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High Reclaimed Asphalt Pavement in hot mix asphalt

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HIGH RECLAIMED ASPHALT PAVEMENT IN HOT MIX ASPHALT

by
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Dedication

I would like to dedicate this manuscript to my mother, Denise L. Norton, my father, Alan J. Norton, and my brother Robert J. Norton. I would also like to dedicate this manuscript to my teacher Dr. Yusuf A. Mehta.

Acknowledgments

I would like to thank God for giving me the strength and wisdom to be able to complete the task of finishing this report. I would like to thank the NJDOT for giving me the opportunity to work on this research project. I would like to thank Dr. Mehta and Aaron Nolan for their support and guidance through the entire research process. I would also like to thank my friends and family in supporting me through my time of research. I would finally like to thank all the people who helped to carry out this research and write this report. The following people placed a lot of effort into preparing specimens, gathering data, and writing: Dr. Mehta, Aaron Nolan, Chris Tomlinson, Darren Reger, Luis Gaitan, Khyati Sonpal, Prashant Shirodkar, Eric Dubois, Dan Kerr, Tom Burns, Ryan Weaver, and Patrick Sullivan. Without their dedication to the project, this research would not have been successful.

Abstract

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When old roads have to be replaced, the existing pavement, known as Reclaimed Asphalt Pavement (RAP) is ripped up, milled, and stockpiled and can be used in the creation of new mixes in order to save money and resources. New Jersey state specifications limit the percentage of RAP that can be used to 15% for surface courses and 25% for the intermediate and base courses; however, other states have implemented much higher RAP percentages. The limitations are placed because the interaction between the virgin and residual RAP binder is unknown, with respect to the amount of residual binder that is active in the mix and the effect that this blended binder will have on performance since aged binder has a tendency to be stiffer. In this report, the methods and findings are explained for low temperature laboratory performance of asphalt mixes with 25% and 35% RAP as well as a control mix and RAP samples from Delaware. In addition to this, a coating study, blending study, variability study, and cost analysis were performed and the use of blending charts was investigated. The Superpave Mix Design Excel Spreadsheet was also modified to account for degree of blending. The final section of the report provides recommendations for the use of RAP in New Jersey.

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Chapter 1

Introduction and Objectives

1.1 Introduction

In the early 1970s, when the oil embargo occurred, states and paving contractors began using alternate methods of cost reduction in asphalt concrete. Recycling during construction and rehabilitation is one of the several economic alternatives available for asphalt pavement. The Asphalt Recycling and Reclamation Association define four different types of recycling methods: Hot recycling, hot in-place recycling, cold in-place recycling and full depth reclamation. As per FHWA, one third of all Hot Mix Asphalt (HMA) removed is recycled into new HMA production.

In hot recycling, old pavement which requires rehabilitation is removed by milling, ripping, or by a crushing operation. This removed pavement material, also known as Reclaimed Asphalt Pavement (RAP), is combined with virgin aggregates and binder in order to produce HMA mixtures. Rejuvenating agents are sometimes added to this mixture in order to make the mixtures less stiff which is known as "softening" the mix. This method of recycling results in less expensive and more environmentally friendly asphalt pavements. The parking lot of Durham Bulls Baseball Stadium in North Carolina is an example of RAP's role in cost avoidance. A total of 66000 cubic yards of virgin aggregate was saved in this project by utilizing 25 percent of RAP in the mix design.

New Jersey generates significantly more Reclaimed Asphalt Pavement (RAP) than it uses. Asphalt plants in New Jersey have stockpiles of RAP that are significantly larger than any other aggregate stockpile located at their facility as well. New Jersey state specifications allow a maximum of 25 percent of RAP in HMA base and intermediate layers and 15 percent for surface layers. This use of RAP is less than the amount generated which leaves behind a large quantity of unused RAP. Larger quantities of RAP must be used in pavements in order to stop, or at least slow, the increase in size of these RAP stockpiles. High percentages of RAP are already being used in other states showing that this is a feasible solution to New Jersey's RAP stockpiling problem; however, there are potential drawbacks to the use of high percentages of RAP. RAP variability within stockpiles, the interaction between the RAP and virgin materials during mixing, as well as the affect of RAP on HMA performance must all be examined before New Jersey can use high percentages of RAP on their roadways.

1.2 Objectives

The following general objectives were used for the studies within this report:

- Develop a thorough understanding of the properties of the mixture and binder with higher percentages of RAP.
- Explore the possibility of designing base, intermediate, and surface asphalt mixtures with high percentages of RAP approaching 35 percent without compromising performance.

The following specific objectives were used to accomplish the objectives previously stated:

- Determine from the existing literature and state of practice the challenges in characterizing binders with RAP, including blending charts, the extraction and recovery process, and testing methodology proposed in AASHTO.

- Conduct an assessment of the variability of RAP stockpiles in the state of New Jersey and develop a systematic way of rating the plants based on their quality control.
- Conduct sensitivity analysis of blended binder properties with the change in percentages of RAP, and virgin binder properties.
- Conduct extensive laboratory testing to quantify and verify the process of extraction and recovery, mixing and characterization for the binders, and the RAP available in the state of New Jersey.
- Conduct laboratory testing of mixtures to determine the Degree of Blending (DOB) and evaluate the impact of various percentages of the RAP on unmodified and modified binders.
- Evaluate the impact of poor quality control procedures on laboratory mixture performance and conduct a life cycle cost analysis of HMA with high percentages of RAP.
- Develop specific recommendations to characterize modified and unmodified binder, and design mixtures with high percentages of RAP.

