 7% air voids at the listed temperature and frequencies.

Table 2-5. FRAP Research Mix Matrix (4)

Research Mix Number	Mix Type	PG grade	FRAP Type	FRAP % Fine/Coarse	Coarse Aggregate Type	Comments
#1 – SMA Binder	SMA	GTR PG 76-22	1	15/0	Crushed Gravel	16 min VMA
#2 – SMA Surface (trap rock)	SMA	GTR PG 76-22	1	15/0	Trap Rock	
#3 – SMA Surface (steel slag)	SMA	GTR PG76-22	1	15/0	Steel Slag	
#4 – IL-19.0 Binder N70	N70 19.0	PG58-22	2	25/15	Cr.Gravel & Stone	
#5 – IL-9.5 Surface N70	N70 9.5	PG64-22	2	15/10	Dolomite	4% air voids
#6a – IL-19.0 Binder N50-28	N50 19.0	PG58-28	2	10/30	Dolomite	3% air voids
#6b – IL-19.0 Binder N50-22	N50 19.0	PG58-28	2	10/30	Dolomite	3% air voids
#7a – IL-19.0 Base-28	N50 Base	PG58-28	2	10/30	Dolomite	2% air voids
#7b – IL-19.0 Base-22	N50 Base	PG58-28	2	10/30	Dolomite	2% air voids

The dynamic modulus data indicated that for all the mixes and all frequencies, the moduli of the FRAP mixtures were higher than the values currently assumed for the IDOT mechanistic design procedure as shown in Figure 2.2. The result demonstrated that the mixes containing fractionated RAP do not require any increase in pavement thickness to improve pavement performance and that the performance of the roadway can be expected to be as good as current materials and designs.

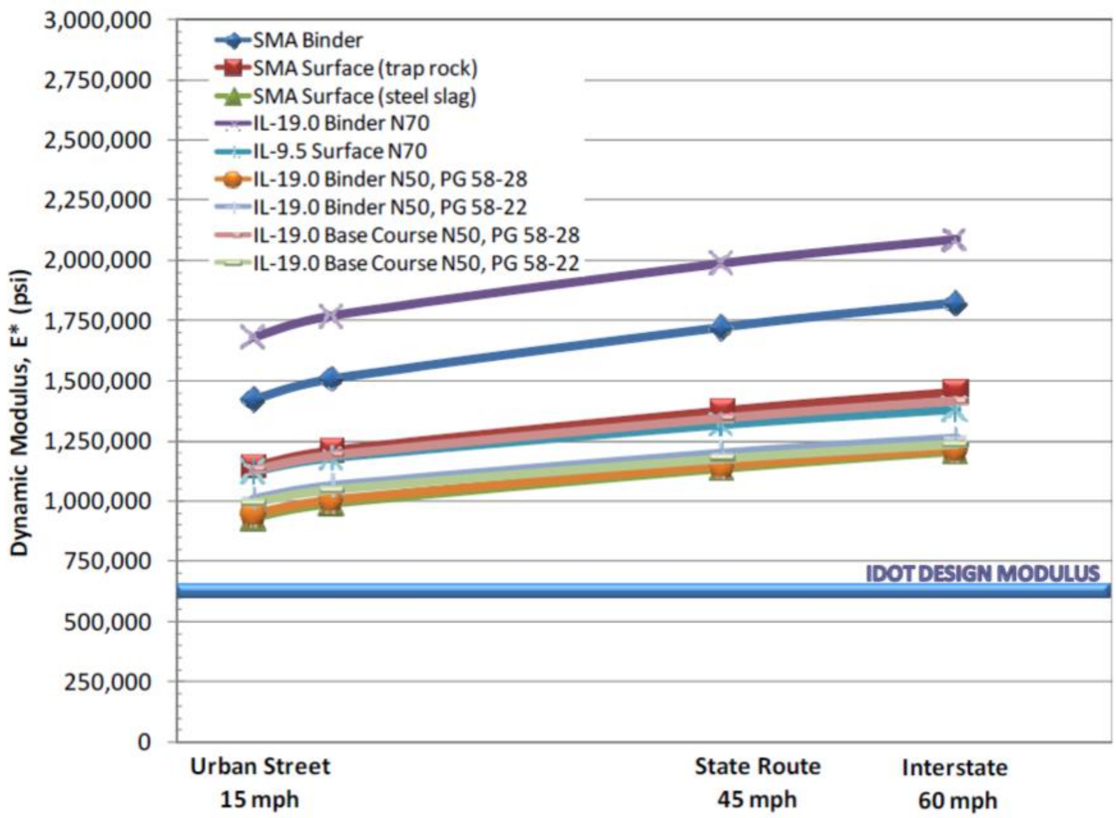

Figure 2.2. Dynamic Test Data at 20°C and Various Highway Speeds with the IDOT Design Range for Northern Illinois (4)

Hence fractionated RAP was seen as an efficient way of reducing project lifetime costs of pavements. It has also been proven to reduce the inconsistencies or variability in the results of the mixes especially those containing higher amounts of RAP.

The Institute for Transportation at Iowa State University undertook the task of addressing research needs of the state DOT and environmental officials to determine the best practices for the use of RAS in Hot-Mix Asphalt applications (5). They compiled the work of many participating agencies which included demonstration projects that focused on evaluating different aspects of RAS like: RAS grind size, RAS percentage and RAS source (post-consumer vs. manufacturer waste). Field mixes from each demonstration project were sampled for conducting tests such as dynamic modulus, flow number, four point beam fatigue, semi-circular bending, and binder extraction and recovery with subsequent binder characterization. The results from these tests were studied in conjunction with pavement condition surveys and meaningful conclusions were made after completion. It was shown from the demonstration projects that pavements with RAS, having the initial benefit of reduced construction cost, also benefited from improved rutting and fatigue cracking resistance with low temperature cracking resistance similar to mixes without RAS (5). The actual pavement conditions after 2 years of construction corroborated with the initial lab test results and no actual signs of rutting, wheel path fatigue cracking, or thermal cracking were exhibited in the pavements. It was shown that for attaining the best results, important QA/QC provisions were followed for incorporating RAS in HMA mixtures. These included appropriate sourcing methods such as separating RAS based on source as RAS from each source had a different binder content with variation in aggregate gradations; sorting of RAS in order to remove deleterious material that would adversely affect the aggregate-binder bonding; drying of RAS prior to batching and mixing because moisture retention capacity of RAS is as high as 20% (5).

The demonstration project conducted by Iowa DOT studied the effects of different percentages of RAS in HMA mixtures and the demonstration project conducted by Minnesota DOT studied the differences encountered due to using similar proportions of either MRAS or PRAS (5). It was concluded that when RAS was used in HMA, the shingle binder blended with the base binder, increasing the performance grade of the base binder on the high and low side. The average results from all the demonstration project mixes showed that for every 1 percent increase in RAS, the low temperature grade of the base binder increased 1.9^{o}C. Therefore, as a rule of thumb, 3 percent RAS would be the maximum amount of recycled material allowed without requiring a low temperature grade bump in the base binder (5). It was also concluded that as the percentage of RAS in the mix increased from 0% to 4%, the fracture energy of the mixtures increased suggesting that the RAS mixtures had improved fracture resistance. Mixtures with RAS had an increased dynamic modulus at high temperatures resulting in improved rutting resistance. The flow number tests on mixtures with RAS resulted in similar conclusions; the flow number increased as the percentage of RAS increased in the mixture. The four point bending beam results showed that fatigue life of the asphalt mixture improved with the addition of RAS in a controlled strain mode; identical to loading in a thin pavement. They attributed this improvement to the presence of fibers in RAS that provided additional ductility to the mixtures. The fracture energies calculated at different low temperatures by conducting semi-circular bending tests on mixtures containing RAS showed that the low temperature cracking resistance of the mixture improved with addition of RAS. Additionally, field condition surveys one and two years after the demonstration project revealed that pavement sections with RAS showed better resistance to reflective cracking than sections without RAS.

The research conducted by Hasan Ozer, Imad L. Al-Qadi, Ahmad I. Kanaan and Dave L. Lippert studied the effects of recycled materials in asphalt mixtures on various performance indicators such as permanent deformation, fracture, fatigue potentials, and stiffness (6). The mixtures in the study were all low N-Design asphalt mixtures including both RAP and RAS and the binder replacement in the mixes were as high as 43% to 64%. They tested mixtures consisting of various percentages of RAS with two virgin asphalt binder grades using the wheel track test method and concluded that the use of RAS clearly improved the rutting resistance of the mixture at high pavement temperatures. Also, high temperature grade bumping to compensate for the presence of stiff RAS binder did not adversely affect the rutting resistance of the mixture (6). As the amount of RAS increased in the mixture, significant changes to the master curve of complex modulus were observed. The increase in RAS resulted in significant increase in the complex modulus at high temperature or low frequencies. In addition, the slope of the master curves, which can be considered an important indicator of the relaxation potential of asphalt mixtures, decreased as the proportion of RAS increased in the mix indicating a reduced performance in fatigue.

A study was conducted by Fuzie Zhou, Joe W. Button, and Jon Epps to report the best practice for using RAS in HMA. They documented the steps and precautions that need to be taken while processing and characterizing RAS, during the RAS mix design, production, and finally at the time of field construction (7).

They proposed that for achieving high quality recycled mixes, QA/QC measures relating to RAS collection, sorting, grinding, screening, and finally storing should be strictly followed. RAS should be devoid of any unwanted matter such as nails, wood, plastic etc. that could hinder the bonding of asphalt binder with aggregate in HMA and RAS should be ground to a size smaller than ½ inch for better blending of asphalt binder in RAS (7). Since the average gradation of ground RAS is very small, RAS stockpiles can absorb a large amount of water. Therefore, it has to be ensured that RAS be dried thoroughly before using it in HMA mix design. They also proposed that RAS should be characterized for its gradation, RAS aggregate gradation, binder content, and the performance grade of the RAS binder before using it in mixture design. The finer the processed RAS is, the better the mixing with virgin binder, hence the need for specifying RAS gradation (7). They found that PRAS had higher binder content as compared to MRAS and MRAS had a slightly finer gradation than PRAS. Also, the RAS variability in terms of asphalt binder content and gradation was low for both MRAS and PRAS. Tests on extracted binder from RAS led to the conclusion that for grading the RAS binder at high temperature, a DSR capable of testing at temperatures around 200°C was needed. Because the RAS binder was so stiff, it was very critical to study blending of the RAS binder with the virgin binder.

They proposed similar guidelines for mix design procedures for RAS mixes. It was suggested that heating of RAS to adequate levels prior to mixing was important for it to be activated. Two methods were proposed for mixing of RAS with virgin materials:

- Preheat the RAS to 60^{o}C for 12-14 hours and then again heat the RAS at the mixing temperature for two hours.
- Superheat the virgin aggregate to ensure heat transfer to the RAS, which is added at room temperature.

Since, the mixing and compaction temperatures are an important factor in mixture volumetrics and consequently Optimum Asphalt Content (OAC), they presented three possible options: temperatures corresponding to virgin binder, temperatures corresponding to blended virgin/RAS binder, and finally, temperatures corresponding to the RAS binder. Due to the high stiffness of RAS binder, temperatures corresponding to the RAS binder would be very high and the virgin binders would undergo extensive aging. Since higher temperatures lead to lower OAC which adversely affects the cracking resistance, the most conservative of the three options, mixing and compaction temperatures corresponding to virgin binder, was proposed for the mix design procedure (7).

Shu Wei Goh and Zhanping You studied the performance of asphalt mixtures containing different proportions of RAS using the Universal Testing Machine (UTM) and the Asphalt Pavement Analyzer (APA) for measuring dynamic modulus and rut depths, respectively (8). They used mixes with 5% and 10% RAS by weight of total mix along with a control virgin HMA mix in their study. They found that the mixes got compacted to different air void levels; that 10% RAS mixes had the highest level of air voids followed by 5% RAS mixes and control virgin HMA mix. The compaction effort for all the mixes was the same and higher mixing and compaction temperatures for RAS mixes were used. The base virgin binder was kept the same in all mixes. They concluded that the reason for the increase in the air voids with increase in RAS in the mix was because the blended binder was stiffer than the virgin binder and would require more compaction effort or even higher mixing and compaction temperatures (8). Dynamic modulus testing was conducted for each of the mix types and they found that at very low temperatures the dynamic modulus values for 10% RAS mixtures was the lowest followed by 5% RAS mixtures; the highest dynamic modulus values were observed for control mixtures. They found that as the testing temperature increased, the relative difference between the dynamic modulus values of the three mixtures decreased and the RAS mixtures were observed to have the highest dynamic modulus values at temperatures close to 40^{o}C. Thus it was concluded from the dynamic modulus tests that, since the RAS mixtures were stiffer at higher temperatures, they were more likely to resist rutting for a longer duration. Since they showed smaller dynamic modulus values at lower temperatures, they would be better resistant to fatigue cracking than the control mixture that did not have any RAS (8). The results from the APA rut depth testing also showed that 10% RAS mixtures showed the least rut depths followed by the 5% RAS mixtures and control mixes showed the highest rut depth.

The Office of Materials and Road Research of Minnesota Department of Transportation conducted a study on HMA pavement mixtures with RAS by conducting extensive laboratory testing of mixtures and field evaluation of in service RAS HMA pavements (9). They studied HMA mixtures with 5% RAS (MRAS or PRAS) and varying proportions of RAP and found that during the process of mixture design, mixtures cooled quicker with the addition of RAS as they noticed a loss in workability during the process of mixing (9). They found that shingles made the mixtures look dryer than those produced without shingles. Mixtures with coarser ground shingles had a tendency to clump up during the mixing process and that mixtures appeared to be more homogenous with the fine ground shingles. From the binder testing of extracted binders from RAS, they concluded that binder in PRAS was stiffer than that in MRAS. The dynamic modulus tests, the APA tests and the moisture sensitivity tests on the various recycled mixtures helped them to conclude that the largest differences in the dynamic modulus values were observed at lower frequencies, which corresponds to higher temperatures and that the stiffening effect of PRAS was the most pronounced among all other waste materials (9). The change in the shape of the master curve and reduction in stiffness due to the use of a softer base virgin binder confirmed the softening effects of using a lower grade virgin binder. The APA results also showed that the rut depth of PRAS mixtures did not vary much with variation in RAP content, whereas, the rut depths of MRAS mixtures varied a lot with a variation in RAP content allowing for the conclusion that PRAS had the most stiffening effect among all other waste materials and that the resistance to rutting of PRAS mixes was higher than that of MRAS mixes. From the results of the TSR data, they concluded that PRAS mixes were more susceptible to moisture damage than MRAS mixes.

3. RESEARCH APPROACH AND METHODOLOGY

3.1 Research Objectives

The goal of this research study was to determine the recycled asphalt binder limits contributed by waste materials. The specific research objectives were:

- Investigate the various sources of recycled binder, including RAP and the two types of RAS i.e. MRAS and PRAS for performance grade of the binder, which should be done using standard binder recovery methods and PG binder grading methods. Extracted binder from PRAS tends to be stiffer than that from MRAS, therefore requiring separate limits for the two types of RAS.
- Using limits defined by PG grading, determine the effects of RAP and RAS on HMA mix by conducting standard test of Dynamic Modulus for performance evaluation.
- Conduct performance analysis of the various recycled mixtures for a simulated test pavement to determine the performance of each recycled mixture in comparison to a control virgin mixture.
- Develop a draft specification utilizing limits for recycled materials based on recycled binder percentage in the mix.

3.2 Research Methodology

To fulfill the aforementioned objectives, the study was divided and organized chronologically into five tasks.

Task 1. Materials Acquisition and Characterization

In this research task, materials needed for completion of the study were selected and procured, including the selection and procurement of RAP and RAS samples and virgin materials. Once the materials were obtained, testing was conducted in order to characterize the recycled materials for their various physical and rheological properties.

Task 1.1 Binder Content by Ignition Oven

In this sub task, representative samples of RAP and RAS were burnt in an ignition oven in accordance with AASHTO T308 “Test Method for Determining the Asphalt Content of HMA by Ignition Method” to determine the asphalt content of each of the recycled materials. These values were later used in Task 3 during the mixture design procedure of recycled mixtures. This method also yielded aggregate from the recycled materials that were used to determine the aggregate gradation, also to be used in mix design procedure in Task 3.

Task 1.2 Aggregate Gradations

Reclaimed aggregate from burning RAP and RAS samples in an Ignition oven were collected for sieve analysis. The gradations of RAP and both MRAS and PRAS aggregates were determined in accordance with AASHTO T27 “Sieve Analysis of Fine and Coarse Aggregates” and AASHTO T11 “Material Finer than 75 micron Sieve in Mineral Aggregates by Washing”.

Task 1.3 Virgin Materials Selection and Procurement

In order to develop applicable results for the NCDOT, virgin materials were selected that were representative of materials used in asphalt concrete pavements in North Carolina. Availability of aggregate in close proximity to North Carolina State University was another controlling factor in the selection of virgin aggregate type due to the economics involved. Granitic aggregate was preferred over limestone aggregate due to its ready availability.

The same factors were also influential in selection of the virgin binder grade for the study. Two virgin binders, namely PG 64-22 and PG 58-28, were selected since the goal of this study was to develop specifications for S9.5B mixes in North Carolina. PG 58-28 was selected because at high percentages of RAP and RAS in HMA mixtures, it was necessary to lower the high temperature grade of the base virgin binder.

Task 2.Performance Grade Testing

In this task, binder from recycled materials samples was extracted in accordance with AASHTO T319 “Quantitative Extraction and Recovery of Asphalt Binder from Hot Mix Asphalt” for determining the grade of the extracted binder. Since the grade of the extracted binders from MRAS and PRAS could not be determined with the available DSR, these binders were blended with virgin binders in two proportions and tested on the DSR for generating the blending charts. The blended binders along with the virgin binders were tested on the DSR in accordance with AASHTO T315 “Test Method for Determining the Rheological Properties of Asphalt Binder Using a Dynamic Shear Rheometer” at both high and intermediate temperatures for generating the blending charts. Binder limits for recycled materials were calculated based on these blending charts.

Task 3. Mix Design

In this research task, mixtures were designed using Superpave mix design methodology for HMA mixtures. Based on the results from Task 2, mixtures were designed using the allowable amounts of recycled materials. These mixtures were used in Task 4 to determine the effects on pavement performance.

Task 3.1 Design of Mixtures Containing 100% Virgin Materials

In this subtask, design of mixtures containing 100% virgin materials was undertaken. The mixture designs were governed by AASHTO R35 “Superpave Volumetric Design for HMA”. The design aggregate structure was initially determined and this aggregate gradation was used to estimate the optimum asphalt content for that mix.

Task 3.2 Design of Mixtures Containing Various Percentages of Recycled Materials

In this subtask, specimens containing various percentages of recycled materials (RAP, MRAS and PRAS) were fabricated for use in analysis during Tasks 4 and 5. It was ensured that the mixtures with recycled materials also had the same aggregate gradation as the control mixture with 100% virgin materials by adjusting the proportion of the virgin aggregates in the mixture. Therefore, the virgin aggregate proportions were adjusted to accommodate the aggregate contributed by recycled materials. The amount of virgin asphalt binder was also adjusted in order to account for the binder contributed by recycled materials.

Task 4. Performance Testing

In this research task, mixtures were characterized by testing them on the Asphalt Mixture Performance Tester (AMPT) in accordance with AASHTO TP79 “Standard Method of Test for Determining Dynamic Modulus of HMA Concrete Mixtures” to determine the fundamental property of dynamic modulus for each mixture. Virgin mixtures were compared to the mixtures containing the allowable amounts of recycled materials. The obtained values were used to develop the dynamic modulus master curves for each of the mixtures. These master curves served as the input for Mechanistic-Empirical Pavement analysis software “AASHTOware Pavement M-E Design” which was used to evaluate the performance of each of the mixtures in a simulated pavement in the next task.

Task 5. Performance Analysis

In this research task, the mixture characteristics obtained in Task 3 and Task 4 were used to evaluate the performance of each of the mixtures in a simulated pavement and determine the service life. Economic analysis was conducted to study the difference in costs in constructing an actual pavement with recycled mixtures and the virgin mixture.

4. MATERIAL CHARACTERISTICS

This chapter will discuss the characteristics of the various materials that have been used in the research to meet the objectives.

4.1 Virgin Materials

The aggregate for the process of mix design and performance testing was procured from Garner quarry in North Carolina and was a granitic aggregate. Granite is the most common aggregate in North Carolina.