Chapter 2

Literature Review

2.1 RAP Variability and Stockpiling Practices

RAP material is obtained by milling the original pavement which sometimes contains patches, chip seal, and other maintenance treatments. The stockpiled RAP material may be from the base, the intermediate, or the surface courses and may also consist of several projects containing different types of RAP. RAP from private projects, which is not built to the same original standards as public projects, may also be included in stockpiles. This variability within RAP stockpiles leads to major concerns in the performance of pavements when using higher percentages of RAP. This variation in stockpiles can be determined through a variety of asphalt property tests such as moisture and asphalt content, maximum specific gravity, and viscosity. The gradation of RAP stockpiles is also used to quantify their variability.

To ensure that all the properties of RAP samples taken from asphalt plants have low variability, standards must be set for stockpiling in the state of New Jersey. In order to do this, all stockpiling methods must be analyzed to determine which methods minimize variability. The US Department of Transportation [7] also has set stockpiling procedures in an effort to minimize variability within aggregate stockpiles. Some of the suggestions proposed by Zhou et al [8] to improve the stockpiling management are as follows:

- Eliminate contamination of RAP stockpiles.
- Keep RAP stockpiles separate as possible.
- Blend thoroughly before processing or fractionating the multiple-source RAP stockpiles.

- Avoid over-processing. (avoid generating too much fines passing # 200 sieve size)
- Use good practice when storing the processed RAP. (such as using the paved, sloped storage area)
- Characterize and number the processed RAP stockpiles.

A survey conducted by West in 2008 [9] gathered information on RAP management practices. Half of the responders indicated that they combined all RAP sources into a single pile for processing, whereas the other half maintained separate stockpiles for different sources of RAP. Reasons for keeping separate stockpiles included the following: Agency specifications allowed only DOT RAP in mixes for DOT projects; millings were to be kept separate from other multiple source RAP material, and to improve the consistency within the RAP stockpiles.

With regard to crushing and processing RAP materials, the pie chart in **figure 2-1** shows how the respondents crush their RAP aggregates. The chart shows that the vast majority of the operations crush all of their RAP stockpiles to a single size. Only a small percentage of operations are currently fractionating RAP into different sizes. The survey also indicated that a small percentage of respondents do not process RAP stockpiles further before using the material in a new mix.

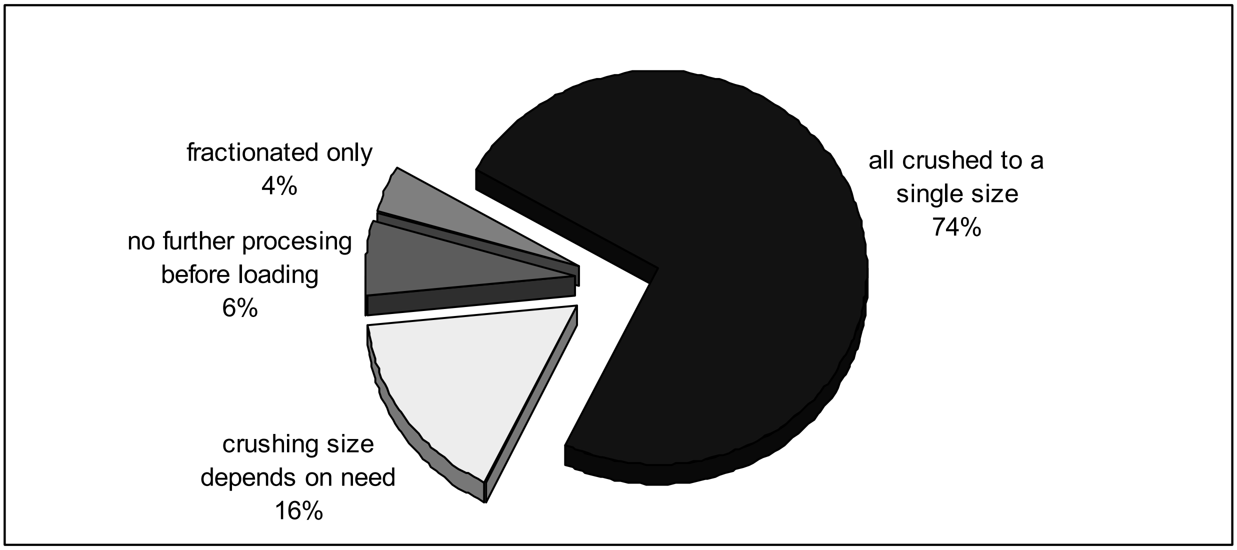

Figure 2-1. Summary of How RAP is Crushed

Table 2-1 shows the screen size (i.e. maximum particle size) to which responders indicated they crush their RAP stockpiles.

Table 2-1. Screen Sizes Used in RAP Crushing

Screen Size	Percent of Responses
< 1/2 inch	6 percent
1/2 inch	52 percent
5/8 inch	16 percent
3/4 inch	11 percent
1 inch	5 percent
> 1 inch	11 percent

Figure 2-2 shows a summary of the responses regarding RAP stockpiling practices. Most of the responders indicated that they treat RAP stockpiles in the same way as other aggregate materials. This indicates that, in general, some improvements in RAP stockpiling can be made. Each of the bottom three practices in **figure 2-2** can benefit the plant operation by reducing RAP moisture contents. This would allow for higher

production rates, lower superheating temperatures for virgin aggregates, better transfer of heat from virgin materials to the RAP, and less fuel usage per ton of mix.