Two sizes of granitic aggregate were procured, namely 78M (Coarse Aggregate) and Washed Screenings (WS) (Fine Aggregate). Once the aggregate was procured, the gradations for the two sizes were determined for use in the mixture design procedure. The aggregates were first sampled according to AASHTO T2 "Sampling of Aggregate" and then reduced to testing size as per AASHTO T248 "Reducing Samples of Aggregate to Testing Size". These reduced samples were tested to determine the percentage of material finer than 75 micron in accordance to AASHTO T11 "Material Finer than 75 micrometer Sieve (No. 200) in Mineral Aggregates by Washing" and the complete gradations were determined in accordance to AASHTO T27 "Sieve Analysis of Coarse and Fine Aggregate". The gradations are shown in Table 4-1.

Table 4-1. Aggregate Gradations for 78M and WS

Sieve size	% Passing	
	78M	**WS**
12.5 mm	100	100.0
9.5 mm	90.8	100.0
4.75 mm	32.0	99.8
2.36 mm	5.6	87.7
1.18 mm	3.6	65.7
600 µm	2.8	44.6
300 µm	2.2	25.2
150 µm	1.5	8.3
75 µm	1.0	3.0
Pan	0.0	0.0

Since in both the aggregates the material passing 75 micron was significantly less, Baghouse Fines were used (material finer than 75 micron) in addition to the above two aggregates to meet the Superpave aggregate gradation criteria for mixture design which will be explained in Chapter 6**.**

The specific gravities of all three aggregates were determined according to AASHTO T84 “Specific Gravity and Absorption of Fine Aggregate” and AASHTO T85 “Specific Gravity and Absorption of Coarse Aggregate”. Specific Gravities of 78M, WS and Pond Fines (Fines) are mentioned in Table 4-2.

Table 4-2. Bulk and Apparent Specific Gravity of 78M and WS

Aggregate	Specific Gravity	
	Bulk	Apparent
78M	2.617	2.644
WS	2.597	2.652
Fines	2.597	2.647

Two virgin asphalt binder grades were used in this research, PG 58-28 and PG 64-22. Both the binders were aged in the Rolling Thin Film Oven (RTFO) in accordance with AASHTO T240 "Standard Method of Test for Effect of Heat and Air on a Moving Film of Asphalt Binder (Rolling Thin-Film Oven Test)" to simulate the short term aging of the binder at the time of mixing and compaction in field construction. These RTFO aged binders were subsequently aged in a Pressure Aging Vessel (PAV) in accordance with AASHTO R28 "Standard Practice for Accelerated Aging of Asphalt Binder Using a Pressurized Aging Vessel (PAV)" to simulate the long term aging of the asphalt binder during the service life of the pavement.

The unaged and aged asphalt binders were tested on the Dynamic Shear Rheometer (DSR) in accordance with AASHTO T315 "Test Method for Determining the Rheological Properties of Asphalt Binder Using a Dynamic Shear Rheometer" to determine the rheological properties of Complex Modulus (G*) and Phase Angle (delta, δ) of each binder at different temperatures. These values were used to verify the high temperature grade and intermediate temperature grade of both the virgin asphalt binders. Verification was done in accordance with AASHTO R29 "Standard Practice for Grading or Verifying the Performance Grade of an Asphalt Binder" which states that the highest temperature at which the conditions of $G^*/\sin\delta \geq 1.0$kPa for unaged binders and G*/Sinδ ≥ 2.2kPa for RTFO aged binders are met simultaneously, is the high temperature grade for that binder and the temperature at which the condition of G*Sinδ ≤ 5000kPa is met, is the intermediate temperature grade for that binder. The results obtained from testing the unaged binders, RTFO aged binders and PAV aged binders on the DSR at various temperatures are shown in Table 4-3, Table 4-4 and Table 4-5**,** respectively.

Table 4-3. Rheological Properties of Virgin Unaged Asphalt Binders

Virgin Binder Grade	**Average G*/Sinδ (kPa) (Standard Deviation) At Test temperature**			
	58^oC	64^oC	70^oC	76^oC
PG 58-28	2.03 (0.03)	0.98 (0.01)	0.50 (0.01)	0.26 (0.01)
PG 64-22	3.43 (0.03)	1.47 (0.01)	0.69 (0.01)	0.34 (0.01)

Table 4-4. Rheological Properties of Virgin RTFO Aged Asphalt Binders

Virgin Binder Grade	**Average G*/Sinδ (kPa) (Standard Deviation) At Test temperature**		
	64^oC	70^oC	76^oC
PG 58-28	3.38 (0.04)	1.66 (0.02)	0.84 (0.02)
PG 64-22	3.85 (0.06)	1.75 (0.02)	0.83 (0.01)

Table 4-5. Rheological Properties of Virgin PAV Aged Asphalt Binders

Virgin Binder Grade	Average G*Sinδ (kPa) (Standard Deviation) At Test temperature			
	28°C	25°C	22°C	19°C
PG 58-28	1151 (71)	1673 (93)	2511 (128)	3784 (187)
PG 64-22	2505 (12)	3681 (18)	5359 (63)	7690 (145)

The virgin unaged asphalt binders were tested on the Rotational Viscometer (RV) in accordance to ASTM D4402 "Standard Method for Viscosity Determination of Unfilled Asphalts Using the Brookfield Thermosel Apparatus" to determine the flow characteristics of the asphalt binder to provide assurance that it can be pumped and handled at the hot mixing facility. The results obtained from testing the virgin unaged binders on the Rotational Viscometer at various temperatures are shown in Table 4-6 below.

Table 4-6. Viscosity of Virgin Unaged Asphalt Binders

Virgin Binder Grade	Average Viscosity (cP) (Standard Deviation) At Test temperature				
	121.1°C	131.1°C	141.1°C	151.2°C	161.2°C
PG 58-28	-	533.3 (11.0)	330.6 (9.6)	213.3 (6.3)	142.5 (6.6)
PG 64-22	1013.7 (13.1)	580.0 (4.5)	352.5 (5.9)	223.8 (7.9)	151.9 (6.4)

The relationship between the viscosity and temperature for the two virgin binders was also used to determine the mixing and compaction temperatures for both the virgin binders. The details of these temperatures are further described in Chapter 6.

4.2 Recycled Waste Materials

Three types of waste materials were used in this research namely RAP (Recycled Asphalt Pavement), MRAS (Manufacturer Waste Recycled Asphalt Shingles) and PRAS (Post-Consumer Recycled Asphalt Shingles). RAP consists of materials including aggregates and asphalt binder that were scraped off of old pavements. MRAS comprises those shingles that have been discarded at the time of production and are rendered as waste. On the other hand PRAS comprises those shingles that have been discarded after use on roof tops. It can thus be stated that the binder in PRAS has further undergone oxidation during its service life and would be much stiffer and more brittle than the air blown asphalt binder in MRAS. Therefore, MRAS and PRAS were treated differently throughout the course of this research.

Samples of each recycled material were taken from the stockpile to determine the properties of binder content and aggregate gradation. The binders from all the samples were extracted for further rheological testing according to AASHTO T319 "Quantitative Extraction and Recovery of Asphalt Binder from Hot Mix Asphalt". This extracted binder was later blended with virgin binders and the blending charts were generated. Samples of recycled materials were also burnt in the Ignition Oven in accordance with AASHTO T308 "Test Method for Determining the

Asphalt Content of Hot Mix Asphalt (HMA) by Ignition Method" to determine the asphalt content.

Sieve analysis was conducted on the residual aggregate to determine the gradations for each recycled material. Table 4-7 below contains the aggregate gradations and Table 4-8 shows the average asphalt contents for each of the recycled materials. RAP was found to be coarser when compared with the MRAS and PRAS with a nominal maximum aggregate size greater than 9.5mm. This high nominal maximum aggregate size would increase the variability in mixtures containing high percentages of RAP. Hence RAP was fractionated into two fractions namely coarse fraction (C.F) and fine fraction (F.F) using the 4.75mm sieve. The gradations of these two fractions were also determined.

Table 4-7. Aggregate Gradations for each Recycled Material

Sieve size	**% Passing**				
	MRAS	**PRAS**	**RAP**		
			RAP	**C.F**	**F.F**
12.5 mm	100.0	100.0	98.4	100.0	100.0
9.5 mm	100.0	100.0	91.4	85.0	100.0
4.75 mm	96.6	98.8	66.0	40.1	100.0
2.36 mm	91.5	97.4	50.5	26.5	82.7
1.18 mm	74.5	82.0	39.9	21.9	63.0
600 µm	55.0	60.2	30.4	17.9	46.5
300 µm	43.5	51	19.9	12.7	31.3
150 µm	32.7	41.5	13.4	8.6	20.4
75 µm	25.6	31.7	8.5	5.3	12.6
Pan	0.0	0.0	0.0	0.0	0.0

Table 4-8. Average Asphalt Binder Contents for each Recycled Material

Waste Material		Average Asphalt Binder Content
RAP	RAP	5.0%
	C.F	3.3%
	F.F	6.2%
MRAS		14.7%
PRAS		18.6%

The extracted binders from the MRAS and PRAS could not be tested on the DSR for determining their high temperature grade as it was beyond the capacity of the available DSR to generate testing temperatures in the range of 150^{o}C to 200^{o}C. In addition, preparation of samples from these binders for testing on the DSR would require preheating the binders to very high temperatures which would in turn affect the properties of the original extracted binders.

5. BINDER CHARACTERIZATION AND BLENDING CHARTS

This chapter will discuss the rheological properties of blended binders obtained by blending known proportions of recycled binder with virgin binders. These properties were used to generate blending charts for limiting the amount of recycled binder that can be added to a virgin binder and still be able to meet the required Superpave binder specifications. This is achieved by estimating the minimum amount of each recycled binder that can be blended with a virgin binder to meet the high temperature criteria at different test temperatures and the maximum amount of each recycled binder that can be blended with a virgin binder to meet the intermediate temperature criteria at different test temperatures. These minimum and maximum percentages of extracted binders were used to draft a set of binder limits that are later used for designing recycled mixes in Chapter 6**.**

Extracted binders from the recycled materials were blended with both virgin binders separately in varying proportions and Table 5-1 below shows the matrix of these blends. The percentage represents the proportion of extracted binder by weight of total blended binder. All of the blended binders contained one of the virgin binders with one of the extracted binders from RAP, MRAS or PRAS but not in combination.

Table 5-1. Binder Blends Matrix

Virgin Binder	**RAP**	**MRAS**	**PRAS**
PG 58-28	25%, 40%, 100%	10%, 20%	10%, 25%
PG 64-22	25%, 40%, 100%	10%, 20%	10%, 25%

Each of the binders in Table 5-1 was tested on the Dynamic Shear Rheometer to determine their rheological properties. These binders were aged in the Rolling Thin Film Oven (RTFO) in accordance with AASHTO T240 “Standard Method of Test for Effect of Heat and Air on a Moving Film of Asphalt Binder (Rolling Thin-Film Oven Test)” to simulate the short term aging of the binder at the time of mixing and compaction in field construction. These RTFO aged blended binders were further aged in a Pressure Aging Vessel (PAV) in accordance with AASHTO R28 “Standard Practice for Accelerated Aging of Asphalt Binder Using a Pressurized Aging Vessel (PAV)” to simulate the long term aging of the asphalt binder during the service life of the pavement.

5.1 Dynamic Shear Rheometer Testing of Unaged Blended Binders

The unaged and aged blended binders were tested on the DSR (Dynamic Shear Rheometer) in accordance with AASHTO T315 “Test Method for Determining the Rheological Properties of Asphalt Binder Using a Dynamic Shear Rheometer” to determine the rheological properties of Complex Modulus (G*) and Phase Angle (delta, δ) at different temperatures.

The mean G*/Sinδ and standard deviation values (in parenthesis) at different test temperatures obtained upon testing the two virgin binders of grade PG 58-28 and PG 64-22 blended with various proportions of binders extracted from recycled materials are as shown in Table 5-2**.**

Table 5-2. G*/Sinδ Values of Unaged Blended Binder

Binder Type	Average G*/Sinδ (kPa) with Standard Deviation at Test Temperature					
	64º C		70º C		76º C	
	G*/Sinδ	Std Dev	G*/Sinδ	Std Dev	G*/Sinδ	Std Dev
PG 58-28 + 25% RAP	2.27	0.01	1.09	0.01	0.55	0.01
PG 58-28 + 40% RAP	4.06	0.05	1.93	0.02	0.95	0.01
PG 64-22 + 25% RAP	3.32	0.04	1.52	0.01	0.73	0.01
PG 64-22 + 40% RAP	4.64	0.03	2.05	0.01	0.99	0.01
100% RAP	22.84	0.06	10.24	0.24	4.89	0.08
PG 58-28 + 10% MRAS	1.39	0.02	0.7	0.01	0.34	0.01
PG 58-28 + 20% MRAS	1.75	0.03	0.89	0.01	0.44	0.03
PG 64-22 + 10% MRAS	-	-	0.88	0.01	0.44	0.01
PG 64-22 + 20% MRAS	-	-	1.13	0.01	0.57	0.01
PG 58-28 + 10% PRAS	4.22	0.02	2.08	0.01	1.02	0.01
PG 58-28 + 25% PRAS	12.24	0.15	6.08	0.06	3.08	0.02
PG 64-22 + 10% PRAS	-	-	1.56	0.03	0.75	0.02
PG 64-22 + 25% PRAS	-	-	10.35	0.02	4.87	0.01

The G*/Sinδ values for unaged blended binders with varying proportions of recycled binders were plotted together with those of unaged virgin binder of grade PG 58-28 on a single plot for each testing temperature to arrive at the blending charts. Figure 5.1 through Figure 5.3 are the blending charts for PG 58-28 with varying proportions of recycled binder at different testing temperatures.

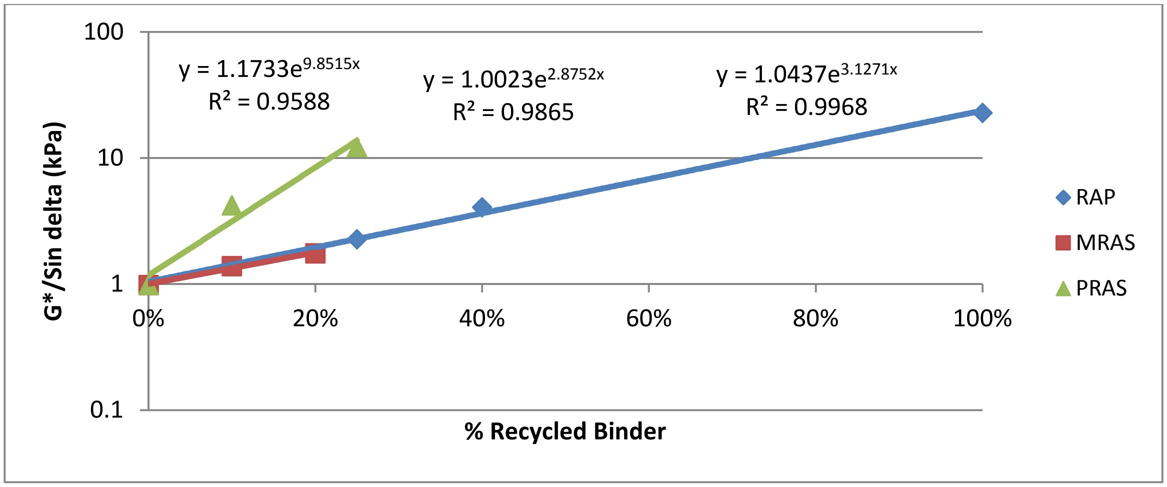

Figure 5.1. Blending Chart for PG 58-28 at 64ºC

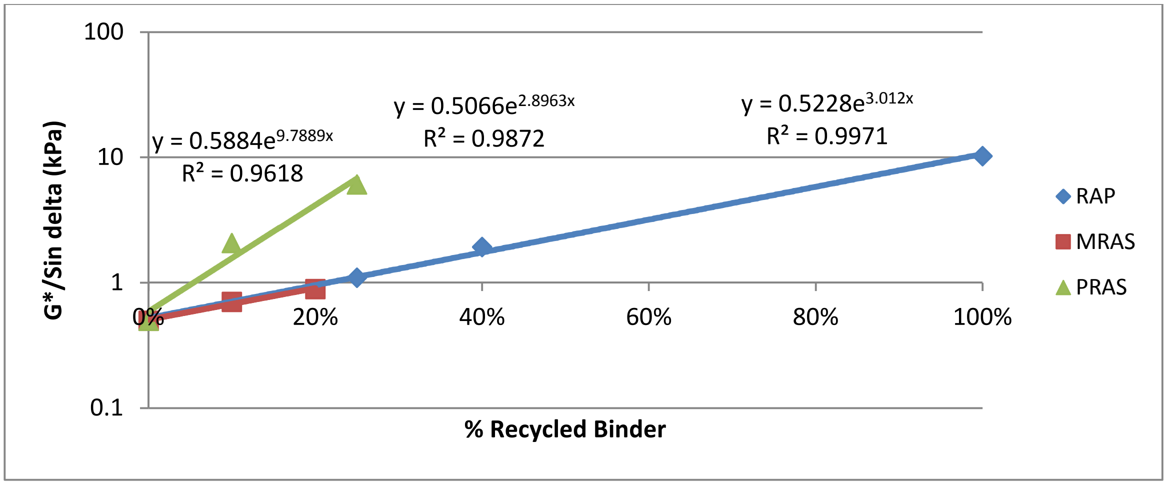

Figure 5.2. Blending Chart for PG 58-28 at 70°C

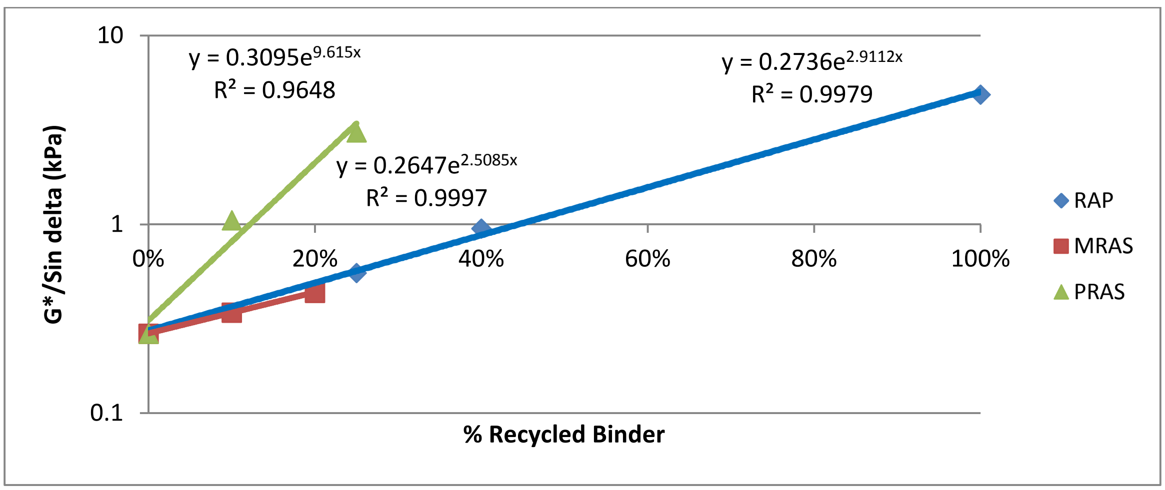

Figure 5.3. Blending Chart for PG 58-28 at 76°C

It can be observed from these blending charts that the stiffness of the blended binder increased with an increase in the proportion of recycled binder at a given temperature. This is expected as the recycled binder in RAP has been oxidized during the pavement service life and the recycled binder in RAS is air blown oxidized and is stiffer than the virgin binder and upon blending the two together the stiffness of the resulting blended binder is higher. This effect is more striking in the case of blended binders obtained by blending virgin PG 58-28 binder with extracted binder from PRAS than the blended binders obtained by blending with extracted binder from RAP and MRAS. This is again expected as the extracted binder from PRAS is substantially stiffer than that extracted from MRAS due to the additional aging incurred during its service life on roof tops. It can thus be noted that the high temperature specifications at higher temperatures can be met for a softer binder by blending it with a known percentage of stiffer recycled binder.

In similar manner, the G*/Sinδ values for unaged blended binders with varying proportions of recycled binders were plotted together with those of unaged virgin binder of grade PG 64-22 on a single plot for each testing temperature to arrive at the blending charts. Figure 5.4 and Figure 5.5 are the blending charts for PG 64-22 with varying proportions of recycled binder at different testing temperatures.

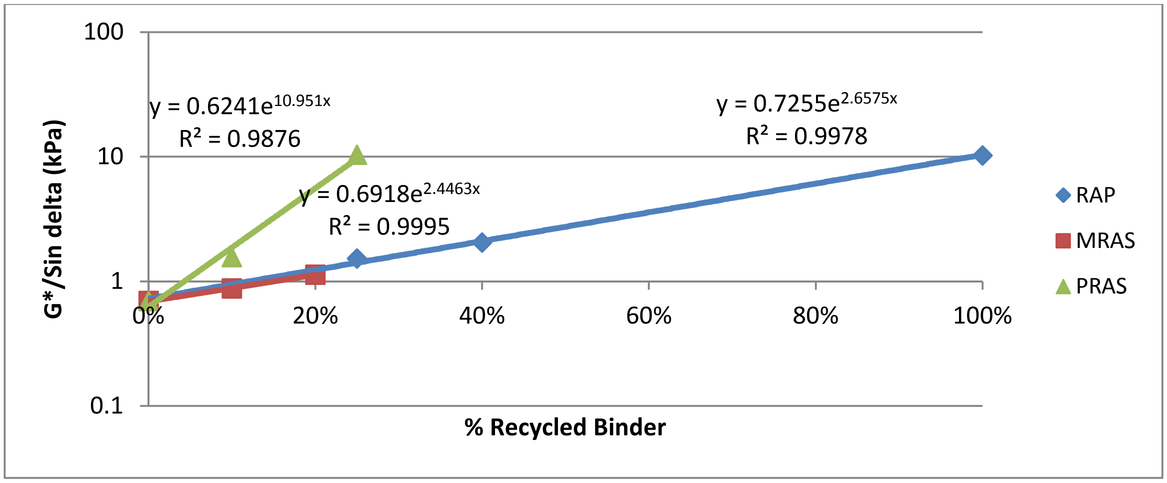

Figure 5.4. Blending Chart for PG 64-22 at 70ºC

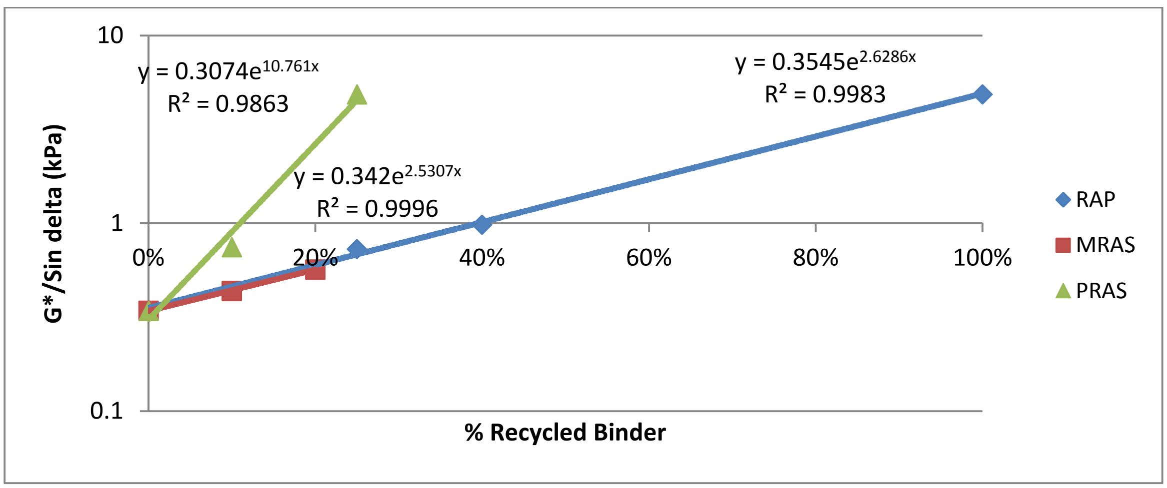

Figure 5.5. Blending Chart for PG 64-22 at 76ºC

It can be again observed from these blending charts that the stiffness of the blended binder increased with an increase in the proportion of recycled binder at a given temperature. Again, this is expected as the recycled binder in RAP has been oxidized during the pavements service life and the recycled binder in RAS is air blown oxidized and is stiffer than the virgin binder and upon blending the two together the stiffness of the resulting blended binder is higher. This effect is more striking in the case of blended binders obtained by blending virgin PG 64-22 binder with extracted binder from PRAS than the blended binders obtained by blending with extracted binder from RAP and MRAS. This can be explained as the extracted binder from PRAS is substantially stiffer than that extracted from RAP and MRAS due to the additional aging incurred during its service life on roof tops.

From the relationship between the percentage recycled binder and $G^*/\sin\delta$ in the above blending charts, minimum percentage recycled binder was estimated such that the blended binder satisfied the Superpave requirement of $G^*/\sin\delta \geq 1.0$kPa in the unaged condition at various test temperatures. Table 5-3 below shows these calculations with the exponential relationship between the percentage recycled binder and $G^*/\sin\delta$ values for both PG 64-22 and PG 58-28 based blended binders.

Table 5-3. Minimum Percentage of Recycled Binder to Satisfy G*/Sinδ = 1.0 kPa for Unaged Blended Binders at Various Test Temperatures

Virgin Binder	Recycled Binder	Temperature (°C)	G*/Sinδ = $Ae^{B(\%RAS)}$		Minimum % of Recycled Binder
			A	B	
PG 58-28	RAP	64	1.044	3.127	-
		70	0.523	3.012	21.6
		76	0.274	2.911	44.6
	MRAS	64	1.002	2.875	-
		70	0.506	2.896	23.5
		76	0.264	2.508	53.1
	PRAS	64	1.173	9.851	-
		70	0.588	9.788	5.4
		76	0.309	9.615	12.2
PG 64-22	RAP	70	0.725	2.657	12.1
		76	0.354	2.628	39.5
	MRAS	70	0.691	2.446	15.1
		76	0.342	2.530	42.4
	PRAS	70	0.624	10.95	4.3
		76	0.307	10.76	11.0

From the above table, it can be noted that on blending a minimum of 21.6% binder from RAP or 23.5% binder from MRAS or 5.4% binder from PRAS with a virgin PG 58-28 binder, the condition of G*/Sinδ ≥ 1kPa is satisfied at a temperature of 70°C. In addition, on blending a minimum of 44.6% binder from RAP or 53.1% binder from MRAS or 12.2% binder from PRAS with a virgin PG 58-28 binder, the condition of G*/Sinδ ≥ 1kPa is satisfied at a temperature of 76°C. This is also similar to stating with regard to unaged binder testing results that the high temperature grade of the blended binder has shifted from 58 to 70 and 76 on blending a virgin PG 58-28 binder with 21.6% and 44.6% of extracted binder from RAP, respectively. Also, with regard to unaged binder testing results, it can be stated that on blending

PG 58-28 binder with 23.5% and 53.1% binder from MRAS, the high temperature grade of the blended binder shifted from 58 to 70 and 76, respectively. Similarly, with regard to unaged binder testing results, it can be stated that on blending PG 58-28 binder with 5.4% and 12.2% binder from PRAS, the high temperature grade of the blended binder shifted from 58 to 70 and 76, respectively. The minimum limits at a temperature of 64°C for PG 58-28 could not be determined from the exponential relationship between percentage recycled binder and G*/Sinδ values. Again, with regard to unaged binder testing results, it can be stated that on blending PG 64-22 binder with 12.1% and 39.5% of binder from RAP the high temperature grade shifted from 64 to 70 and 76, respectively. On blending PG 64-22 with 15.1% and 42.4% of binder from MRAS the high temperature grade shifted from 64 to 70 and 76, respectively and on blending PG 64-22 binder with 4.3% and 11% of binder from PRAS the high temperature grade shifted from 64 to 70 and 76, respectively.

5.2 Dynamic Shear Rheometer Testing of RTFO aged Blended Binders

The RTFO aged blended binders were tested on the DSR (Dynamic Shear Rheometer) in accordance with AASHTO T315 "Test Method for Determining the Rheological Properties of Asphalt Binder Using a Dynamic Shear Rheometer" to determine the rheological properties of Complex Modulus (G*) and Phase Angle (delta, δ) at different temperatures.

The mean G*/Sinδ and standard deviation values (in parenthesis) at different test temperatures obtained upon testing RAP and RAS based blended binders with the two virgin binders of grade PG 58-28 and PG 64-22 after RTFO aging are shown in Table 5-4.

Table 5-4. G*/Sinδ Values of RTFO aged Blended Binder

Binder Type	Average G*/Sinδ (kPa) with Standard Deviation at Test Temperature					
	64º C		70º C		76º C	
	G*/Sinδ	Std Dev	G*/Sinδ	Std Dev	G*/Sinδ	Std Dev
PG 58-28 + 25% RAP	9.22	0.09	4.49	0.05	2.23	0.02
PG 58-28 + 40% RAP	14.54	0.2	6.98	0.07	3.41	0.02
PG 64-22 + 25% RAP	-	-	4.21	0.02	1.94	0.02
PG 64-22 + 40% RAP	-	-	8.94	0.03	4.08	0.02
100% RAP	146.57	2.45	63.69	0.63	29.83	0.31
PG 58-28 + 10% MRAS	4.41	0.03	2.20	0.01	1.06	0.01
PG 58-28 + 20% MRAS	7.86	0.08	3.91	0.02	1.90	0.03
PG 64-22 + 10% MRAS	-	-	3.33	0.02	1.56	0.01
PG 64-22 + 20% MRAS	-	-	5.38	0.09	2.54	0.03
PG 58-28 + 10% PRAS	8.72	0.07	4.32	0.02	2.18	0.01
PG 58-28 + 25% PRAS	32.68	0.23	16.41	0.04	8.55	0.06
PG 64-22 + 10% PRAS	-	-	7.79	0.16	3.60	0.07
PG 64-22 + 25% PRAS	-	-	23.47	0.22	10.86	0.11

The G*/Sinδ values for RTFO aged blended binders with varying proportions of recycled binders were plotted together with those of RTFO aged virgin binder of grade PG 58-28 on a single plot for each testing temperature to arrive at the blending charts. Figure 5.6 through Figure 5.8 show the blending charts for PG 58-28 with varying proportions of recycled binders at different testing temperatures.

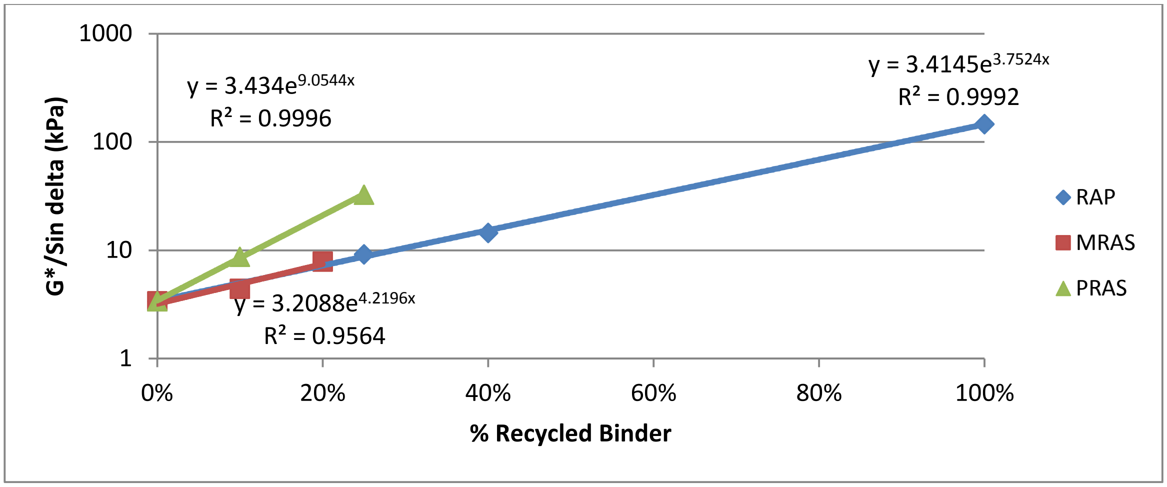

Figure 5.6. Blending Chart for PG 58-28 at 64ºC (RTFO)

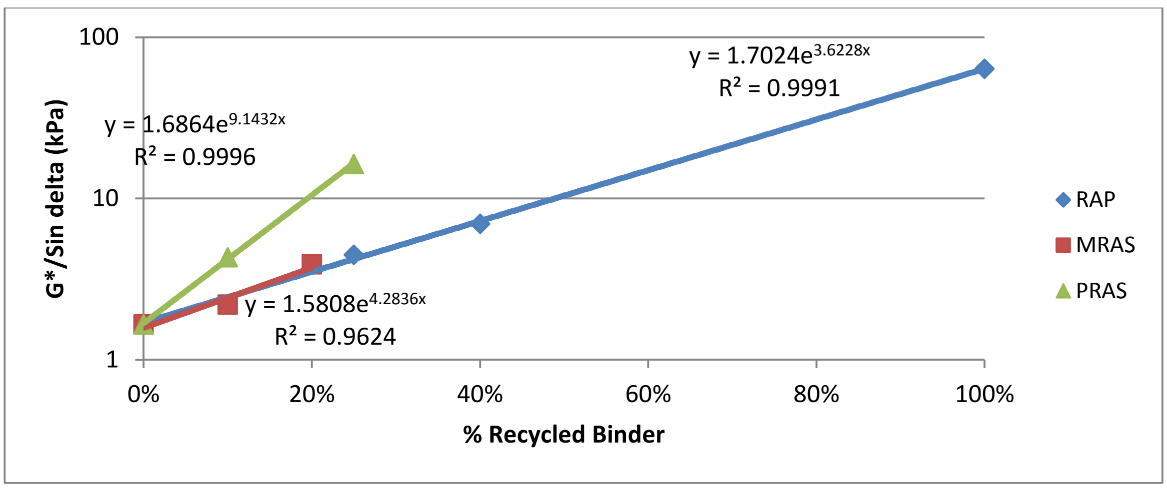

Figure 5.7. Blending Chart for PG 58-28 at 70ºC (RTFO)

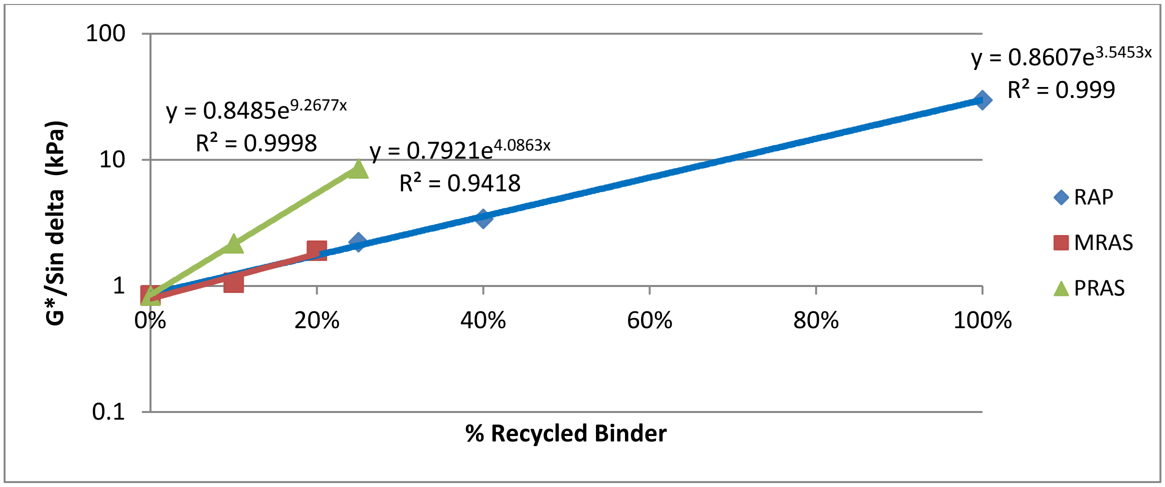

Figure 5.8. Blending Chart for PG 58-28 at 76°C (RTFO)

It can be observed from these blending charts that the stiffness of the blended binder increased with an increase in the proportion of recycled binder. This trend is similar to the one observed with unaged blended binders. It can be safely assumed that stiffer binders grow further stiff than softer binders upon aging in an RTFO.

The G*/Sinδ values for RTFO aged blended binders with varying proportions of recycled binders were plotted together with those of RTFO aged virgin binder of grade PG 64-22 on a single plot for each testing temperature to arrive at the blending charts. Figure 5.9 and Figure 5.10 are the blending charts for PG 64-22 with varying proportions of recycled binders at different testing temperatures as mentioned.

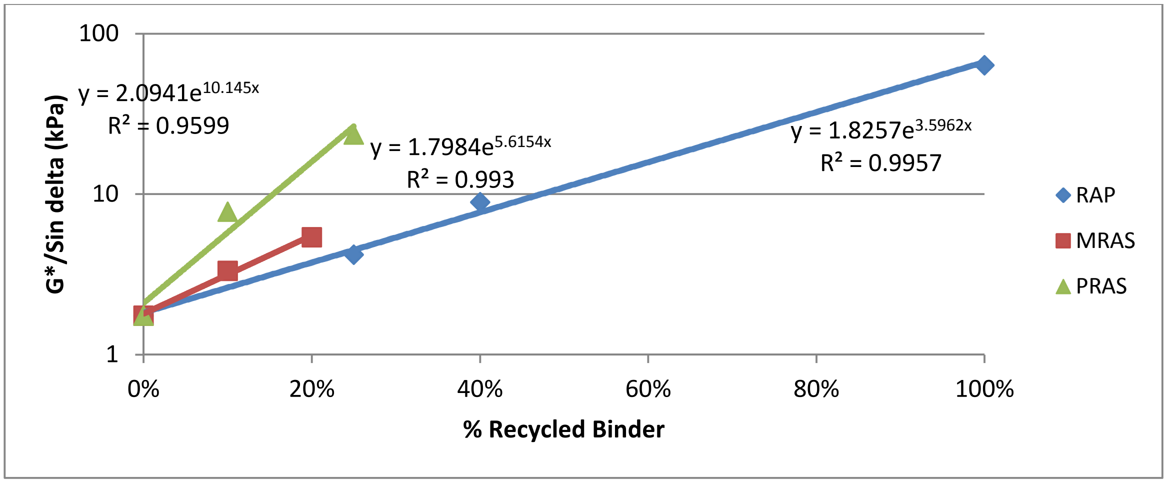

Figure 5.9. Blending Chart for PG 64-22 at 70ºC (RTFO)

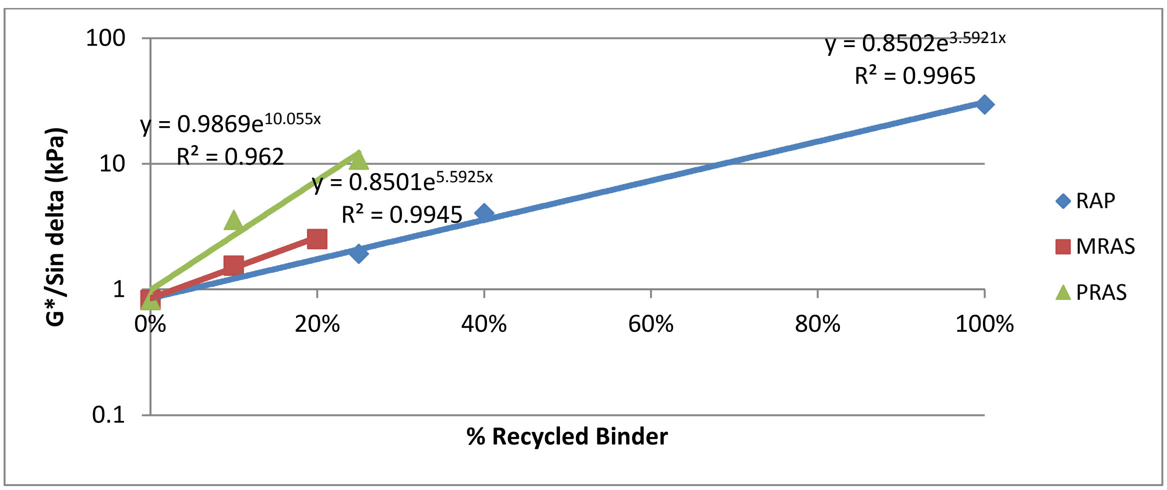

Figure 5.10. Blending Chart for PG 64-22 at 76ºC (RTFO)

It can be observed from these blending charts that the stiffness of the blended binder increased with an increase in the proportion of recycled binder. This trend is similar to the one observed with unaged blended binders. It can be safely assumed that stiffer binders grow further stiff than softer binders upon aging in an RTFO.

From the relationship between the percentage recycled binder and G*/Sinδ values in these RTFO aged binder blending charts, minimum percentage recycled binder was estimated such that the blended binder satisfied the Superpave requirement of G*/Sinδ ≥ 2.2kPa in the RTFO aged condition at various test temperatures. Table 5-5 below shows these calculations with the exponential relationship between the percentage recycled binder and G*/Sinδ values for both PG 64-22 and PG 58-28 based blended binders.