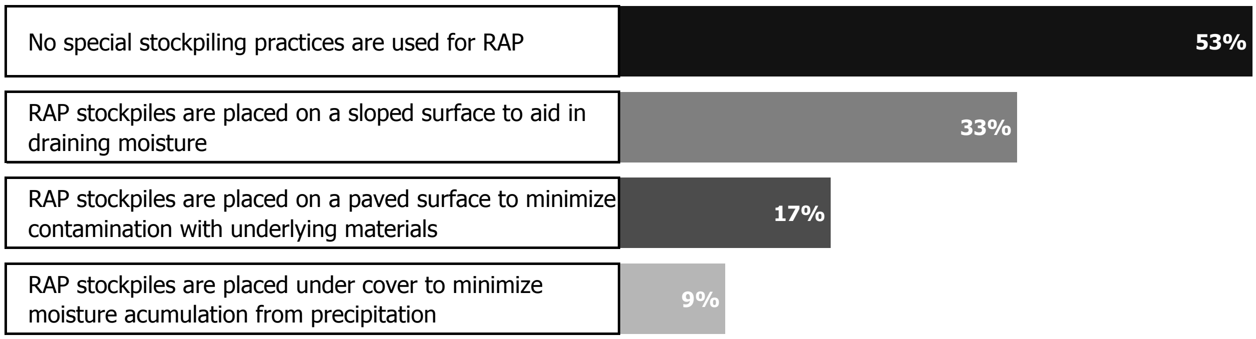

Figure 2-2. Summary of RAP Stockpiling Practices

In recent years, state agencies have been increasingly emphasizing that plants be categorized depending upon RAP stockpile variability. Depending upon this grading of the plants, the maximum allowable percentage of RAP for the plant can be determined. This allowable percentage of RAP depends upon the standard deviation of the RAP aggregate gradation and RAP binder content. RAP aggregate gradation and binder content can be determined either by the ignition oven method, solvent extraction method or the Abson Method. The two most commonly used solvent extraction and recovery methods were used for this study. These two methods used the following specifications for extraction and recovery: Extractions using either AASHTO T319 (modified SHRP procedure) or AASHTO T164 and recovery by the procedure outlined in either AASHTO T319 or ASTM D5404. Different procedures have different configurations which affect the time required to recover the solvent and the recovered binder properties. The extraction and recovery process is further discussed in Section 2.5 below.

For the ignition oven, the asphalt content is calculated by the weight loss in the furnace at high temperatures. A concern associated with this method is that this weight loss may also include a small portion of aggregate mass. This would cause the asphalt content obtained using Ignition to be higher than if solvent extraction method was used. This difference is also known as the correction factor. The Ignition Oven correction factor for virgin aggregates is determined by burning the asphalt of a HMA mix with known binder content. This correction factor is difficult to accurately measure since the percentage of asphalt content in the RAP is not known. Since plants regularly use IO as a standard method of determining asphalt content, an incorrect IO correction factor may have significant impact in the volumetric properties of asphalt concrete. Therefore, there is a need to determine a methodology of calculating accurate IO for RAP stockpiles.

2.2 Interaction of RAP binder with Virgin Binder

Determining how RAP will interact with virgin materials within an HMA mixture is important if high percentages RAP pavement are to perform well. Current recommendations for the use of RAP in asphalt mixtures follow those developed under National Cooperative Highway Research Program (NCHRP) Project 9-12, *Incorporation of Reclaimed Asphalt Pavement in the Superpave System*;

- No change in binder selection necessary for RAP percentages less than 15 percent;
- Select virgin binder grade one grade softer than normal for RAP percentages between 15 and 25 percent; and

- Follow recommendations from blending charts when RAP percentages are greater than 25 percent.

One of the issues with using blending charts to determine appropriate percentage of RAP in asphalt mixtures is that it assumes a condition in which RAP asphalt binder fully blends with the virgin asphalt binder. This type of blending is also known as 100 percent blending or full blending. This assumption could lead to problems with the design of RAP HMA since research has shown that this type of blending is most likely not what is occurring. Huang et al conducted a laboratory investigation attempting to measure the blending of RAP into virgin HMA mixtures during laboratory mixing. A screened RAP source was blended with virgin aggregate under; 1) pure mechanical blending with virgin aggregates only and 2) realistic blending incorporating virgin asphalt binder. A staged extraction process was then used to "peel" away layers of asphalt from the RAP particles for further analysis. Their work showed that the mechanical blending affected only a small portion of the RAP asphalt binder and that the aged asphalt binder of the RAP formed a stiff layer coating the RAP aggregate particles and did not necessarily blend with the virgin asphalt binder.

2.3 Performance at lower and intermediate temperatures

Researchers have shown that fatigue is the critical issue observed when a high percentage of RAP is used in the mixture. No significant trend was observed by all the researchers and the discrepancies amongst all the researchers are outlined below.