Table 5-5. Minimum Percentage of Recycled Binder to Satisfy G*/Sinδ = 2.2kPa for RTFO Aged Blended Binders at Various Test Temperatures

Virgin Binder	Recycled Binder	Temperature (°C)	G*/Sinδ = $Ae^{B(\%RAS)}$		Minimum % of Recycled Binder
			A	B	
PG 58-28	RAP	64	3.414	3.752	-
		70	1.702	3.622	7.1
		76	0.860	3.545	26.5
	MRAS	64	3.208	4.219	-
		70	1.580	4.283	7.7
		76	0.792	4.086	25.0
	PRAS	64	3.434	9.054	-
		70	1.686	9.143	2.9
		76	0.848	9.267	10.3
PG 64-22	RAP	70	1.825	3.596	5.2
		76	0.850	3.592	26.5
	MRAS	70	1.798	5.615	3.6
		76	0.850	5.592	17.0
	PRAS	70	2.094	10.140	0.5
		76	0.986	10.050	8.0

From the above table, it can be noted that on blending a minimum of 7.1% binder from RAP with a virgin PG 58-28 binder, the condition of G*/Sinδ ≥ 2.2kPa is satisfied at a temperature of 70°C and on blending a minimum of 26.5% binder from RAP with a virgin PG 58-28 binder, the condition of G*/Sinδ ≥ 2.2kPa is satisfied at a temperature of 76°C for RTFO aged conditions. Similarly, it can be noted that on blending a minimum of 7.7% binder from MRAS with a virgin PG 58-28 binder, the condition of G*/Sinδ ≥ 2.2kPa is satisfied at a temperature of 70°C and on blending a minimum of 25.0% binder from MRAS with a virgin PG 58-28 binder, the condition of G*/Sinδ ≥ 2.2kPa is satisfied at a temperature of 76°C for RTFO aged conditions. This is also similar to stating with regard to RTFO aged binder testing results that the high temperature grade of the blended binder has shifted from 58 to 70 and 76 on blending a virgin PG 58-28 binder with 7.1% and 26.5% of extracted binder from RAP, respectively. This is also similar to stating with regard to RTFO aged binder testing results that the high temperature grade of the blended binder has shifted from 58 to 70 and 76 on blending a virgin PG 58-28 binder with 7.7% and 25.0% of extracted binder from MRAS, respectively. In similar fashion, with regard to RTFO aged binder testing results, it can be stated that on blending PG 58-28 binder with 2.9% and 10.3% binder from PRAS, the high temperature grade of the blended binder shifted from 58 to 70 and 76, respectively. The minimum limits at a temperature of 64°C for PG 58-28 could not be determined from the exponential relationship between percentage recycled binder and G*/Sinδ values. Again, with regard to RTFO aged binder testing results, it can be similarly stated that on blending PG 64-22 binder with 5.2% and 26.5% of binder from RAP the high temperature grade shifted from 64 to 70 and 76, respectively and on blending PG 64-22 binder with 3.6% and 17.0% of binder from MRAS the high temperature grade shifted from 64 to 70 and 76, respectively and on blending PG 64-22 binder with 0.5%

and 8% of binder from PRAS the high temperature grade shifted from 64 to 70 and 76, respectively.

5.3 Dynamic Shear Rheometer Testing of PAV aged Blended Binders

The PAV aged blended binders were tested on the DSR (Dynamic Shear Rheometer) in accordance with AASHTO T315 "Test Method for Determining the Rheological Properties of Asphalt Binder Using a Dynamic Shear Rheometer" to determine the rheological properties of Complex Modulus (G*) and Phase Angle (delta, δ) at different temperatures.

The mean G*Sinδ and standard deviation values (in parenthesis) at different test temperatures obtained upon testing virgin binders blended with binders extracted from various recycled materials is shown in Table 5-6.

Table 5-6. G*Sinδ Values of PAV aged Blended Binder

Binder Type	Average G*Sinδ (kPa) with Standard Deviation at Test Temperature							
	28º C		25º C		22º C		19º C	
	G*Sinδ	Std Dev	G*Sinδ	Std Dev	G*Sinδ	Std	G*Sinδ	Std Dev
PG 58-28 + 25% RAP	2424	160	3373	219	4847	306	6945	438
PG 58-28 + 40% RAP	3304	103	4495	141	6338	199	8903	286
PG 64-22 + 25% RAP	3752	34	5263	60	7373	87	-	-
PG 64-22 + 40% RAP	4974	237	6793	321	9278	437	-	-
PG 58-28 + 10% MRAS	1369	60	1953	101	2858	112	4195	172
PG 58-28 + 20% MRAS	1791	101	2481	136	3537	197	5030	288
PG 64-22 + 10% MRAS	2875	56	4068	59	5734	74	-	-
PG 64-22 + 20% MRAS	3063	29	4241	46	5893	47	-	-
PG 58-28 + 10% PRAS	1912	20	2666	39	3833	87	5530	165
PG 58-28 + 25% PRAS	3481	244	4578	308	6233	409	8491	546
PG 64-22 + 10% PRAS	3724	25	5171	43	7159	67	-	-
PG 64-22 + 25% PRAS	5233	553	6862	737	9015	978	-	-

The G*Sinδ values for PAV aged blended binders with varying proportions of recycled binders were plotted together with those of PAV aged virgin binder of grade PG 58-28 on a single plot for each testing temperature to arrive at the blending charts. Figure 5.11 through Figure 5.14

are the blending charts for PG 58-28 with varying proportions of recycled binders at different testing temperatures.

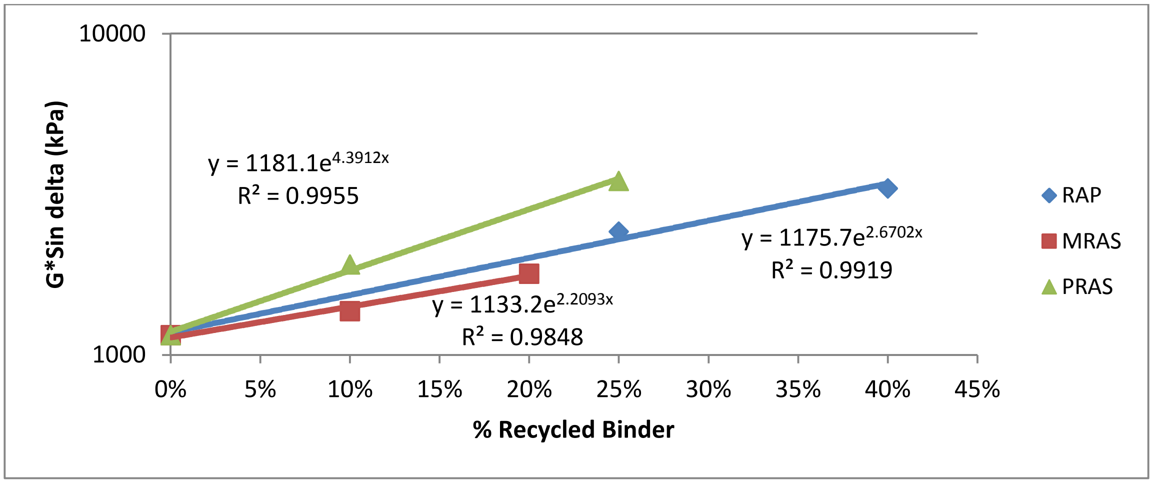

Figure 5.11. Blending Chart for PG 58-28 at 28ºC (PAV)

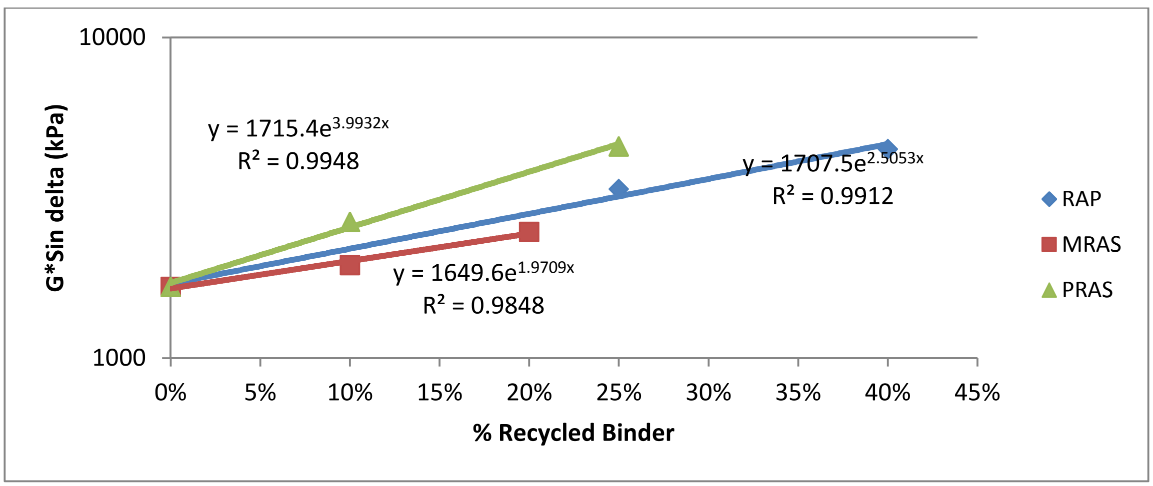

Figure 5.12. Blending Chart for PG 58-28 at 25ºC (PAV)

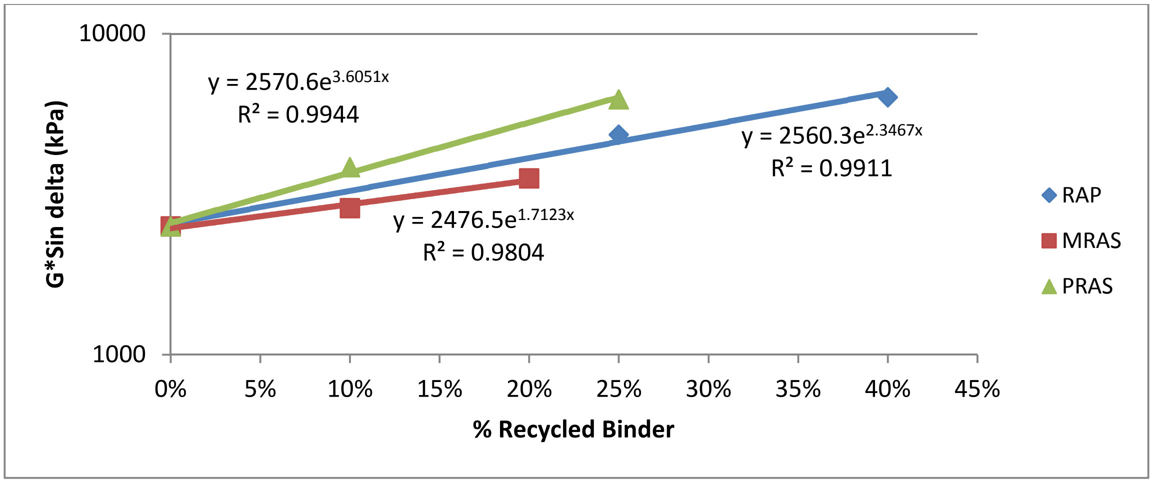

Figure 5.13. Blending Chart for PG 58-28 at 22ºC (PAV)

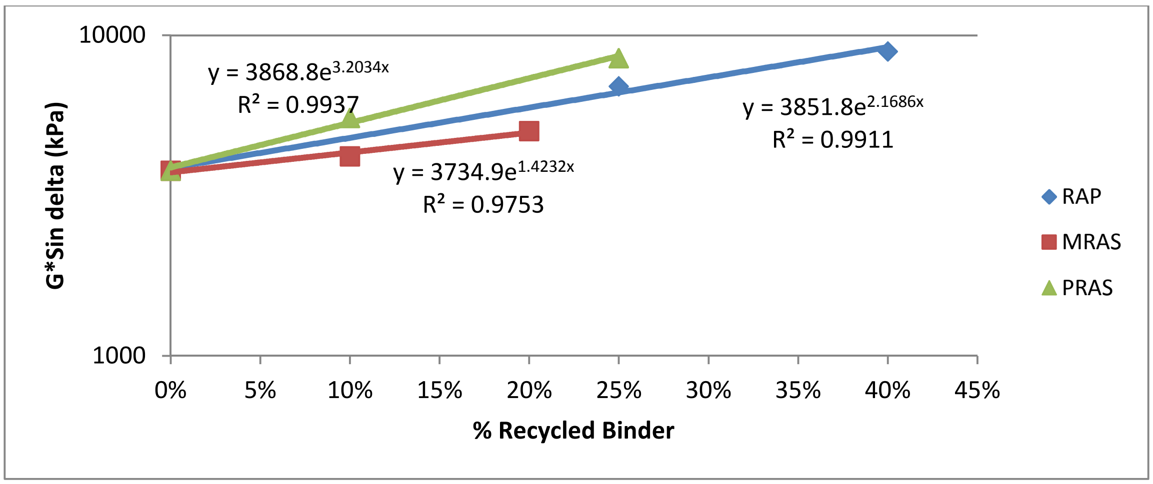

Figure 5.14. Blending Chart for PG 58-28 at 19ºC (PAV)

It can be observed from these blending charts that the stiffness of the blended binder increased with an increase in the proportion of recycled binder. This trend is similar to the one observed with unaged and RTFO aged blended binders.

The G*Sinδ values for PAV aged blended binders with varying proportions of recycled binders were plotted together with those of PAV aged virgin binder of grade PG 64-22 on a single plot for each testing temperature to arrive at the blending charts. Figure 5.15 through Figure 5.18 are the blending charts for PG 64-22 with varying proportions of recycled binder at different testing temperatures.

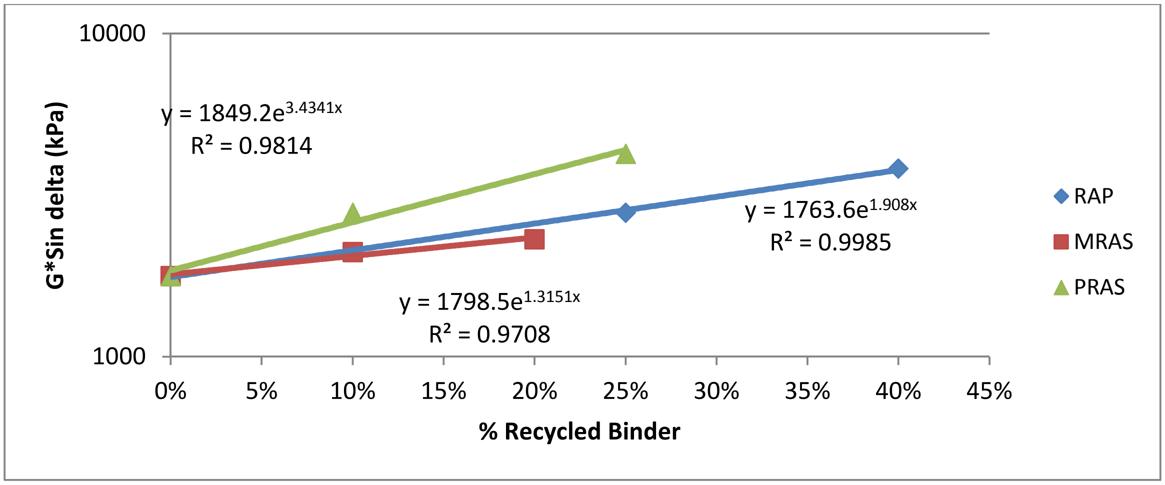

Figure 5.15. Blending Chart for PG 64-22 at 31ºC (PAV)

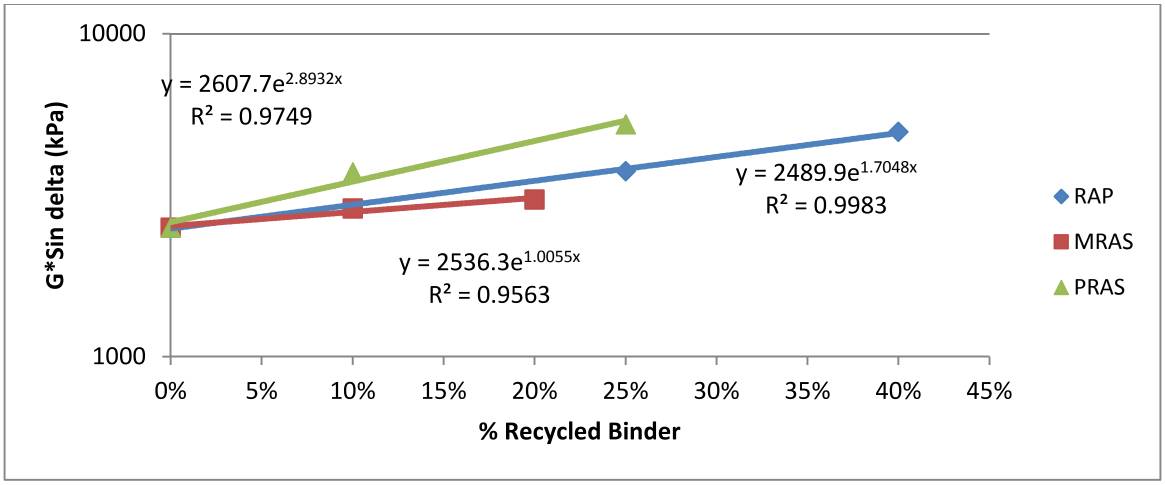

Figure 5.16. Blending Chart for PG 64-22 at 28ºC (PAV)

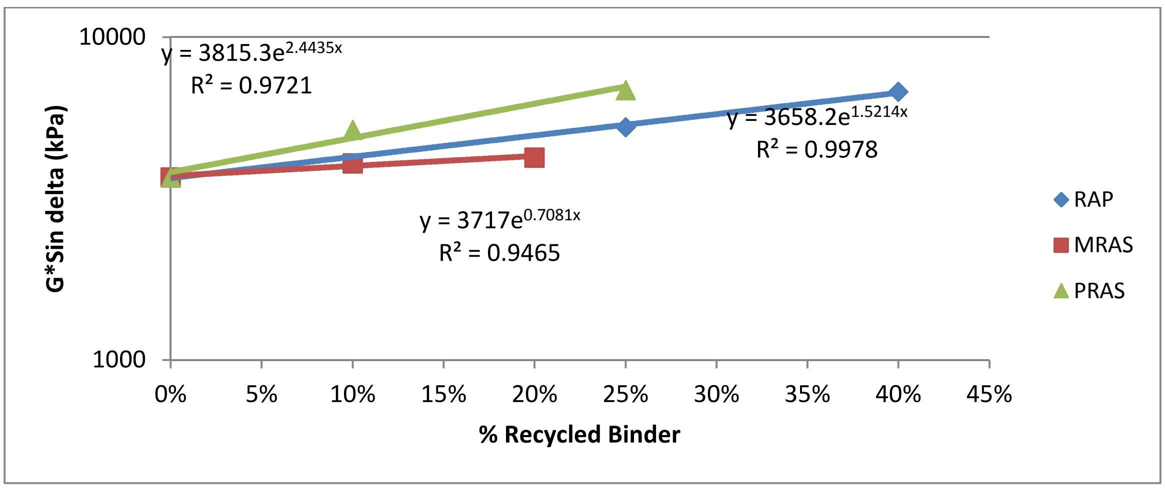

Figure 5.17. Blending Chart for PG 64-22 at 25ºC (PAV)

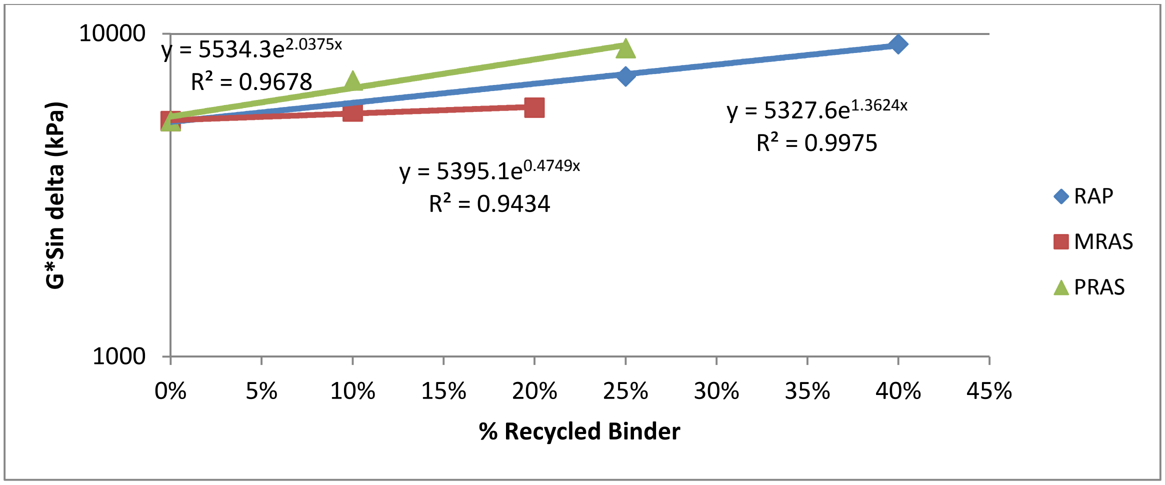

Figure 5.18. Blending Chart for PG 64-22 at 22ºC (PAV)

It can be observed from these blending charts that the stiffness of the blended binder increased with an increase in the proportion of recycled binder. This trend is similar to the one observed with unaged and RTFO aged blended binders.