When tests were performed using the Superpave Shear Tester (Al-Qadi & L. [16]), and the indirect tensile strength (Kim, Byron, Sholar, & Kim [17]) it was observed that as the percentage of RAP increased from zero percent to 45 percent, the fatigue life decreased (Lee, Soupharath, Shukla, Franco, & Manning [18]). Testing conducted for the NCHRP 9-12 study also confirmed that when RAP content is greater than 20 percent, lower fatigue life is observed. Unfortunately, not all studies on RAP HMA performance have been found to have a consistent trend. Another study discovered that when tested with the indirect tensile strength test, semi-circular bending test, and the four-point beam fatigue test, an increase in RAP content from 0 percent to 30 percent showed an improvement on fatigue life. Al-Qadi [17] commented that the results for fatigue cracking are very unpredictable for higher percentage of RAP. The fatigue life measured using the constant strain testing method increased with the increase in RAP percentage; however, no consistent level of increase in the fatigue life is observed. The beam fatigue tests performed at different strain limits (low, high and intermediate strain levels) showed no significant difference between average test result values for high (30 percent RAP) and control (0 percent RAP) samples.

2.4 Moisture Susceptibility

Another issue to be considered with a RAP mixture is durability. Moisture susceptibility is generally the cause of poor mixture durability. It is caused by moisture intrusion which strips the binder from the aggregate structure of HMA. This action is also known as stripping, and often starts at the top of the pavement and progresses downward, resulting in raveling which is where the pavement particles dislodge. Raveling causes a reduction in skid resistance and can lead to hydroplaning. It is primarily a function of aggregate type, although it can be caused by other factors such as poor drainage or inadequate compaction. Moisture susceptibility can be evaluated in the laboratory by performing stability, resilient modulus, or tensile strength testing on unconditioned and moisture conditioned samples.

From the previous studies [21]-[22], it was observed that there was no significant difference detected between average test result values for high-RAP and control mixes when tested with fatigue tests, rut tests, and Tensile Strength Ratio (TSR) tests; therefore, the predicted performance is equal.

2.5 Extraction and Recovery Methods (Comparison)

When using high RAP in HMA, the allowable percentage of RAP and grade of virgin binder is dependent upon the characteristics and content of asphalt and the gradation and shape of the aggregate in RAP. These parameters are determined only after the binder and aggregates of RAP are separated. According to Zhang [23], solvent extraction and the ignition oven method assists in the determination of binder content and aggregate gradation, both of which are required to design HMA while using high RAP. The following two methods have been explained in detailed: Solvent Extraction Method and Extraction by Ignition Oven.

2.5.1 Solvent Extraction

It is necessary to use extraction and recovery procedures on RAP in order to determine quality control, performance, and design parameters for hot mix asphalt. Through extraction and recovery procedures with solvent solutions, the binder is removed from the aggregates and is retrieved along with the aggregates for the determination of its properties. There are many characteristics of interest for the reclaimed binder such as aging, stiffness, and temperature susceptibility. The aggregate gradation of the RAP is important because the RAP aggregates will be used along with virgin materials to produce an asphalt mixture.

2.5.1.1 Extraction Methods:

There are many methods for the extraction of asphalt binder as outlined in ASTM and AASHTO standards. The general extraction methods from ASTM D2172-05/ AASHTO T 164-08 are the centrifuge extraction (Method A), reflux extraction (Methods B, C, D), and vacuum extraction (Method E). Methods A and B, the centrifuge and reflux methods respectively, are the most popular among technicians and researchers because of the simplicity of these test methods. The centrifuge and reflux methods are cold and hot solvent processes, respectively. A cold solvent extraction method is preferred over the hot solvent reflux methods because of the aging effects that occur within asphalt binder samples from the high temperatures. The binder that is extracted is known to be an accurate representation of the binder's properties. The disadvantage with this method is that it leaves up to four percent of asphalt binder on the reclaimed aggregate which is much higher than that of reflux extraction method.

There is another relatively new method for the extraction of asphalt binder as outlined in AASHTO T 319-08. This method uses an extraction vessel that was developed by Strategic Highway Research Program (SHRP). The uniqueness of the method is that the vessel is cylindrical in shape and contains baffles inside so that while the vessel is rotated horizontally, the solution and reclaimed asphalt cement inside mix more efficiently. The vessel is then placed vertically and the solvent and asphalt solution are extracted using a vacuum. Inside the vessel, there is a filtering system which consists of a series of different size mesh screens and metal spacers. The combination of spacers creates void spaces for the fines to collect. The different size screens are used to remove unwanted particles from the solvent mixture. The binder and the solvent mixture that are extracted from the vessel are then transported into a flask where they will then be filtered through a 20-µm retention filter which catches the remaining amount of fines. The advantage of this new extraction method is that it allows for more complete extraction of the binder from the reclaimed aggregates, only leaving approximately one percent. The one disadvantage of this method is that the dissembling and cleaning of the vessel after each test sample is labor intensive. **Table 2-2** summarizes different extraction methods.

Table 2-2. Summary of Extraction Methods

Extraction	Method	Solvent	Advantage	Disadvantage
Centrifuge	A	Cold	Simple test	Leaves four percent binder
			Widely practiced	
			Can be used for binder properties	
Reflux	B C D	Hot	Widely practiced	Aging effects from high temp
				Causes hardening of binder
				Leave too much binder
				Should not be used for binder properties
Vacuum	E	Cold	No aging from high temp	Not much in known
SHRP	-	Cold	Leaves 1 percent binder	Labor intensive test
			No aging from high temp	Costly (vessel machining/owner supply)
			Can be used for binder properties	

2.5.1.2 Recovery Methods:

There are two methods used for recovering asphalt binder from extraction solvent. The first method is the Abson recovery method (ASTM D1856-95a (2003) and AASHTO T 170-00). As per previous research, this method leaves a considerable amount of residual solvent in the binder which creates a reduction in the binder's stiffness. This method also uses high temperatures which ages the binder. The second method employs a rotary evaporator (ASTM D5404-03 and AASHTO T319-08). This method has several advantages over the Abson method in that it uses lower temperatures, mixing with a uniform binder consistency, and a simple and less labor intensive procedure. In this method, most of the residual solvent gets removed with the rotary action. A benefit of using lower temperatures is that it results in less binder aging. A summary of recovery methods can be found in **table 2-3** below.

Table 2-3. Summary of Recovery Methods

<table>
<tr><th>Recovery</th><th>Advantage</th><th>Disadvantage</th></tr>
<tr><td rowspan="4">Abson</td><td rowspan="2">Widely practiced (1930s)</td><td>Leaves residual solvent (lowers stiffness)</td></tr>
<tr><td>Skewed binder properties</td></tr>
<tr><td rowspan="2">Less Costly Procedure</td><td>High energy (ages binder)</td></tr>
<tr><td>Labor Intensive</td></tr>
<tr><td rowspan="4">Rotary Evaporator</td><td>Widely practiced (1970s)</td><td rowspan="4">Aging effects from high temp</td></tr>
<tr><td>Less heat (less aging of binder)</td></tr>
<tr><td>Mixes for a uniform binder consistency</td></tr>
<tr><td>Less labor intensive</td></tr>
</table>

2.5.1.3 Solvents Used for Extraction and Recovery:

There are several solvents that can be used in the extraction and recovery process. Each solvent has different properties related to its ability to dissolve asphalt binder and the quality of the asphalt you get after the process is completed. These solvents also have several safety and health concerns that must be addressed for the well being of those performing the extraction and recovery process.

The most widely accepted solvent used is Trichloroethylene (TCE), but there are a lot of concerns with this solvent. TCE had been identified as a carcinogen that is known to cause other health concerns such as headaches, dizziness, and tremors. Exposure at high levels has even been known to cause death. The possible alternative to this is EnSolv which has as its primary component n-propyl bromide. This alternative is not currently designated as a carcinogen and has no recorded cases of death or respiratory ailments.

Tests were performed on both solvents to in order to compare their properties. The difference in mean solubility found between the two solvents varied by only 0.098 percent. With the exception of two of the asphalt samples tested, the difference between the solubility of the two solvents proved to be statistically insignificant. The tests were repeated for the samples that were excluded from the previously stated conclusion and it was found that the difference between the two solvents was 0.013 percent for one and 0.105 percent for the other. Due to the small values for all practical purposes there was very little difference between solvents. The results for the extraction and recovery process showed that EnSolv and recovered EnSolv from the standpoint of extraction would be a suitable replacement for TCE. The EnSolv and recovered EnSolv were also shown to require less time in completing the recovery process than TCE. Viscosities of all recovered binders from both solvents were similar.

2.5.2 Ignition Method

In the ignition method, the change in mass of asphalt concrete is obtained after burning the RAP sample in an oven at 538^{o}C until the asphalt is burned off. This change in mass is then used to give the RAP binder content. In this process, some aggregate mass also gets burned off which can cause an error in the prediction of asphalt content. Brown and Mager [33] carried out a round robin study at NCAT (National Center for Asphalt Technologies) to determine accuracy and precision of the method. In this study, it was found that the ignition method can determine asphalt content of HMA with precision greater than the extraction recovery method without significantly affecting the gradation of the aggregate. They also described the method of determining the correction factor of the ignition oven through the use of an aggregate-only sample. Through this method, an aggregate-only sample is placed into the ignition oven and the aggregate mass loss is measured. This value is then used to calibrate HMA samples in order to account for any aggregate loss during heating. Sondag et al. [22] recommended keeping the 2000 gram sample at 110^{o}C for 40 min before ignition test to remove most of the moisture from the sample. Simplicity and accuracy of this method makes it popular among RAP plant operators. As per the NCAT survey, **figure 2-3**, approximately 85 percent of responders determine asphalt content using ignition method.