From the relationship between the percentage recycled binder and G*Sinδ in these PAV aged binder blending charts, maximum percentage recycled binder is estimated that can be blended with a virgin binder such that the blended binder satisfied the Superpave requirement of G*Sinδ ≤ 5000kPa in the PAV aged condition at various test temperatures. Table 5-7 below shows these calculations with the exponential relationship between the percentage recycled binder and G*Sinδ values for both PG 64-22 and PG 58-28 based blended binders.

Table 5-7. Maximum Percentage of Recycled Binder to Satisfy G*Sinδ = 5000kPa for PAV Aged Blended Binders at Various Test Temperatures

Virgin Binder	Recycled Binder	Temperature (°C)	G*Sinδ = $Ae^{B(\%RAS)}$		Maximum % of Recycled Binder
			A	B	
PG 58-28	RAP	28	1175	2.670	54.2
		25	1707	2.505	42.9
		22	2560	2.346	28.5
	MRAS	28	1133	2.209	67.2
		25	1649	1.970	56.3
		22	2476	1.712	41.1
		19	3734	1.423	20.5
	PRAS	28	1181	4.391	32.9
		25	1715	3.993	26.8
		22	2570	3.605	18.5
		19	3868	3.203	8.0
PG 64-22	RAP	31	1763	1.908	54.6
		28	2489	1.704	40.9
		25	3658	1.521	20.5
	MRAS	31	1798	1.315	77.8
		28	2536	1.005	67.5
		25	3717	0.708	41.9
		22	5395	0.474	-
	PRAS	31	1849	3.434	29.0
		28	2607	2.893	22.5
		25	3815	2.443	11.1
		22	5534	2.037	-

From the above table, it can be noted that on blending a maximum of 54.2% binder from RAP or 67.2% binder from MRAS or 32.9% binder from PRAS with a virgin PG 58-28 binder, the condition of G*Sinδ ≤ 5000kPa is satisfied at a temperature of 28°C. On blending a maximum of 42.9% binder from RAP or 56.3% binder from MRAS or 26.8% binder from PRAS with a virgin PG 58-28 binder, the condition of G*Sinδ ≤ 5000kPa is satisfied at a temperature of

25^{o}C. In addition, on blending a maximum of 41.1% binder from MRAS or 18.5% binder from PRAS with a virgin PG 58-28 binder, the condition of G*Sinδ ≤ 5000kPa is satisfied at a temperature of 22^{o}C and on blending a maximum of 20.5% binder from MRAS or 8.0% binder from PRAS with a virgin PG 58-28 binder, the condition of G*Sinδ ≤ 5000kPa is satisfied at a temperature of 19^{o}C. In similar fashion, it can be noted that on blending a maximum of 54.6% binder from RAP or 77.8% binder from MRAS or 29.0% binder from PRAS with a virgin PG 64-22 binder, the condition of G*Sinδ ≤ 5000kPa is satisfied at a temperature of 31^{o}C and on blending a maximum of 40.9% binder from RAP or 67.5% binder from MRAS or 22.5% binder from PRAS with a virgin PG 64-22 binder, the condition of G*Sinδ ≤ 5000kPa is satisfied at a temperature of 28^{o}C. Finally, on blending a maximum of 20.5% binder from RAP or 41.9% binder from MRAS or 11.1% binder from PRAS with a virgin PG 64-22 binder, the condition of G*Sinδ ≤ 5000kPa is satisfied at a temperature of 25^{o}C.

5.4 Summary of Binder Testing Results and Conclusions

The minimum percentage recycled binder values obtained from unaged binder testing (Table 5-3) and RTFO aged binder testing (Table 5-5) were compared and the larger of the two values was taken for establishing the minimum limits for percentage recycled binder that can be added to a virgin binder to meet the specifications at a given high temperature and the results from the PAV aged binder testing at intermediate temperatures (Table 5-7) were used as the maximum limits for the percentage recycled binder that can be added to a virgin binder to meet the specifications at a given intermediate temperature. Table 5-8 is the summary of the binder testing results constructed by following the above principle and combining the results from, Table 5-3, Table 5-5and Table 5-7.

Table 5-8. Minimum and Maximum Limits of Binder Extracted from Recycled Materials that can be Used in a S9.5B Mix

Virgin Binder	Recycled Binder	High Temperature (Minimum)			Intermediate Temperature (Maximum)				
		64°C*	**70°C**	**76°C**	**19°C**	**22°C**	**25°C**	**28°C**	**31°C**
PG 58-28	RAP	-	21.6%	44.6%	12.0%	28.5%	42.9%	54.2%	-
	MRAS	-	23.5%	53.1%	20.5%	41.1%	56.3%	67.2%	-
	PRAS	-	5.4%	12.2%	8.0%	18.5%	26.8%	32.9%	-
PG 64-22	RAP	-	12.1%	39.5%	-	-	20.5%	40.9%	54.6%
	MRAS	-	15.1%	42.4%	-	-	41.9%	67.5%	77.8%
	PRAS	-	4.3%	11.0%	-	-	11.1%	22.5%	29.0%

**The regression parameters estimated from the blending charts could not be used to calculate the minimum limits of recycled binder at 64°C.*

Since this research focuses on S9.5B mixes in North Carolina and the binder is required to meet the specifications of a PG 64-22 binder, limits from the above Table 5-8 have been selected accordingly. In Table 5-9 below are mentioned the recycled binder limits (rounded to the nearest 5%) derived from Table 5-8 that would satisfy the specifications of a PG 64-22 binder for both high and intermediate temperatures.

Table 5-9. Binder Limits for S9.5B Mixes

Recycled Binder	Virgin Binder	Maximum Limits (% Binder)
RAP	PG 58-28	45%
	PG 64-22	20%
MRAS	PG 58-28	55%
	PG 64-22	40%
PRAS	PG 58-28	25%
	PG 64-22	10%

The maximum limits shown in Table 5-9 are the maximum allowable weights of recycled binder by weight of total binder in the HMA mixture. Thus, it can be stated that for designing a S9.5B mixture with RAP in North Carolina, a binder of grade PG 64-22 can be used with a maximum allowable binder replacement of 20% and for designing a S9.5B mixture with MRAS in North Carolina, a binder of grade PG 64-22 can be used with a maximum allowable binder replacement of 40%. Similarly, for a S9.5B mixture with PRAS, a binder of grade PG 64-22 can be used with a maximum allowable binder replacement of 10%. Additionally, if a binder of grade PG 58-28 were to be used with RAP, the maximum allowable binder replacement is 45% and if the same virgin binder was used with MRAS, the maximum allowable binder replacement is 55% and if PG 58-28 were to be used with PRAS, the maximum allowable binder replacement is 25%. These limits were used as the guideline for designing recycled mixtures in Chapter 6 and subsequently the designed mixtures were tested on the AMPT to be able to compare the performance with that of a virgin HMA pavement and recommend a change in the current NCDOT regulations if needed.

6. MIXTURE DESIGN

This chapter will discuss the design of HMA mixtures and determining the optimum asphalt binder content for virgin HMA mixture and mixtures incorporating RAP and RAS. Binder limits that were determined in the previous chapter are used here as a guideline for limiting the proportions of RAP and RAS in HMA. Virgin HMA mixture design was initially conducted to arrive at the design aggregate structure and this design aggregate structure was used further to estimate the optimum asphalt binder content for HMA mixtures incorporating waste materials.

6.1 Virgin Mixture Design

The aggregates mentioned in Chapter 4 namely 78M, WS and Fines were blended in varying proportions to arrive at different trial aggregate blend gradations. These blend gradations were compared to the NCDOT Aggregate Gradation Criteria for S9.5B mixes and were within the control points. Since the research focuses on S9.5B mixtures, mix design procedures using virgin aggregates and a virgin binder of grade PG 64-22 were conducted initially to determine both optimum asphalt binder content and the design aggregate structure. The ranges of mixing and compaction temperatures for this binder were calculated from the viscosity-temperature relationship determined using a Rotational Viscometer (Table 4-6). The ranges of mixing and compaction temperatures thus calculated are 156^{o}C – 161^{o}C and 144^{o}C – 150^{o}C, respectively. Table 6-1 below shows the control points for S9.5B mixtures and the three trial aggregate gradations based on which aggregates were batched, mixed and compacted at various asphalt binder contents.

Table 6-1. Trial Aggregate Gradations for Virgin HMA Mix Design

Sieve size	% Passing			Control Points (% Passing)	
	Trial 1	Trial 2	Trial 3	Min	Max
12.5 mm	100.0	100.0	100.0	100.0	-
9.5 mm	94.5	97.1	96.3	90.0	100.0
4.75 mm	59.1	78.1	72.3	-	90.0
2.36 mm	38.9	61.8	55.0	32.0	67.0
1.18 mm	29.8	46.9	41.9	-	-
600 µm	21.8	32.9	29.9	-	-
300 µm	14.4	20.1	18.9	-	-
150 µm	7.9	8.9	9.2	-	-
75 µm	5.7	5.3	6.1	4.0	8.0
Pan	0	0	0		

These trial gradations were arrived at by combining the three different aggregate types (78M, WS & Fines) in varying proportions. The proportions are shown in Table 6-2 below. The fines were needed in order to meet the control point criteria of material passing 75 micron, as the material finer than 75 micron in both 78M and WS was considerably lower than the control point requirement.

Table 6-2. Percent Proportions for Trial Gradations

Aggregate Type	% Combinations		
	Trial 1	Trial 2	Trial 3
78M	60.0%	32.0%	40.5%
WS	36.0%	65.0%	55.5%
Fines	4.0%	3.0%	4.0%

Figure 6.1 below shows the virgin aggregate gradations and the three trial aggregate gradations on a 0.45 power chart.

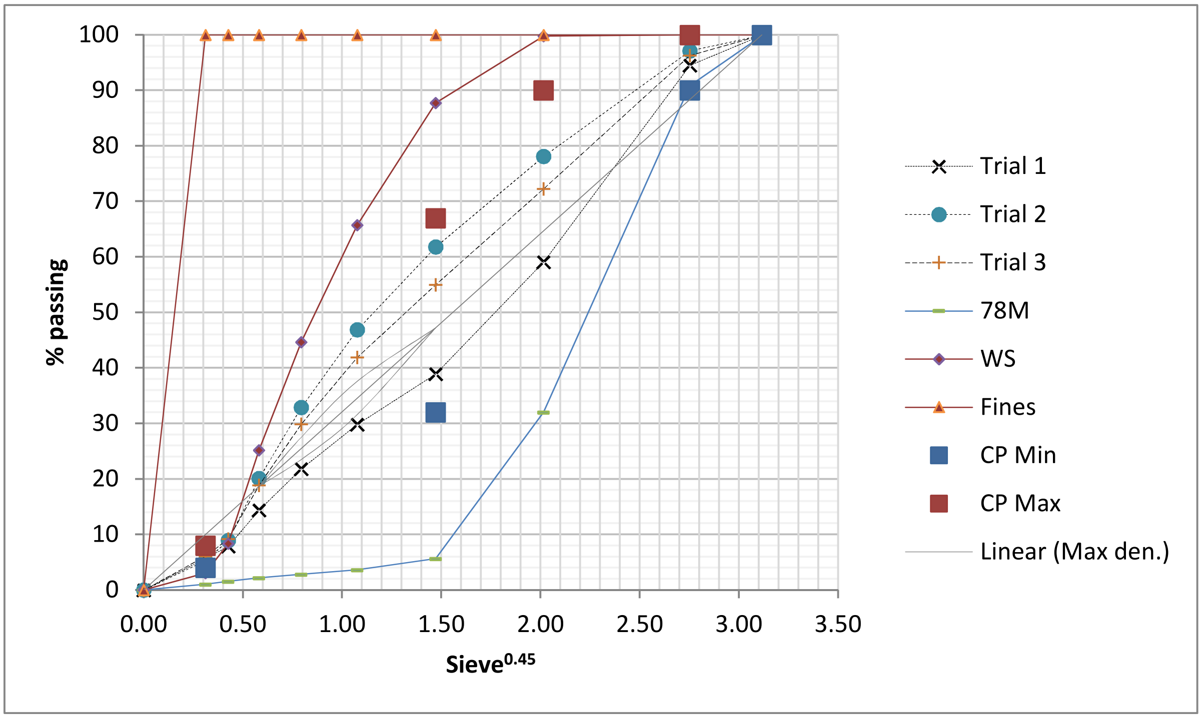

Figure 6.1. Blended Trial Aggregate Gradations with Control Points and Virgin Aggregate Gradations

The specific gravities for the three trial gradations were calculated based on the proportions of the three aggregates and their individual aggregate specific gravities. The specific gravities of the three types of aggregates and the three trial aggregate gradations are shown in Table 6-3**.**

Table 6-3. Specific Gravities of Aggregate and Trial Gradations

Aggregate/Trial	Gsb	Gsa
78M	2.617	2.644
WS	2.597	2.652
Fines	2.597	2.647
Trial 1	2.609	2.647
Trial 2	2.603	2.649
Trial 3	2.605	2.649

Samples were mixed, conditioned and compacted as per AASHTO R35 “Superpave Volumetric Design for HMA Mixtures” and AASHTO R30 “Mixture Conditioning of HMA” and their bulk specific gravities and maximum specific gravities determined as per AASHTO T166 “Determining Bulk Specific Gravity of HMA” and AASHTO T209 “Determining Theoretical Maximum Specific Gravity of HMA mixtures”. The volumetrics were calculated for each trial gradation with varying asphalt binder contents and were compared to the NCDOT Superpave Mix Design Criteria (Table 6-4).

Table 6-4. Superpave Mix Design Criteria (Table 610-3, NCDOT QMS Manual)

Mix	**Design ESALS** (Million)	**Binder Grade**	**Compaction Levels (G_{mm} @)**		**Max Rut Depth** (mm)	**Volumetric Properties**			
			N_{ini}	**N_{des}**		**VMA** (%min)	**VTM** (%)	**VFA** (Min-Max)	**%G_{mm}@ N_{ini}**(Max)
S9.5B	0.3-3	64-22	7	65	9.5	15.5	3-5	65-80	90.5
	Design Parameter					**Design Criteria**			
	Dust to binder ratio ($P_{0.075}/P_{be}$)					0.6 - 1.4			

On comparison of the mixture volumetric properties obtained after mixing and compaction with the three trial gradations and various binder contents, only the volumetric properties of Trial 1 with 6% asphalt binder content satisfied the mix design criteria. The mixture volumetric properties for Trial 1 aggregate gradation and 6% asphalt binder content are shown in Table 6-5 below.

Table 6-5. Mixture Volumetrics for Trial 1 Aggregate Gradation

Binder Grade	Binder Content	Air Voids	Compaction Levels (G_{mm} @)		Volumetric Properties		
			N_{ini}	N_{des}	VMA (%)	VFA (%)	%G_{mm}@ N_{ini}
64-22	6%	4.2%	7	65	16	74	87.9%
	Design Parameter				**Design Criteria**		
	Dust to binder ratio ($P_{0.075}/P_{be}$)				1.0		

Since this research focuses on addition of waste materials to the virgin mixes, as the proportion of the waste materials is increased there will be a need to reduce the binder grade of the base virgin binder. In view of this, it was necessary to use softer grade asphalt binder instead of the usual asphalt binder as the base virgin binder in the HMA mixtures with higher percentage of waste materials. Although the binder used was a softer grade binder, the aggregate gradations were kept the same so that the comparison of performance in mixes incorporating recycled materials with that of virgin materials was done appropriately and any differences were attributed to the change in the binder stiffness rather than to a change in aggregate structure. Since the available binder with a grade below the above mentioned PG 64-22 binder was PG

58-28, mix design specimens were mixed and compacted using this binder at appropriate mixing and compaction temperatures (determined by rotational viscometer) at the same optimum asphalt content of 6% and the volumetrics were calculated. Although these volumetrics were slightly different from the ones for PG 64-22, they were within the Superpave mix design criteria. This step was necessary so as to ensure that HMA mixes with different virgin asphalt binders did not undergo a significant change in mixture volumetrics and that they would meet the Superpave mix design criteria.

It can thus be concluded that the optimum asphalt content for the S9.5B virgin mixes using a PG 64-22 asphalt binder and the two different types of aggregates (78M & WS) in addition to pond fines was 6%. This optimum asphalt binder content for the virgin mixes together with the Trial 1 aggregate gradations was used as the basis to arrive at optimum asphalt content for mixes with recycled waste materials.

6.2 Design of Mixtures with RAP

A mix design procedure incorporating RAP was conducted to determine the optimum asphalt binder contents for each of the RAP mixes. RAP was treated as a separate aggregate stockpile in the mix design procedure and was blended with the virgin aggregates (78M, WS and Fines) to have a blend gradation close to the Trial 1 gradation or the design aggregate structure. Adjustments were made in the proportions of the virgin materials to account for the aggregate and the binder contributed by the RAP.

Mixes were designed with PG 64-22 or PG 58-28 virgin binders depending upon the proportion of RAP in the HMA mixture. Results in Table 5-9 were used as the guideline for determining the base virgin binder to be used in the mix. This step is necessary to conduct performance testing on a range of mixtures to select the optimum mixture proportions for best performance and also satisfying the limits derived from rheological testing on binders alone.

The design aggregate structure and the optimum asphalt binder content obtained by virgin mix design were tested with mixtures incorporating RAP and the obtained volumetrics were compared to the NCDOT specifications. The design procedure was carried out by sampling in accordance with AASHTO T248 “Reducing Samples of Aggregate to Testing Size” and batching appropriate amounts of air dried RAP such that the amount of binder replaced by the recycled binder from RAP in the total mix was not greater than the limits established by rheological testing on blended binders and the blending charts (Table 5-9). Care was also taken to selectively remove foreign matter from samples of RAP since their presence could hinder the binding of the aggregate with the asphalt binder.

Table 6-6 below shows the different mix types or combinations for mixture designs incorporating RAP by weight of total binder replaced.

Table 6-6. Proportions of RAP by Weight of Total Binder Replaced

Virgin Binder	RAP
PG 58-28	45%
	20%
	8%
PG 64-22	20%
	8%

For HMA mixes with proportions of RAP higher than 30% by weight of total mix, fractionated RAP was used so as to lower the levels of variability obtained upon incorporating such high proportions of RAP. Adjustments were made accordingly in the virgin aggregate proportions so as to account for the aggregate and binder contributed by both the fractions of RAP. NCHRP guidelines were followed for modifications in the HMA mixture design procedure when incorporating recycled materials. The recycled materials were heated at 110^{o}C for a duration not exceeding 2 hours prior to mixing. The virgin aggregate was heated to temperatures higher than mixing temperatures to account for the reduced temperatures of the recycled materials. During the mixing process, it was ensured that RAP was mixed with the overheated aggregate prior to the addition of the virgin binder in order for the total mixture to reach the mixing temperature. Mixing and Compaction temperatures were determined based on the mix type, i.e. S9.5B mix. Samples were mixed; short term aged and compacted for determining the mixture volumetrics. Initially samples were compacted using a total asphalt binder content of 6% so as to maintain consistency with the virgin mix design. Only when the volumetrics were not met, changes were made in the total asphalt binder content. Table 6-7 below shows the optimum asphalt content for the different mixtures shown in Table 6-6.

Table 6-7. Optimum Asphalt Content (OAC) for RAP Mixes

Virgin Binder	RAP	OAC
PG 58-28	45%	5.4%
	20%	5.5%
	8%	6.0%
PG 64-22	20%	5.6%
	8%	6.0%

Thus, it can be explained that when a binder replacement of 45% was achieved in a mix with a virgin PG 58-28 binder with the same design aggregate structure as the virgin mix, the optimum asphalt content was reduced to 5.4% from 6%. Similarly, when a binder replacement of 20% was achieved in a mix with a virgin PG 58-28 binder with the same design aggregate structure as the virgin mix, the optimum asphalt content was reduced to 5.5% from 6%. Additionally, when a binder replacement of 8% was achieved in a mix with a virgin PG 58-28 binder with the same design aggregate structure as the virgin mix, the optimum asphalt content was unaffected at 6%. On the contrary, when a binder replacement of 20% and 8% was achieved in a mix with a virgin PG 64-22 binder with the same design aggregate structure as the virgin mix, the optimum asphalt binder content was 5.6% and 6.0%, respectively.