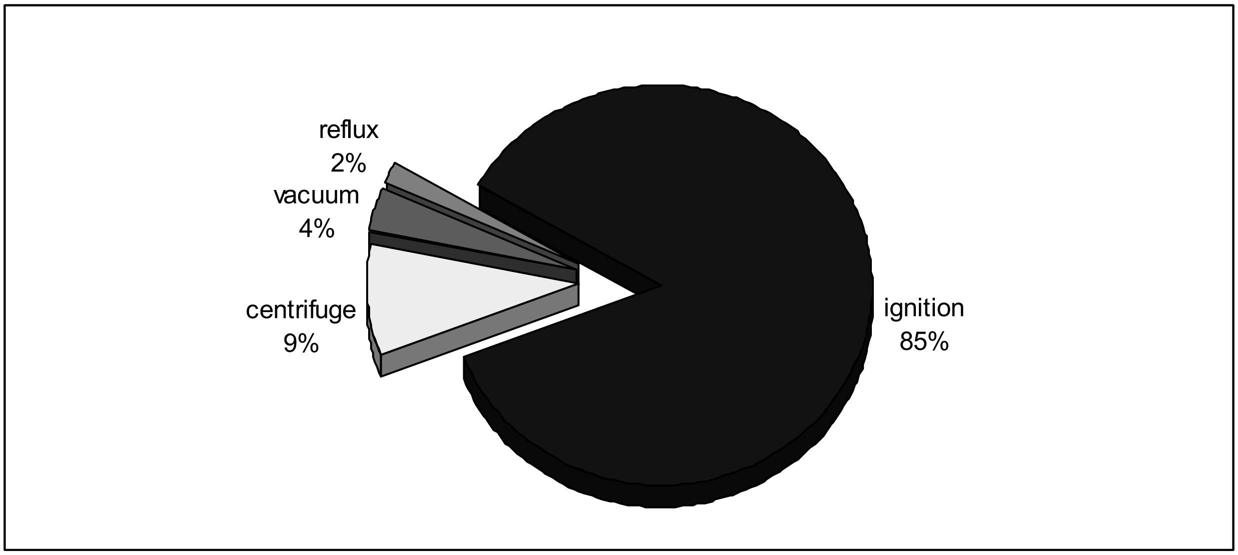

Figure 2-3. Methods Used to Determine Asphalt Content of RAP Stockpiles

2.6 RAP Binder Properties

The recovered RAP binder sample is tested to evaluate its rutting and fatigue performance properties. These properties are influenced by RAP binder aging during its production and service life. Asphalt aging affects the chemical, mechanical and rheological properties of asphalt binder. The following topics are discussed in detail about the binder aging and the tests performed to evaluate binder performance:

- 2.7.1 Binder aging
- 2.7.2 Superpave binder tests
- 2.7.3 Rejuvenation of RAP binder

2.6.1 Binder aging

Asphalt binder undergoes two types of aging, short term aging and long term aging. Short term aging is primarily due to volatilization during the heating process of HMA production while long term aging occurs during the service life of pavement and is caused by oxidization. Both short term aging and long term aging cause an increase in binder viscosity. This increase in viscosity results in increased cracking failure and moisture susceptibility and decreased mixture wear resistance.

Asphalt is a petroleum product made up of a variety of hydrocarbons with other minor components such as sulfur, nitrogen, oxygen and metals. The chemical composition of asphalt depends upon the crude oil source and the refining method. Asphalt binder consists of two chemical groups, asphaltenes and maltenes. Maltenes consist of oils and resins are generally semisolid or solid in character. These resins are fluid when heated and brittle after cooling. Resins act as agents to disperse the asphaltenes throughout the oil to provide a homogenous liquid. Corbett [35] studied the process of aging and found that as asphalt ages, maltenes are transformed into asphaltenes. This transformation leads to an increase in asphaltene content and decrease in maltenes content, resulting in fewer maltenes available to disperse the asphaltenes. The large presence of asphaltenes causes flocculation without the presence of enough maltenes for dispersion, leading to increased viscosity and decreased ductility, both of which are indicators of poor pavement performance. The extent of aging is tested with standard tests like the Rolling Thin Film Oven Test (RTFO) and the Pressure Aging Vessel (PAV). The flow and stiffness properties of binders are tested by using the Dynamic Shear Rheometer (DSR) and the Bending Beam Rheometer (BBR) respectively.

2.6.2 Superpave Binder tests

In the DSR test, the sample is subjected to rotational shear. This is achieved by keeping the lower plate fixed and oscillating the upper plate at ten rad/sec. In DSR, the plate size is 25 mm for un-aged and RTFO samples and eight mm for a PAV sample. This test is completely software controlled with strain values for un-aged, RTFO aged and PAV aged as 10 percent, 12 percent, and one percent, respectively. Depending upon the use of different software modules, the DSR test is referred to as un-aged DSR, RTFO DSR and PAV DSR in this manuscript (AASHTO T315). Plant and field aging is simulated by RTFO and PAV tests. The RTFO (ASTM D2872) simulates short term aging caused by in-plant heating. The impact of short term aging on binder properties is used to compare rutting performance with those of new asphalt by conducting the DSR test. Long term aging is simulated by PAV as developed by the Strategic Highway Research Program (SHRP). Residue from the PAV is used to estimate the physical and chemical properties of an asphalt binder after five to 10 years in the field.

After conditioning asphalt binder through the RTFO and PAV, fatigue and thermal cracking performance is evaluated using the DSR and BBR. DSR is used to compute complex shear modulus (G*) and phase angle (δ) at high and intermediate service temperatures. These two parameters represent the asphalt binder's resistance to shear deformation in the linear viscoelastic region. Complex modulus has two components, the storage modulus or elastic portion ($G' = G^*/\sin\delta$) which represents rutting performance, and the loss modulus or viscous portion ($G'' = G^* \sin\delta$) which represents fatigue performance. As per Performance Grade (PG) specification, the storage modulus should be greater than or equal to 1 kPa and 2.2 kPa for original and RTFO asphalt binder, respectively. The fatigue parameter requires loss modulus to be a maximum of 5000 kPa for PAV aged binder. BBR is used to determine the low temperature thermal cracking performance of asphalt binder. In BBR, a simply supported prismatic beam of asphalt binder is subjected to a constant load applied at its midpoint to calculate creep stiffness (S) and the slope of master stiffness curve (m-value). As per PG specification creep stiffness should be a maximum 300 MPa and the m-value should be a minimum 0.3.

2.6.3 Rejuvenation of RAP binder

The aforementioned tests are carried out on the recovered RAP binder to determine the extent the RAP binder has been aged. The level of aging, or stiffness, can be used to determine the amount of rejuvenating material required to add for better performance of the entire mix. Rejuvenating materials are generally types of oil that help RAP binder regain its mechanical and chemical properties, which are lost during the aging process. This rejuvenating material could be a lower grade binder or flux oil.

2.7 Superpave Mix Design of RAP mix with lower grade virgin binder

2.7.1 Marshall/Hveem

One of the first comprehensive methods for RAP mix design was published by Epps et al. [39] in a 1980 NCHRP report titled "Guidelines for Recycling Pavement Materials". This reference was intended to be a source of information regarding the recycling processes and a RAP mix design incorporating asphalt modifiers. A detailed mix procedure is outlined in the appendix report, which was modeled after the work of Davidson et al (1977), Dunning et al (1978), Canessa et al (1977), and Terrel and Fritchen (1977). [40]-[43]

A very similar recycled mix design procedure is presented in the Asphalt Institute (Mix Design Methods [44]) MS-2 Marshall and Hveem mix design methods manual. The recommended procedure from the Asphalt Institute is as follows:

1. Determine RAP aggregate gradation.
2. Determine RAP asphalt content and asphalt binder viscosity.
3. Blend RAP and virgin aggregates to obtain a gradation which meets specifications.
4. Approximate the asphalt demand of the combined aggregates. This may be done by the Centrifuge Kerosene Equivalent test or by the empirical formula in the manual which is dependent on the proportion of aggregate retained on the No. 8 sieve, passing the No. 8 sieve, and passing the No. 200 sieve, with a constant given for each proportion.
5. Estimate the percentage of new asphalt in the mix. This is estimated with a formula in the manual.
6. Select the grade of the new asphalt (or recycling agent). This is determined by using a target viscosity, the viscosity of the virgin asphalt, the viscosity of the asphalt in the RAP, and a viscosity blending chart.
7. Perform a trial mix design using the Marshall or the Hveem method. Brownie et al (1977) report that the addition of recycling agents may bring the asphalt content above optimum, resulting in a mix with lower stability. For this reason, it is important to try a range of asphalt contents, both above and below the estimated asphalt demand.
8. Select the job-mix formula.

2.7.2 Superpave

Superpave is a mix design system developed in 1991 by the Strategic Highway Research Program (SHRP). This system was developed in an effort to improve the performance and durability of roadways constructed in the US. The Superpave system focuses on three pavement distress types: rutting, fatigue cracking, and low temperature cracking.

The volumetric design aspect of Superpave develops quality mix designs that can be used to make durable roadways. Through this design process, the optimal binder content yielding 4 percent air voids in samples is found for a given mix gradation, or Job Mix Formula (JMF). The mix design is then checked against three limits: Voids in Mineral Aggregate (VMA), Voids Filled with Asphalt (VFA), and Dust-to-Binder Ratio (DB). These limits check that enough asphalt is in the mix to result in good adhesion of aggregates as well as a stable mix structure. Once these limits are passed, testing can be conducted on 7 percent air void samples to find the performance properties of a given mix. This amount of air voids is chosen because it best simulates field conditions for roadways.

2.7.3 Superpave Mix Design of RAP mix with lower grade virgin binder:

In 1997, Expert Task Group Guidelines were described by Bukowski, which were based on discussions with industry professionals. Though recommendations were not based on valid experimental results, the concepts behind the recommendations were sound. Bukowski [47] suggested that general Superpave mix design requirements would remain the same for RAP mix and proposed a three-tier system which facilitated the selection of

PG grade and percentage of virgin binder in RAP mix. The three-tier system is described as follows:

Tier 1: Less than 15 percent of RAP could be incorporated in mix design without any change in binder grade.

Tier 2: 15 percent to 25 percent of RAP could be incorporated by lowering the upper and lower grade of the virgin binder by one grade.

Tier 3: To incorporate RAP percentages higher than 25 percent, blending charts can be used.

Kandhal and Foo [48] at NCAT confirmed the use of the three tier system and also developed a "sweep blending chart" to determine the percentage of RAP if a three-tier system was not used. The "sweep blending chart" required the determination of storage ($G^*/\sin\delta$) and loss ($G^* \sin\delta$) modulus for different percentages of virgin binder at high and intermediate temperatures. The percentage of RAP obtained by the intermediate temperature sweep blending chart (average 37 percent) was higher than the typical average practice of around 15 – 20 percent. To rectify the discrepancy between calculated percentage of RAP and actual practice, Kandhal and Foo recommended a "specific grade" blending chart **figure 2-4** which has reduced the effort of developing three sweep blending charts.