Table 6-8 below shows the proportions of RAP by weight of total mixtures. The conversion from weight of total binder replaced to weight of total mix for each mix type was done using the asphalt binder content of 5.0% for RAP and their respective mixture OAC's.

Table 6-8. Proportions of RAP by Weight of Total Mix

Virgin Binder	RAP
PG 58-28	48.8%
	22.1%
	10.0%
PG 64-22	22.5%
	10.0%

Therefore, in order to achieve a 45%, 20% and 8% binder replacement in recycled mixtures with PG 58-28, the weight of RAP should be 48.8%, 22.1% and 10.0% by weight of total mix, respectively. Similarly, in order to achieve a 20% and 8% binder replacement in recycled mixtures with PG 64-22, the weight of RAP should be 22.5% and 10.0% by weight of total mix, respectively.

6.3 Design of Mixtures with MRAS

A mix design procedure incorporating MRAS was conducted to determine the optimum asphalt binder contents for each of the MRAS mixes. MRAS was treated as a separate aggregate stockpile in the mix design procedure and was blended with the virgin aggregates (78M, WS and Fines) to have a blend gradation close to the Trial 1 gradation or the design aggregate structure. Adjustments were made in the proportions of the virgin materials so as to account for the aggregate and the binder contributed by the MRAS.

Mixes were designed with PG 64-22 or PG 58-28 virgin binders depending upon the proportion of MRAS in the HMA mixture. Results in Table 5-9 were used as the guideline for determining the base virgin binder to be used in the mix. This step is necessary to be able to conduct performance testing on a range of mixtures to select the optimum mixture proportions for best performance and also satisfying the limits derived from rheological testing on binders alone.

The design aggregate structure and the optimum asphalt binder content obtained by virgin mix design were tested with mixtures incorporating MRAS and the obtained volumetrics were compared to the NCDOT specifications. The design procedure was carried out by batching appropriate amounts of air dried MRAS such that the amount of binder replaced by the recycled binder from MRAS in the total mix was not greater than the limits established by rheological testing on blended binders and the blending charts (Table 5-9). Care was also taken to selectively remove foreign matter from samples of MRAS since their presence could hinder the binding of the aggregate with the asphalt binder.

Table 6-9 below shows the different mix types or combinations for mixture designs incorporating MRAS by weight of total binder replaced.

Table 6-9. Proportions of MRAS by Weight of Total Binder Replaced

Virgin Binder	MRAS
PG 58-28	55%
	30%
PG 64-22	40%
	20%

NCHRP guidelines were followed for modifications in the HMA mixture design procedure when incorporating recycled materials. The recycled materials were heated at 110ºC for a duration not exceeding 2 hours prior to mixing. The virgin aggregate was heated to temperatures higher than mixing temperatures to account for the reduced temperatures of the recycled materials. During the mixing process, it was ensured that MRAS was mixed with the overheated aggregate prior to the addition of the virgin binder in order for the total mixture to reach the mixing temperature. Mixing and Compaction temperatures were determined based on the mix type, i.e. S9.5B mix. Samples were mixed; short term aged and compacted for determining the mixture volumetrics. Initially samples were compacted using a total asphalt binder content of 6% so as to maintain consistency with the virgin mix design. Only when the volumetrics were not met, changes were made in the total asphalt binder content. Table 6-10 below shows the optimum asphalt content for the different mixtures shown in Table 6-9.

Table 6-10. Optimum Asphalt Content (OAC) for MRAS Mixes

Virgin Binder	MRAS	OAC
PG 58-28	55%	5.7%
	30%	5.8%
PG 64-22	40%	6.0%
	20%	6.0%

Thus it can be explained that when a binder replacement of 55% was achieved in a mix with a virgin PG 58-28 binder with the same design aggregate structure as the virgin mix, the optimum asphalt content was reduced to 5.7% from 6%. Similarly, when a binder replacement of 30% was achieved in a mix with a virgin PG 58-28 binder with the same design aggregate structure as the virgin mix, the optimum asphalt content was reduced to 5.8% from 6%. On the contrary, when a binder replacement of 40% and 20% was achieved in a mix with a virgin PG 64-22 binder with the same design aggregate structure as the virgin mix, there was no change in the optimum asphalt content. This could possibly be attributed to the tendency of the blended binder to be much stiffer in the case of PG 64-22 than in PG 58-28. Since there is no change in the compaction effort as the number of gyrations and axial load are kept the same for all mixtures and the blended binder grows stiffer as the proportion of MRAS in the mix increases, the volumetrics are achieved fairly at a similar OAC as that of the virgin mix in the case of PG 64-22 binder. This might not be the case with the PG 58-28 binder. Although the stiffness of the blended binders was following a very similar trend when tested on a DSR, the behavior of these binders changed to a significant degree in the presence of the aggregate.

Table 6-11 below shows the proportions of MRAS by weight of total mixtures. The conversion from weight of total binder replaced to weight of total mix for each mix type was done using the asphalt binder content of 14.7% for MRAS and their respective mixture OAC's.

Table 6-11. Proportions of MRAS by Weight of Total Mix

Virgin Binder	MRAS
PG 58-28	19.4%
	10.8%
PG 64-22	14.9%
	7.5%

Therefore, in order to achieve a 55% and 30% binder replacement in recycled mixtures with PG 58-28, the weight of MRAS should be 19.4% and 10.8% by weight of total mix, respectively. Similarly in order to achieve a 40% and 20% binder replacement in recycled mixtures with PG 64-22, the weight of MRAS should be 14.9% and 7.5% by weight of total mix, respectively.

6.4 Design of Mixtures with PRAS

A mix design procedure incorporating PRAS was conducted to determine the optimum asphalt binder contents for each of the PRAS mixes. PRAS was treated as a separate aggregate stockpile in the mix design procedure and was blended with the virgin aggregates (78M, WS and Fines) to have a blend gradation close to the Trial 1 gradation or the design aggregate structure. Adjustments were made in the proportions of the virgin materials so as to account for the aggregate and the binder contributed by the PRAS.

Mixes were designed with PG 64-22 or PG 58-28 virgin binders depending upon the proportion of PRAS in the HMA mixture. Results in Table 5-9 were used as the guideline for determining the base virgin binder to be used in the mix. This step is necessary to be able to conduct performance testing on a range of mixtures to select the optimum mixture proportions for best performance and also satisfying the limits derived from rheological testing on binders alone.

The design aggregate structure and the optimum asphalt binder content obtained by virgin mix design were tested with mixtures incorporating PRAS and the obtained volumetrics were compared to the NCDOT specifications. The design procedure was carried out by batching appropriate amounts of air dried PRAS such that the amount of binder replaced by the recycled binder from PRAS in the total mix was not greater than the limits established by rheological testing on blended binders and the blending charts (Table 5-9). Care was also taken to selectively remove foreign matter from samples of PRAS since their presence could hinder the binding of the aggregate with the asphalt binder.

Table 6-12 below shows the different mix types or combinations for mixture designs incorporating PRAS by weight of total binder replaced.

Table 6-12. Proportions of PRAS by Weight of Total Binder Replaced

Virgin Binder	PRAS
PG 58-28	25%
PG 64-22	15%

NCHRP guidelines were followed for modifications in the HMA mixture design procedure when incorporating recycled materials. The recycled materials were heated at 110^{o}C for duration not exceeding 2 hours prior to mixing. The virgin aggregate was heated to temperatures higher than mixing temperatures to account for the reduced temperatures of the recycled materials. During the mixing process, it was ensured that PRAS was mixed with the overheated aggregate prior to the addition of the virgin binder in order for the total mixture to reach the mixing temperature. Mixing and Compaction temperatures were determined based on the mix type, i.e. S9.5B mix. Samples were mixed; short term aged and compacted for determining the mixture volumetrics. Initially samples were compacted using a total asphalt binder content of 6% so as to maintain consistency with the virgin mix design. Only when the volumetrics were not met, changes were made in the total asphalt binder content. Table 6-13 below shows the optimum asphalt content for the different mixtures shown in Table 6-12.

Table 6-13. Optimum Asphalt Content (OAC) for PRAS Mixes

Virgin Binder	PRAS	OAC
PG 58-28	25%	6.0%
PG 64-22	15%	6.0%

Thus it can be explained that when a binder replacement of 25% was achieved in a mix with a virgin PG 58-28 binder with the same design aggregate structure as the virgin mix, there was no reduction in the optimum asphalt content from 6%. Similarly, when a binder replacement of 15% was achieved in a mix with a virgin PG 64-22 binder with the same design aggregate structure as the virgin mix, there was no reduction in the optimum asphalt content from 6%.

Table 6-14 below shows the proportions of PRAS by weight of total mixtures. The conversion from weight of total binder replaced to weight of total mix for each mix type was done using the asphalt binder content of 18.6% for PRAS and their respective mixture OAC's.

Table 6-14. Proportions of PRAS by Weight of Total Mix

Virgin Binder	PRAS
PG 58-28	7.0%
PG 64-22	4.2%

Therefore, in order to achieve a 25.0% binder replacement in recycled mixtures with PG 58-28, the weight of PRAS should be 7.0% by weight of total mix and in order to achieve a 15.0% binder replacement in recycled mixtures with PG 64-22, the weight of PRAS should be 4.2% by weight of total mix.

7. ASPHALT MIXTURE PERFORMANCE TESTING

This chapter discusses the process and the results of testing each of the mixtures designed in Chapter 6 on an Asphalt Mixture Performance Tester (AMPT). The mixtures designed in Chapter 6 were tested on the AMPT for determining the mixture properties of dynamic modulus and phase angle. Each of the recycled mixtures along with the virgin HMA mixture was tested and the results used for comparisons amongst different mixtures. These results are later used to conduct pavement analysis and evaluate the performance of each of the mixtures.

The AMPT is a compact servo-hydraulic testing machine that is capable of subjecting a compacted asphalt mixture sample of standard dimensions to cyclic loading over a range of temperatures and frequencies. The device is used to evaluate asphalt mixture properties of dynamic modulus and phase angle that are in turn used to assess the potential performance of these mixtures in actual pavements. Tests are conducted at a range of temperatures and frequencies and the results are compiled and restructured to generate a dynamic modulus master curve. Dynamic Modulus master cuve is representative of material property and differs from mix to mix depending on their properties. The dynamic modulus master curve serves as an input for many mechanistic-empirical design procedures, the results or outputs of which are a direct indication of the performance of mixture in an actual layered pavement.

The specimens for testing on the AMPT were a result of a rigorous procedure that involved mixing of asphalt mixtures, conditioning for a standard duration, compacting the loose mixtures to a standard height, coring to a standard diameter and finally sawing the larger cored sample to a sample of reduced height. Asphalt mixtures were first mixed according to standard HMA mix design procedures with NCHRP modifications for recycled mixtures and then conditioned in accordance with AASHTO R30 “Mixture Conditioning of HMA” and finally compacted to a height of 178mm and a diameter of 150mm. These compacted specimens were allowed to cool overnight and were later cored to smaller diameter specimens of 100mm and finally equal cuts were made on both sides to bring to a height of 150mm. The reduced samples were allowed to air dry overnight and were again dried in the Coredry apparatus in a vacuum chamber before testing for the air voids which were targeted at 4%. This procedure was followed for each of the recycled mixes mentioned in Chapter 6 along with the virgin HMA mix and is required for preparing all AMPT specimens so as to ensure uniform air void distribution throughout the reduced sample.

For achieving target air voids of 4% in the reduced sample, 178mm height samples for each of the mix type were mixed and compacted with a range of target air voids in the 178mm height samples and depending on the obtained air voids in the final reduced sample, modifications were made in the target air voids for the 178mm height samples and this procedure was followed until 4% air voids in the final reduced samples were obtained. Guidelines from AASHTO PP60 “Standard Practice for Preparation of Cylindrical Performance Test Specimens Using the Superpave Gyratory Compactor (SGC)” were followed for preparation of all of the specimens.

7.1 Dynamic Modulus Testing of Virgin, RAP, MRAS and PRAS Mixtures

AMPT samples for virgin HMA mix and all the mix types mentioned in Chapter 6 with varying proportions of RAP, MRAS and PRAS were prepared with target air voids of 4%. Four samples for each of the mix type were prepared and the three best samples having air voids closest to 4% were used for testing on the AMPT. Samples were also checked for end parallelism and planarity so as to eliminate loading eccentricity. Dimensions of height and diameter for each of the samples were recorded. The test was conducted in accordance with AASHTO TP79 "Determining Dynamic Modulus of Hot Mix Asphalt (HMA)". Three LVDT's (Linear Variable Differential Transformer) were attached to each of the sample at locations 120^{o} apart for recoding the strains at the time of the test. The LVDT's were attached in a manner so as to provide a gauge length of 70mm. Each of the samples was tested at three different temperatures of 4^{o}C, 20^{o}C and 40^{o}C and three frequencies of 0.1 Hertz, 1 Hertz and 10 Hertz at each testing temperature. Table 7-1, Table 7-2, Table 7-3 and Table 7-4 below show the results of the dynamic modulus tests on the RAP, MRAS, PRAS and virgin HMA mixtures, respectively.

Table 7-1. Dynamic Modulus Test Results for RAP Mixtures

Mix Type	Dynamic Modulus (MPa)								
	4ºC			20ºC			40ºC		
	10Hz	1Hz	0.1Hz	10Hz	1Hz	0.1Hz	10Hz	1Hz	0.1Hz
PG 58-28 + 45%RAP	19067	14847	10821	9320	5815	3251	2763	1268	598
PG 58-28 + 20%RAP	17617	12951	8659	7341	4171	2161	1879	832	423
PG 58-28 + 8%RAP	13170	9012	5502	4714	2318	1048	1058	411	199
PG 64-22 + 20%RAP	18778	14610	10699	8830	5598	3232	2620	1152	539
PG 64-22 + 8%RAP	16074	12002	8226	6586	3644	1798	1607	645	276

Table 7-2. Dynamic Modulus Test Results for MRAS Mixtures

Mix Type	Dynamic Modulus (MPa)								
	4ºC			20ºC			40ºC		
	10Hz	1Hz	0.1Hz	10Hz	1Hz	0.1Hz	10Hz	1Hz	0.1Hz
PG 58-28 + 55%MRAS	15490	12353	9386	8043	5474	3528	2757	1495	833
PG 58-28 + 30%MRAS	14819	10922	7481	6267	3656	2004	1822	843	433
PG 64-22 + 40%MRAS	17335	13762	10443	8406	5754	3701	3463	1959	1123
PG 64-22 + 20%MRAS	16656	12634	8892	7279	4367	2346	1974	898	436

Table 7-3. Dynamic Modulus Test Results for PRAS Mixtures

Mix Type	Dynamic Modulus (MPa)								
	4ºC			20ºC			40ºC		
	10Hz	1Hz	0.1Hz	10Hz	1Hz	0.1Hz	10Hz	1Hz	0.1Hz
PG 58-28 + 25%PRAS	17538	13280	9472	8223	4884	2886	2325	1093	587
PG 64-22 + 15%PRAS	17931	14281	10808	8947	5714	3429	2797	1397	717

Table 7-4. Dynamic Modulus Test Results for Virgin HMA Mixture

Mix Type	Dynamic Modulus (MPa)								
	4°C			20°C			40°C		
	10Hz	1Hz	0.1Hz	10Hz	1Hz	0.1Hz	10Hz	1Hz	0.1Hz
PG 64-22 Virgin	17210	12990	9103	7349	4262	2219	1773	733	335

It can be noted that as the test temperature increased, the recorded dynamic modulus for a given mixture decreased at a given test frequency. Similarly the dynamic modulus for a given mixture decreased at a given test temperature as the frequency decreased. Also, the dynamic modulus increased for all temperatures and frequencies as the proportion of the recycled binder in the mix increased when the base virgin binder was kept constant. So for mixes with a base virgin binder of PG 58-28, as the proportion of the recycled binder increased the dynamic modulus also increased for all temperatures and frequencies. This is expected as the binder in the mix is stiffer when there is a larger proportion of recycled binder present. Mixtures with a base virgin binder of PG 64-22 showed higher values of dynamic modulus as compared to mixtures with base virgin binder of PG 58-28. Though rheological testing with DSR did not show significant difference in stiffness between PG 58-28 and PG 64-22 binders, dynamic modulus test results showed that mixtures containing PG 64-22 binder were much stiffer than those containing PG 58-28. This can be attributed to the factor that binder testing was conducted at higher temperatures and dynamic modulus testing was conducted at low and intermediate temperatures. The recycled mixtures with PRAS exhibited higher modulus values as compared to recycled mixtures with RAP and MRAS. These results are again expected as the binder in PRAS is much stiffer than the binders in RAP and MRAS.

7.2 Dynamic Modulus Master Curves

The dynamic modulus data from AMPT testing of the mixtures were used along with their mixture volumetrics to generate the master curves for dynamic modulus at a pre-defined reference temperature. The master curves were generated in accordance with AASHTO PP61 “Provisional Standard Practice for Developing Dynamic Modulus Master Curves for Hot Mix Asphalt (HMA) Using the Asphalt Mixture Performance Tester” based on time-temperature superposition principle. These master curves served as the input for the Mechanistic Empirical Design Software based on which a structured pavement was analyzed for the evolution of distresses. In Figure 7.1 below are the master curves for RAP mixtures with PG 58-28 binder and in Figure 7.2 are the master curves for RAP mixtures with PG 64-22 binder plotted along with virgin HMA mix with PG 64-22 binder at a reference temperature of 70^{o}F.

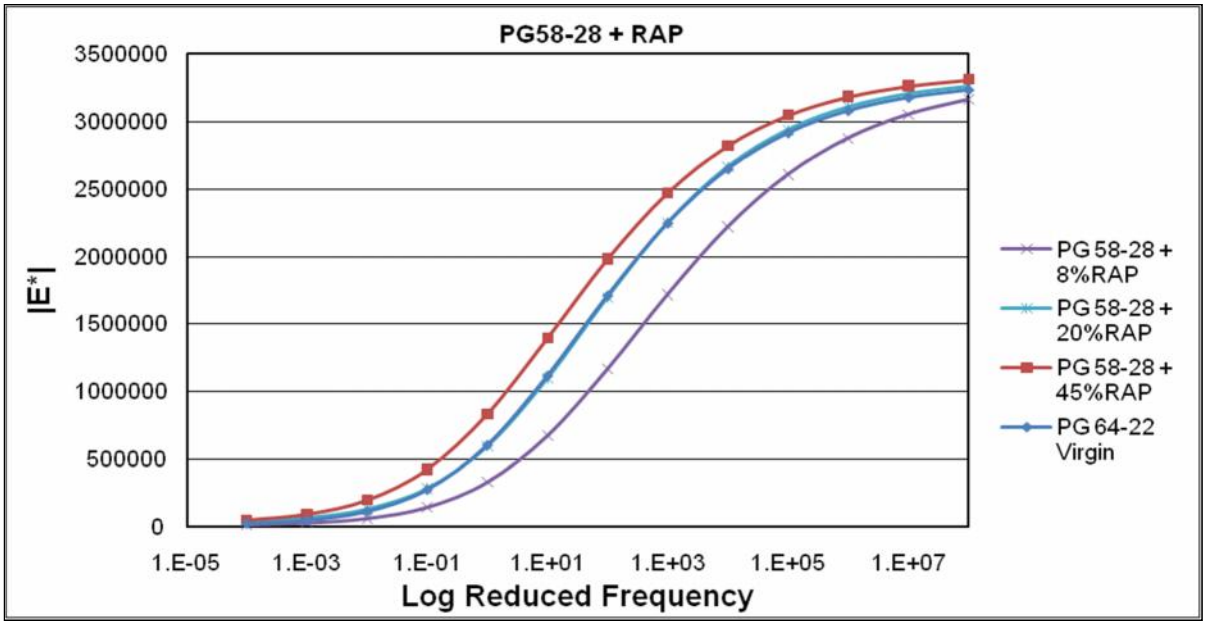

Figure 7.1. Dynamic Modulus Master Curves for PG 58-28 + RAP Mixtures & PG 64-22 Virgin Mixture at 70ºF

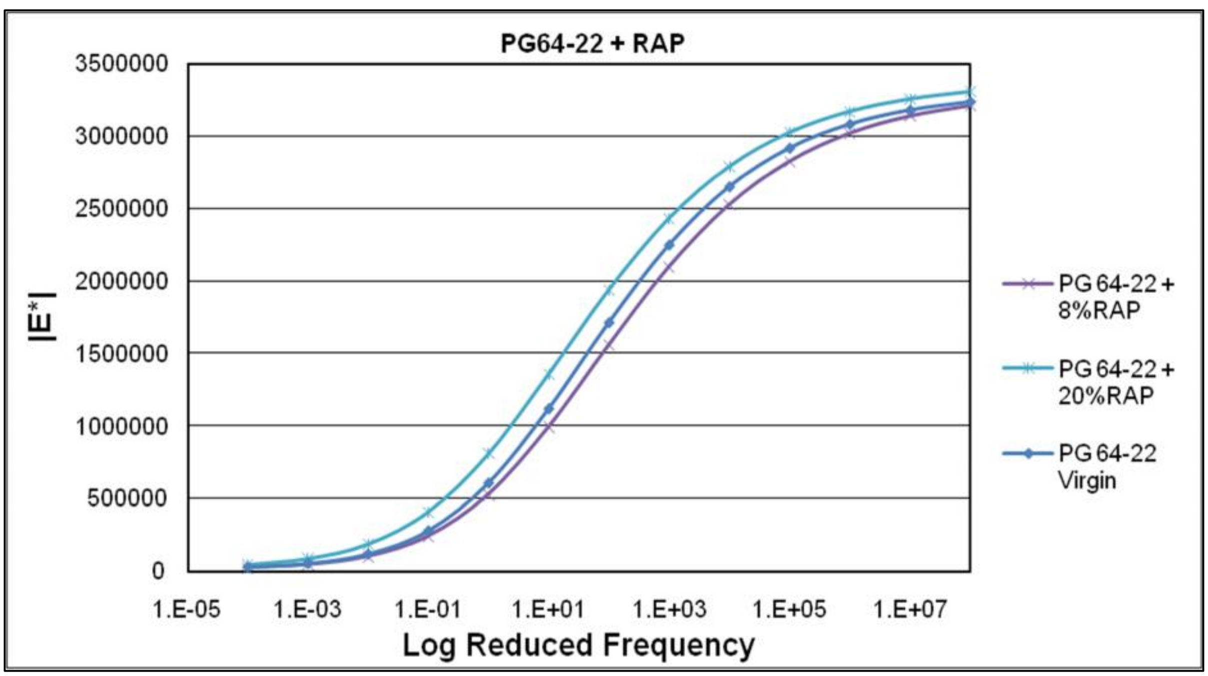

Figure 7.2. Dynamic Modulus Master Curves for PG 64-22 + RAP Mixtures & PG 64-22 Virgin Mixture at 70ºF

The curves were adjusted based on the results obtained from dynamic modulus testing and the mixture volumetrics to account for the differences in the VMA and VFA from mixture to mixture. It was observed that mixtures with a larger proportion of recycled binder were stiffer than mixtures with a smaller proportion for almost all frequencies at the reference temperature. The dynamic modulus values at highest and lowest frequencies were relatively same for different mixtures. The behavior of the mixture at very high frequencies is equivalent to the behavior of the mixture at very low temperatures which can be explained based on time-temperature superposition principle of visco-elastic asphalt concrete mixtures. Since at very low temperatures, the differences in the proportion of RAP binder in the total binder does not greatly affect the stiffness of the total asphalt binder, it can be understood that at very low temperatures, the relative difference between the stiffness of the binders in the two mixes is significantly reduced. Since the stiffness of the asphalt concrete mixtures is also the stiffness of the aggregate together with the asphalt binder, the modulus values for the mixtures at very low temperatures or otherwise at very high frequencies are relatively same so long as the gradation of the aggregates is kept constant. The same can be explained at very low frequencies which is also equivalent to studying mixtures at high temperatures. At very high temperatures the asphalt binder is relatively less viscous and does not necessarily contribute toward the mixture modulus to a great degree. Therefore, despite the differences in the composition of the asphalt binder in the mixtures, the dynamic modulus of the mixtures is not affected as long as the gradation of the aggregates is kept constant. It is however interesting to note that the presence of RAP binder with PG 58-28 binder in the mixture makes the mixture behavior completely different from a virgin HMA mixture of PG 64-22 binder at other frequencies.

Although the gradations were kept the same in the three mixtures, the mixtures responded to frequency variation in different ways. The PG 58-28 based RAP mixture with 45% RAP was the stiffest of all mixtures in the plot and the PG 58-28 based RAP mixture with 20% RAP was almost equivalent to the virgin HMA mixture with PG 64-22 binder at all frequencies, whereas, the PG 58-28 based RAP mixture with 8% RAP was softer than the virgin mixture for the entire range of frequencies. As the proportion of RAP binder in the PG 58-28 based HMA mixture increased to 20%, the modulus values were comparable to that of the virgin HMA mixture. It can therefore be concluded that as the proportion of RAP binder increased in the recycled HMA mixture with PG 58-28 virgin binder, the mixture modulus increased for all frequencies at a given temperature.

Similarly, in the case of recycled HMA mixtures with PG 64-22 as the virgin binder, for a given temperature and frequency, the mixture modulus increased with an increase in the proportion of RAP binder in the mixture. The HMA mixture with 20% RAP binder and PG 64-22 as the virgin binder showed the highest mixture modulus followed by the virgin HMA mixture and finally the mixture with 8% RAP binder. The dynamic modulus values for the HMA mixture with 8% RAP binder and PG 64-22 binder being lesser than that of the virgin HMA mixture with PG 64-22 binder stands as an ambiguity as it is expected that the introduction of RAP binder into the HMA mixture should lead to an increase in dynamic modulus when all other factors are kept the same.

Figure 7.3 below shows the master curves for MRAS mixtures with PG 58-28 along with the master curve for the virgin HMA mix with PG 64-22 binder at a reference temperature of 70°F.

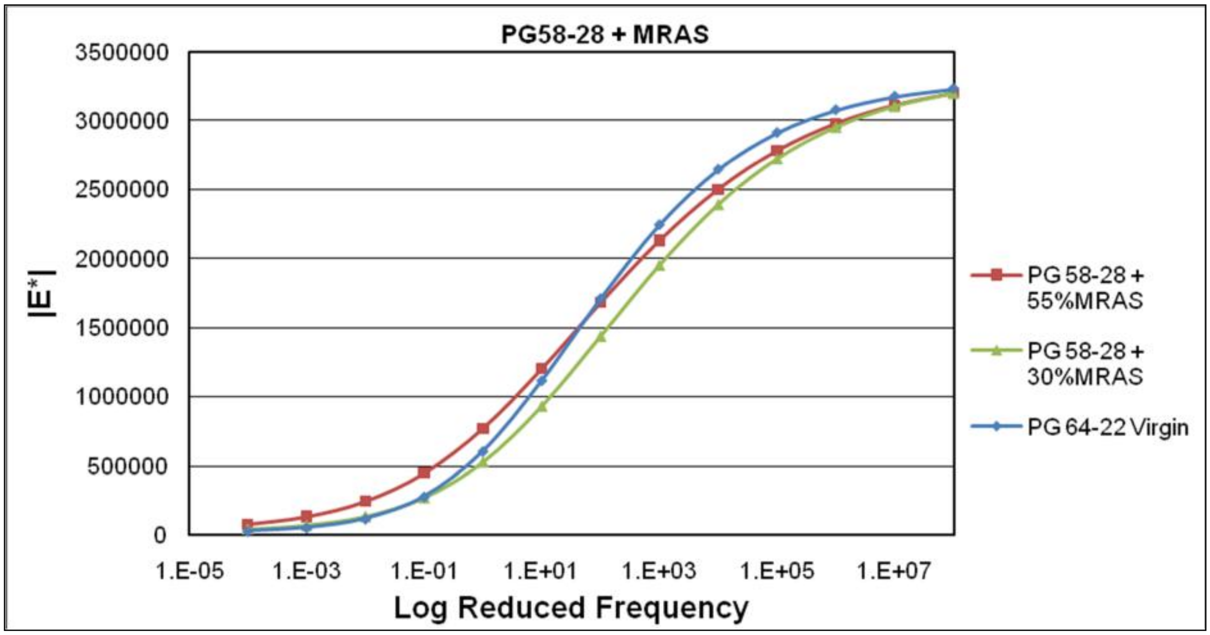

Figure 7.3. Dynamic Modulus Master Curves for PG 58-28 + MRAS Mixtures & PG 64-22 Virgin Mixture at 70°F

The curves were adjusted based on the obtained results from the dynamic modulus tests and the mixture volumetrics to account for the differences in the VMA and VFA from mixture to mixture. It was observed that the mixture with a larger proportion of recycled binder was stiffer than the mixture with a smaller proportion for almost all frequencies at the reference temperature. The dynamic modulus values at very high frequencies and very low frequencies were relatively same for the two mixtures. The behavior of the mixture at very high frequencies is equivalent to the behavior of the mixture at very low temperatures which can be explained based on time-temperature superposition principle of visco-elastic asphalt concrete mixtures.

Since at very low temperatures the differences in the proportion of MRAS binder in the total binder does not greatly affect the stiffness of the total asphalt binder, it can be understood that at very low temperatures the relative difference between the stiffness of the binders in the two mixes is significantly reduced. And since the stiffness of the asphalt concrete mixtures is also the stiffness of the aggregate together with the asphalt binder, the modulus values for the mixtures at very low temperatures or otherwise at very high frequencies are relatively the same so long as the gradation of the aggregates is kept constant. The same can be explained at very low frequencies which is also equivalent to studying mixtures at high temperatures. At very high temperatures the asphalt binder is relatively less viscous and does not necessarily contribute toward the mixture modulus to a great degree. Therefore, despite the differences in the composition of the asphalt binder in the mixtures, the dynamic modulus of the mixtures is not affected as long as the gradation of the aggregates is kept constant. It is however interesting to note that the presence of MRAS binder with PG 58-28 binder in the mixture makes the mixture behavior completely different from a virgin HMA mixture with PG 64-22 binder. Although the gradations were kept the same in the three mixtures, the mixtures responded to frequency variation in unique ways. The PG 58-28 based MRAS mixture with 55% MRAS was stiffer than the virgin mixture in the lower half of the frequency range and was softer than the virgin mixture in the upper half of the frequency range, whereas, the PG 58-28 based MRAS mixture with 30% MRAS was softer than the virgin mixture for the entire range of frequencies. It can therefore be concluded that as the proportion of MRAS binder increased in the recycled HMA mixture with PG 58-28 virgin binder, the mixture modulus increased to a relatively larger degree for lower frequencies than for higher frequencies. This can also be stated differently in the temperature domain that as the proportion of MRAS binder in the mixture increased, the mixture modulus increased to a larger degree for high temperatures as compared to the mixture modulus at low temperatures.

Figure 7.4 below shows the master curves for MRAS mixtures with PG 64-22 along with the master curve for the virgin HMA mix with PG 64-22 binder at a reference temperature of 70°F.

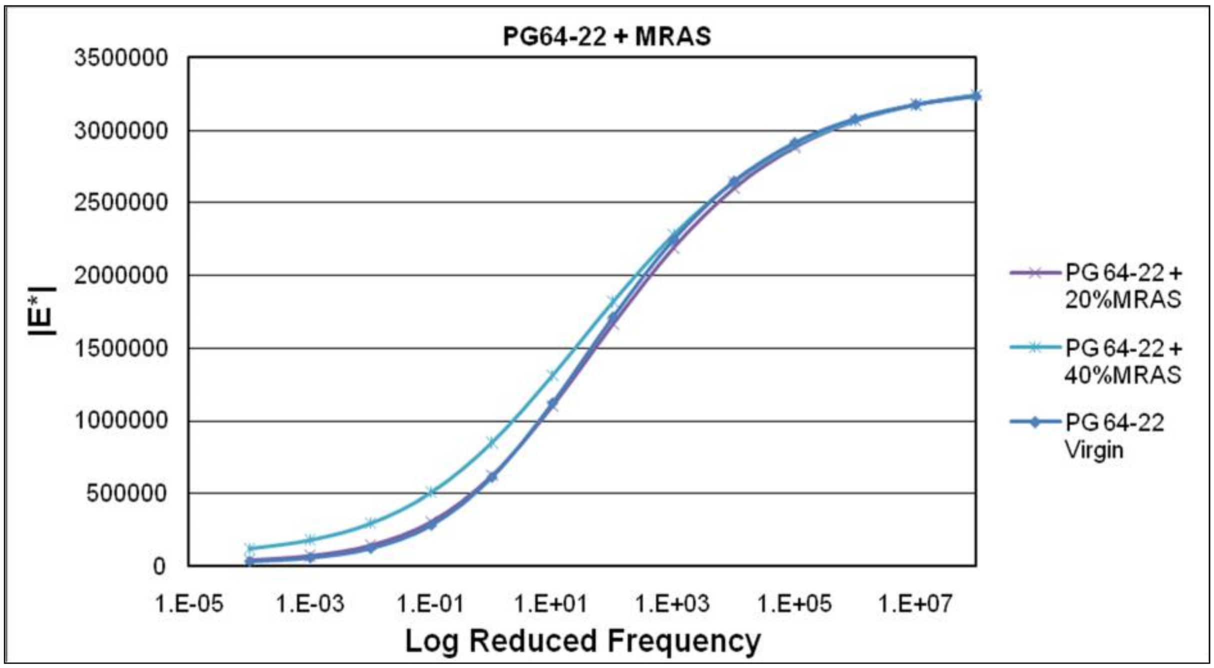

Figure 7.4. Dynamic Modulus Master Curves for PG 64-22 + MRAS Mixtures & PG 64-22 Virgin Mixture at 70°F

The curves were adjusted based on the obtained results from the dynamic modulus tests and the mixture volumetrics to account for the differences in the VMA and VFA from mixture to mixture. It was observed again that the mixture with a larger proportion of recycled binder was stiffer than the mixture with a smaller proportion for almost all frequencies at the reference temperature. The dynamic modulus values at very high frequencies and very low frequencies were relatively same for the two mixtures. The behavior of the mixture at very high frequencies was equivalent to the behavior of the mixture at very low temperatures which can be explained based on time-temperature superposition principle of visco-elastic asphalt concrete mixtures. Since at very low temperatures the differences in the proportion of MRAS binder in the total binder does not greatly affect the stiffness of the total asphalt binder, it can be understood that at very low temperatures, the relative difference between the stiffness of the binders in the two mixes is significantly reduced. And since the stiffness of the asphalt concrete mixtures is also the stiffness of the aggregate together with the asphalt binder, the modulus values for the mixtures at very low temperatures or otherwise at very high frequencies are relatively same so long as the gradation of the aggregates is kept constant. The same can be explained at very low frequencies which is also equivalent to studying mixtures at high temperatures. At very high temperatures the asphalt binder is relatively less viscous and does not necessarily contribute toward the mixture modulus to a great degree. Therefore, despite the differences in the composition of the asphalt binder in the mixtures, the dynamic modulus of the mixtures is not affected as long as the gradation of the aggregates is kept constant. It is however interesting to note that the presence of MRAS binder with PG 64-22 binder in the mixture does not have any significant effect up to a binder replacement of 20%. The PG 64-22 based MRAS mixture with 40% MRAS was stiffer than the virgin mixture in the entire frequency range whereas the PG 64-22 based MRAS mixture with 20% MRAS was almost identical to that of the virgin HMA mixture with PG 64-22 binder. It can also be concluded from the graph that as the proportion of MRAS binder increased in the recycled HMA mixture with PG 64-22 virgin binder, the mixture modulus increased to a relatively larger degree for lower frequencies than for higher frequencies. This can also be stated differently in the temperature domain that as the proportion of MRAS binder in the mixture increased, the mixture modulus increased to a larger degree for high temperatures as compared to the mixture modulus at low temperatures.

Dynamic modulus master curves were constructed for PRAS mixtures in a similar manner based on the results of the AMPT and the mixture volumetrics. Figure 7.5 Figure 7.5below shows the dynamic modulus master curves for the PRAS mixtures along with the master curve of virgin HMA mixture at a reference temperature of 70^{o}F.

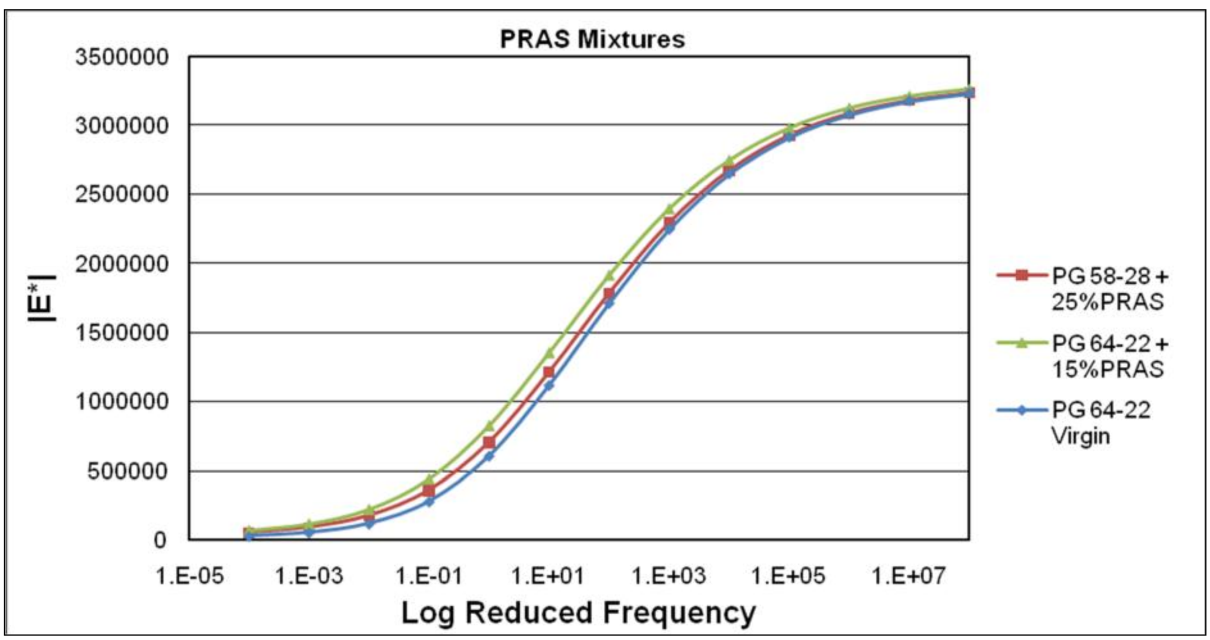

Figure 7.5. Dynamic Modulus Master Curves for PRAS Mixtures at 70^{o}F

It can be noted from the above figure that with an increase in the proportion of PRAS binder in the mixture, the dynamic modulus of the mixture increased over the entire range of frequencies. The mixture with 15% PRAS binder with a base PG 64-22 binder had the largest values of dynamic modulus over the entire range of frequencies, followed by the mixture with 25% PRAS binder with a base PG 58-28 binder. Both the recycled mixtures had a larger dynamic modulus than that of virgin HMA mixture over the entire frequency range. It is interesting to note however, that mixtures behaved differently in the case of PRAS than mixtures with MRAS when the base virgin binder was PG 58-28. Based on the obtained results from the test mixtures it can be observed that blending of MRAS with PG 58-28 binder was significantly different from blending of PRAS with PG 58-28 binder in the presence of aggregates.

The values from the above dynamic modulus master curves are used in the next chapter for pavement analysis to determine the performance of the mixtures in a structured pavement. AASHTOware Pavement M-E Design software was used for the analysis and determining the life of a pavement which was later used for economic analysis.

8. MIXTURE PERFORMANCE ANALYSIS

The results from dynamic modulus testing of the mixtures were used as the input for the AASHTOware Pavement ME Design software. This chapter discusses the analysis of each of the RAP, MRAS and PRAS based recycled HMA mixtures using the software, the results of which are the number of years to failure considering all the major distresses of fatigue, rutting and thermal cracking. AASHTOware Pavement ME Design software builds upon the mechanistic-empirical pavement design guide and is an expansion and an improvement over the NCHRP 1-37A MEPDG software.

8.1 Input Parameters & Design Criteria

Dynamic modulus is a fundamental material property and is related to various distresses in the pavement structure. AASHTOware Pavement ME Design software is a model that relates this fundamental material property to the distresses in a layered pavement at a user defined reliability level, traffic loading and climatic pattern. Dynamic modulus values from the fitted master curves in Chapter 7, binder properties from Chapter 5, anticipated traffic loading corresponding to the design traffic level for NCDOT B-mixes, climatic loading, reliability level and pavement layer properties were used as the input for the pavement analysis. Analysis was conducted for a design life of 20 years for a two way four lane pavement. The section used for analysis is a 5 layer pavement consisting of an asphalt concrete surface layer at the top over an intermediate and base course layers of asphalt concrete over a layer of chemically stabilized sub-grade and finally a sub-grade of compacted earth. Figure 8.1 below is a section of the pavement that has been used for the analysis. The top layer is an asphalt concrete surface layer with a Nominal Maximum Aggregate Size (NMAS) of 9.5mm. The intermediate and base course layers are standard NCDOT designated asphalt concrete layers with a NMAS of 19mm (I19.0B) and 25mm (B25.0B), respectively. Dynamic modulus values from the fitted master curves in Chapter 7 and binder properties from Chapter 5 were used as the input parameters for the surface layer. Level 3 input parameters were used for both the intermediate and base course layers and aggregate gradations for both the layers were assumed based on NCDOT's aggregate gradation control point criteria (Tables A1, A2 & A3 of Appendix). The material properties for sub-grade are assumed values typical in pavement analysis. Climatic data pertaining to a region in North Carolina was used for the analysis with an operational traffic speed of 45 miles per hour and an AADTT of 900 in both directions (distribution of traffic in Table A4 of appendix). A reliability of 90% was targeted for fatigue (alligator cracking), rutting (permanent deformation), thermal cracking and longitudinal cracking (top down cracking) for all the analysis.

S9.5B, 3", (E from Dynamic Modulus Master Curves), μ = 0.35

I19.0B, 2.5", Level 3 Input Parameters (Appendix), μ = 0.35

B25.0B, 4", Level 3 Input Parameters (Appendix), μ = 0.35

Chemically Stabilized Sub-grade, 8", Er = 2000000 psi, μ = 0.2

Sub-grade, Semi-infinite, Er = 10000 psi, μ = 0.35

Figure 8.1. Pavement Cross Section for Analysis

A 25% cracked area on the surface was defined as the failure criteria for fatigue and a 0.75 inches permanent deformation in the entire pavement thickness was defined as the failure criteria for rutting. Cracking up to 1000ft/mile was considered as the failure criteria for thermal cracking and up to 2000ft/mile was considered as the failure criteria for top down longitudinal cracking.

8.2 Pavement Analysis Results

The performance of each of the pavements with the recycled mixtures and the virgin HMA mixture as the surface layer was analyzed using the aforementioned input parameters and pavement structure. None of the pavements showed failure of any kind at a 90% reliability level. Reliability levels of 98% and more were achieved for all distresses and for all mixtures. Table 8-1 summarizes the results of the pavement analysis for various mixtures.

Table 8-1. Pavement Analysis Results for Various Mixtures

Mix Type	Failure Mode	Reliability Achieved
PG 58-28 + 8%RAP	None	>98%
PG 58-28 + 20%RAP	None	>98%
PG 58-28 + 45%RAP	None	>98%
PG 64-22 + 8%RAP	None	>98%
PG 64-22 + 20%RAP	None	>98%
PG 58-28 + 30%MRAS	None	>98%
PG 58-28 + 55%MRAS	None	>98%
PG 64-22 + 20%MRAS	None	>98%
PG 64-22 + 40%MRAS	None	>98%
PG 58-28 + 25%PRAS	None	>98%
PG 64-22 + 15%PRAS	None	>98%
PG 64-22 Virgin HMA	None	>98%

Since, none of the pavements showed any failure, it eliminates the need for a life cycle cost analysis and it can be stated that all the mixtures performed well under the given criteria of climate, traffic, failure, and reliability and material properties.

8.3 Discussion

The prediction of pavement distresses using the AASHTOware Pavement ME Design software depends on the pavement layer structure, traffic, climatic and material property parameters. The ability to predict failure for an assumed pavement section is contingent upon the layer structure being weaker than the applied traffic loading. Traffic level used in this study corresponds to that expected on a pavement where an NCDOT S9.5B mix is used, i.e. less than 3 Million ESALs.

The surface mixes containing recycled materials had higher modulus values, which also led to the pavement showing distress levels much lower than the failure criterion. The models used in the prediction of fatigue and top-down cracking and rutting predict higher number of load repetitions to failure for stiffer mixes. Also, the transfer functions are not explicitly calibrated to account for the effect of RAP in asphalt mixtures. The LTPP study conducted by NCAT "Reclaimed Asphalt Pavement in Asphalt Mixtures: State of the Practice" (10) showed that there is no statistically significant difference between field performance of virgin mixtures and mixtures containing up to 30% RAP. Therefore, the predicted performance obtained from the Mechanistic-Empirical (M-E) analysis in this study directly reflect the increase in mix stiffness due to addition of recycled materials and is not dependent on other design variables.

9. ECONOMIC ANALYSIS

This chapter deals with the economics of constructing a 5 layer pavement with the aforementioned structure and properties (Chapter 8) with the various recycled HMA mixtures and virgin HMA mixture designed in Chapter 6. Since none of the pavements showed failure of any kind during a design life of 20 years as discussed in Chapter 8, the difference in costs for pavements constructed with the recycled and virgin HMA mixtures can be accounted towards a difference in only the initial material costs. It should however be noted that the economic analysis in this chapter is highly conservative and is just a basic estimate for understanding the differences in costs for using recycled HMA mixtures over virgin HMA mixtures as this analysis does not consider the costs involved in disposing the waste materials in landfills that have long term environmental impacts.

9.1 Material Costs

The material costs for pavement construction are shown in Table 9-1 below. The cost of asphalt concrete surface course mixture (S9.5B) and the cost for screening and processing waste materials are used to calculate the costs for all the other recycled HMA mixtures.

Table 9-1. Material Costs for Pavement Construction

Description	Cost ($/Ton)
Asphalt Concrete Surface Coarse Mixture (S9.5B)	40.00
Screening and Processing of Waste (RAP and RAS)	14.00

The above costs are assumed values for estimating the cost savings associated with incorporating recycled waste materials in HMA mixtures. The cost of each of the recycled mixtures was calculated based on the above two costs by assuming that recycled mixtures will have a deduction in cost equivalent to the amount of recycled materials in the mixture, but will incur an additional cost for screening and processing. Table 9-2 below shows the cost of various mixtures incorporating either RAP or RAS. Columns 2 and 3 show the amount of recycled materials by weight of total binder and by weight of total mix. Percentage by weight of total mix values were used for estimating the cost reduction due to waste materials in the mixture. The material cost reduction achieved in these mixtures was in the range of 3% to 32%.

Table 9-2. Material Costs for Recycled Mixtures

Mix Type	**% Waste by Binder**	**% Waste by Total Weight**	**Cost ($/Ton)**	**% Savings**
PG 58-28 + 8%RAP	8%	10.0%	37.40	7%
PG 58-28 + 20%RAP	20%	22.1%	34.25	14%
PG 58-28 + 45%RAP	45%	48.8%	27.31	32%
PG 64-22 + 8%RAP	8%	10.0%	37.40	7%
PG 64-22 + 20%RAP	20%	22.5%	34.15	15%
PG 58-28 + 30%MRAS	30%	10.8%	37.21	7%
PG 58-28 + 55%MRAS	55%	19.4%	34.97	13%
PG 64-22 + 20%MRAS	20%	7.5%	38.06	5%
PG 64-22 + 40%MRAS	40%	14.9%	36.14	10%
PG 58-28 + 25%PRAS	25%	7.0%	38.19	5%
PG 64-22 + 15%PRAS	15%	4.2%	38.91	3%

9.2 Conclusions

It can thus be concluded from the economic analysis that the use of recyclable waste materials in HMA mixtures could be associated with savings up to 32%. A mixture with a 20% binder from RAP and a base virgin binder of PG 58-28 led to savings up to 14% whereas a mixture with 45% binder from RAP and a base virgin binder of PG 58-28 led to savings up to 32%. Similarly, a mixture with an 8% binder from RAP and a base virgin binder of PG 64-22 led to savings up to 7% whereas a mixture with 20% binder from RAP and a base virgin binder of PG 64-22 led to savings of 15%. A mixture with a 55% binder from MRAS and a base virgin binder of PG 58-28 led to savings up to 13% whereas a mixture with 30% binder from MRAS and a base virgin binder of PG 58-28 led to only savings of 7%. Similarly, a mixture with a 40% binder from MRAS and a base virgin binder of PG 64-22 led to savings up to 10% whereas a mixture with 20% binder from MRAS and a base virgin binder of PG 64-22 led to only savings of 5%. In mixtures with PRAS as the waste material and a base virgin binder of PG 64-22, the savings were 3% and with a base virgin binder of PG 58-28, the savings were 5%. It can therefore be concluded that incorporating waste materials such as RAP and RAS up to specific levels of recycled binder replacement into a surface HMA mixture for constructing a pavement with aforementioned cross section and material properties can lead to considerable savings in the form of material cost reduction and also relaxing the need to dispose such waste into landfills causing extensive environmental damage. It is however essential to note that such reduction in costs for constructing an asphalt concrete pavement can be achieved only by an appropriate choice of pavement structure with adequate thicknesses and properties for every layer.

10. SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

10.1 Summary

The objective of this study was to determine the allowable limits for the usage of recyclable waste materials (RAP & RAS) in HMA mixes by testing for rheological properties of blended binders both at high temperatures and intermediate temperatures. The obtained limits from rheological testing were then validated by conducting performance tests on S9.5B mixes having the same proportions of recyclable waste materials as the limits determined from rheological testing of blended binders. The results from the performance tests were used to analyze the performance of a 5 layer test pavement having a 3 inch thick surface asphalt concrete layer. Economic analysis was performed on the test pavement constructed from various recycled HMA mixtures for a comparison of costs. Results from economic analysis further encouraged recycled HMA mixtures designed based upon limits established by rheological testing of blended binders as they performed similar to virgin HMA mixtures. These limits would be recommended to the NCDOT for adopting them as guidelines and specifications for usage of recyclable waste materials in S9.5B HMA mixes.

10.2 Conclusions

- The allowable limits on the amount of recycled binder by weight of total binder based on rheological testing of blended binders depend on the virgin binder in the mix and the specifications of the target binder. The softer the virgin binder, the larger the proportion of recycled binder that it can accommodate. The softer the recycled binder, the higher are the allowable limits.

- For the recycled binders used in this study, maximum allowable recycled binder contents were determined for use with two virgin PG binders, PG 58-28 and PG 64-22. In order to meet the PG high temperature criteria with PG 58-28 as virgin binder, the blended binder can consist of up to 45% RAP, 55% MRAS or 25% PRAS binders. Similarly, when a PG 64-22 virgin binder is used, the blended binder can consist of a maximum of 20% RAP, 45% MRAS or 10% PRAS binders.
- The optimum asphalt content determined for virgin S9.5B HMA mixtures was 6%. The optimum asphalt contents for PG 58-28+45% RAP, PG 58-28+20% RAP and PG 58-28+8%RAP mixes were 5.4%, 5.5% and 6%, respectively. Similarly, the optimum asphalt contents for PG 64-22+20% RAP and PG 64-22+8% RAP mixes were 5.6% and 6%, respectively. In addition, the optimum asphalt contents for PG 58-28+55% MRAS and PG 58-28+30% MRAS mixes were 5.7% and 5.8%, respectively. Similarly, the optimum asphalt contents for PG 64-22+40% MRAS and PG 64-22+20% MRAS mixes were 6% and 6%, respectively. Finally, the optimum asphalt contents for PG 58-28+25% PRAS and PG 64-22+15% PRAS mixes were 6% and 6%, respectively.
- The VMA values of a mixture decreased on using a softer virgin binder in the mix. Therefore, VMA values for mixtures with PG 58-28 virgin binder were lesser than that of virgin HMA mixture with PG 64-22 binder. The VMA values were also affected by the proportion of recycled materials in the mix.

- The amount of recycled materials that can be incorporated into HMA depends on the design aggregate structure and the number of aggregate stockpiles that are blended to arrive at the design aggregate structure. The fact that MRAS and PRAS have a very large fraction of material finer than 75 micron makes it the limiting factor for the amount of RAS that can be incorporated in HMA mixtures. Also the availability of larger number of stockpiles for blending provides greater degree of freedom to be able to match the design aggregate structure when incorporating large proportions of RAP and RAS.
- The dynamic modulus of a mixture in general increased with an increase in the recycled binder in the HMA mixture for a given base virgin binder. The dynamic modulus values for PG 58-28+45% RAP mixtures were higher than PG 58-28+20% RAP mixtures followed by PG 58-28+8% RAP mixtures for all frequencies at the reference temperature. Similarly, the dynamic modulus values for PG 64-22+20% RAP mixtures were higher than that of PG 64-22+8% RAP mixtures for all frequencies at the reference temperature. Dynamic modulus values for PG 58-28+55% MRAS mixtures were higher than PG 58-28+30% MRAS mixtures for all frequencies at the reference temperature. Similarly, the dynamic modulus values for PG 64-22+40% MRAS mixtures were higher than PG 64-22+20% MRAS mixtures for all frequencies at the reference temperature. Also the dynamic modulus values for PG 64-22+15% PRAS mixtures were higher than that of PG 58-28+25% PRAS mixtures for all frequencies at the reference temperature. All mixtures with PG 64-22 binder with any proportion of recycled materials showed higher values of dynamic modulus than virgin mixture with

PG 64-22 binder at the reference temperature excepting that of PG 64-22 with 8% RAP binder. The dynamic modulus values for PG 64-22+8% RAP being lesser than that of the virgin HMA mixture with PG 64-22 is an anomalous observation considering that when all the other factors are kept the same and a softer binder is replaced by a stiffer binder in the mixture, the dynamic modulus of the mixture is expected to increase. The trend in dynamic modulus of mixtures with PG 58-28 as the virgin binder with MRAS as the recycled material was different compared to that of recycled mixtures with PG 64-22 as the virgin binder. Although, it was observed during rheological testing that with addition of a very little recycled binder, PG 58-28 met the specifications of PG 64-22 at both high and intermediate temperatures; the trend did not translate to the HMA mixtures in a similar pattern. At higher frequencies virgin HMA mixture with PG 64-22 binder showed higher dynamic modulus than all PG 58-28 + MRAS mixtures whereas at lower frequencies, mixtures with PG 58-28 virgin binder and 55% MRAS showed higher dynamic modulus values than virgin HMA mixtures with PG 64-22 binder. The increase in the dynamic modulus due to an increase in recycled binder in the mixture is felt to a larger degree at lower frequencies than at higher frequencies. In other words, the effects of recycled binder on dynamic modulus of a mixture are more evident at high temperatures than at low temperatures.

- When considering the economic analysis of a pavement, the cost savings associated with laying a 3 inch surface AC layer in a 5 layer pavement with recycled waste materials ranged from 3% to 32%. Savings due to use of PG 58-28+45% RAP, PG 58-28+20% RAP and PG 58-28+8% RAP recycled mixtures were 32%, 14% and 7%, respectively. Savings due to use of PG 64-22+20% RAP and PG 64-22+8% RAP recycled mixtures were 15% and 7%, respectively. Savings due to use of PG 58-28+55% MRAS and PG 64-22+40% MRAS recycled mixtures were 13% and 10%, respectively. Savings due to use of PG 58-28+30% MRAS and PG 64-22+20% MRAS recycled mixtures were 7% and 5%, respectively. Savings due to use of PG 58-28+25% PRAS and PG 64-22+15% PRAS recycled mixtures were 5% and 3%, respectively.

- The results from the economic analysis further supports the use of recycled materials in HMA pavements.
- Therefore, for S9.5B HMA mixtures designed with RAP as the waste material, the maximum allowable limit for the percentage weight of recycled binder by weight of total binder in the mix is 20% with a base virgin binder of PG 64-22. When the percent binder replaced is higher than 20% but less than 45% bump the virgin binder to a softer grade binder, PG 58-28.
- For S9.5B HMA mixtures designed with MRAS as the waste material, the maximum allowable limit for the percentage weight of recycled binder by weight of total binder in the mix is 40% with a base virgin binder of PG 64-22. When the percent binder replaced is higher than 40% but less than 55% bump the virgin binder to a softer grade binder, PG 58-28.
- For S9.5B HMA mixtures designed with PRAS as the waste material, the maximum allowable limit for the percentage weight of recycled binder by weight of total binder in the mix is 10% with a base virgin binder of PG 64-22. When the percent binder

replaced is higher than 10% but less than 25% bump the virgin binder to a softer grade binder, PG 58-28.

10.3 Recommendations

Although a majority of the recycled pavements have resulted in cost savings, the analysis is highly dependent on the pavement structure and the properties of the other layers in the pavement. Therefore, it is recommended that a project-specific analysis be performed to estimate cost savings for the project. In addition, since the savings in costs are also dependent on prices of raw materials and other associated costs, it would be greatly beneficial to formulate a relationship between the percentage limits and the final costs. Additionally, since a large proportion of mineral filler is contributed by both MRAS and PRAS toward recycled HMA mixtures and mineral filler is a very important factor that determines the mixture properties, research should be conducted to study the effects of variability within waste materials and variability due to source on the allowable limits. Also, the effect of mixing and compaction temperatures on mixture volumetrics and properties of recycled mixtures should be studied in significant detail for mixtures with varying proportions of waste materials. This study focused on the performance of the blended binders at high and intermediate temperatures only and the allowable limits for recycled materials did not consider the rheological properties of the blended binder at low temperatures. Therefore, it is recommended that appropriate testing of blended binders at low temperatures be done in order to warrant the determined allowable limits from any possible failure due to thermal cracking. Finally, this study assumed 100% blending between the recycled binder and virgin binder in a recycled mix which might not be true in all cases as blending depends on a variety of factors. Therefore, it is recommended that future studies should also focus on the effect of blending on the mixture volumetrics and mixture properties.

IMPLEMENTATION AND TECHNOLOGY TRANSFER PLAN

The products of this research are the recycled asphalt binder limits contributed by waste materials for S9.5B mixtures in North Carolina. These limits are based on the percentage by weight of recycled asphalt binder to the total weight of asphalt binder in the mix.

The materials and testing division of NCDOT can use these products for specifying a set of limits for efficiently incorporating recycled materials in HMA.

For the implementation of these products, there is no additional training needed.

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APPENDIX

Table A1

TABLE 610-2 SUPERPAVE AGGREGATE GRADATION CRITERIA (Percent Passing Control Points)								
Standard Sieves (mm)	**Mix Type (Nominal Max. Aggregate Size)**							
	9.5 mm[A]		**12.5 mm[A]**		**19.0 mm**		**25.0 mm**	
	Min	*Max*	*Min*	*Max*	*Min*	*Max*	*Min*	*Max*
50.0	-	-	-	-	-	-	-	-
37.5	-	-	-	-	-	-	100	-
25.0	-	-	-	-	100	-	90.0	100
19.0	-	-	100	-	90.0	100	-	90.0
12.5	100	-	90.0	100	-	90.0	-	-
9.50	90.0	100	-	90.0	-	-	-	-
4.75	-	90.0	-	-	-	-	-	-
2.36	32.0[B]	67.0[B]	28.0	58.0	23.0	49.0	19.0	45.0
1.18	-	-	-	-	-	-	-	-
0.075	4.0	8.0	4.0	8.0	3.0	8.0	3.0	7.0

Table A2 - Level 3 Material Properties for I19.0B Asphalt Concrete Mix

Gradation	Percent Passing
3/4-inch Sieve	94
3/8-inch Sieve	75
No.4 Sieve	50
No.200 Sieve	5

Table A3 - Level 3 Material Properties for B25.0B Asphalt Concrete Mix

Gradation	Percent Passing
3/4-inch Sieve	85
3/8-inch Sieve	63
No.4 Sieve	43
No.200 Sieve	4.5

Table A4 - Distribution of Vehicles by Class

Vehicle Class	AADTT Distribution (%)	Growth Rate (%)
Class 4	3.3%	3%
Class 5	34%	3%
Class 6	11.7%	3%
Class 7	1.6%	3%
Class 8	9.9%	3%
Class 9	36.2%	3%
Class 10	1%	3%
Class 11	1.8%	3%
Class 12	0.2%	3%
Class 13	0.3%	3%

Table A5 - Number of Axles per Truck

Vehicle Class	Single Axle	Tandem Axle	Tridem Axle	Quad Axle
Class 4	1.62	0.39	0	0
Class 5	2	0	0	0
Class 6	1.02	0.99	0	0
Class 7	1	0.26	0.83	0
Class 8	2.38	0.67	0	0
Class 9	1.13	1.93	0	0
Class 10	1.19	1.09	0.89	0
Class 11	4.29	0.26	0.06	0
Class 12	3.52	1.14	0.06	0
Class 13	2.15	2.13	0.35	0