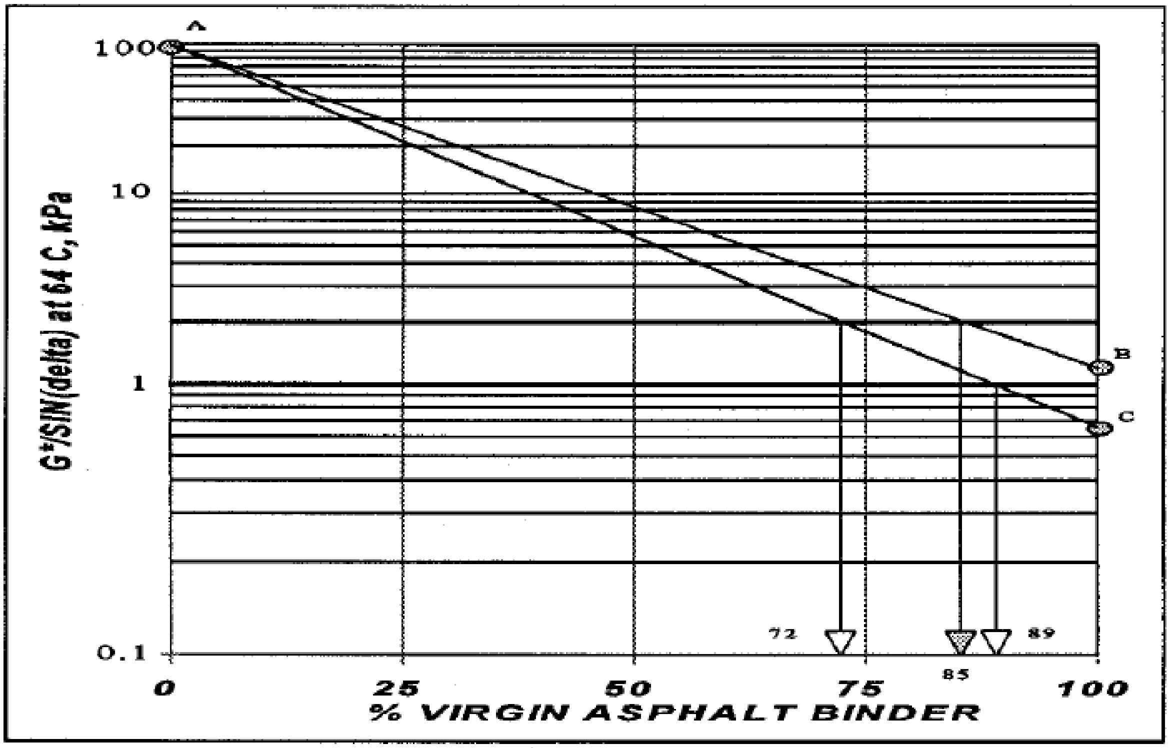

Figure 2-4. Specific Grade Blending Chart

A "specific grade" blending chart is developed by plotting G*/sin δ values for virgin and RAP binder on log-log scale at required target high temperature grade. Consider an example given in **figure 2-4** where the target high temperature is 64°C and G* /sin δ of RAP binder is 100 KPa (Point A). For the virgin binder, two binder grades (PG 64-28 and PG 58-34) are considered whose G*/sin δ values are 1.13KPa (Point B) and 0.65 KPa (Point C) respectively. The parallel stiffness line of 1KPa gives the minimum G* /sin δ for the un-aged virgin binder at its upper PG grade temperature while the stiffness line of 2.2KPa gives the minimum required G* /sin δ for the RTFO virgin binder at that temperature. From the plot it can be seen that 85 to 100 percent of virgin binder (or zero to 15 percent of RAP) is required if PG 64-28 binder is used and 72 to 89 percent of virgin binder (or 11 to 28 percent of RAP) is required if PG 58-34 is used. The scope of the study performed by Kandhal and Foo [48] did not encompass the lower temperature grade.

NCHRP 9-12 (McDaniel & Anderson [49]) recommended the use of the latest three-tier system, shown in **table 2-4**, which was modified to incorporate the low temperature grade. This new three-tier system allows a maximum of 20 percent RAP without a change in binder selection and up to 30 percent RAP by lowering one grade softer for low grade PGxx-22 and lower. PGxx-16 and xx-10 and higher are more stringent with respect to the amount of RAP allowed. For the use of high RAP design, a blending chart is recommended.

Table 2-3. Selection Guideline for RAP Mixture

	RAP Percentage		
	Recovered RAP Grade		
Recommended Virgin Asphalt Binder Grade	**PG xx-22 or lower**	**PG xx-16**	**PG xx-10 or higher**
No change in binder selection	<20%	<15%	<10%
Select virgin binder one grade softer than normal (e.g., select a PG 58-28 if a PG 64-22 would normally be used)	20–30%	15–25%	10–15%
Follow recommendations from blending charts	>30%	>25%	>15%

The design of a blending chart is dependent upon the grade of virgin binder, percentage of RAP, and target PG grade. Some of these variables may be fixed based on state specifications or local availability of materials. Blending charts can determine the PG grade of the virgin binder if the target PG grade, the percentage of RAP, and the RAP binder properties are known or the percentage of RAP can be determined if the PG grade of virgin binder, the RAP binder properties and the target PG grade are known.

Consider following two cases which illustrate use of a blending chart:

- Determination of PG grade of virgin binder.
- Determination of Percentage of RAP.

To determine the high and the low grade of virgin binder, the high, low, and intermediate critical temperatures of the RAP binder are required. The critical temperature is the temperature at which storage modulus (G*/sin δ), loss modulus (G* sin δ), creep stiffness (S) and slope of master stiffness curve (m-value) for un-aged (original), RTFO and PAV samples reach the critical values specified by the Superpave specification and can be determined through BBR or DSR testing. **Table 2-5** gives an example of the critical temperature of recovered RAP binder.

Table 2-4. Critical Temperature of Recovered RAP binder

Aging	**Property**	**Critical Temperature, °C**	
Original	DSR G*/sin δ	High	86.6
RTFO	DSR G*/sin δ	High	88.7
PAV*	DSR G* sin δ	Intermediate Low Low	30.5 -4.5 -1.7
	PG	Actual MP1	PG 86-11 PG 82-10
* Test RTFO-aged recovered RAP binder as if PAV-aged.			

Using a linear assumption based on these critical temperatures, the percentage of RAP and target critical temperature can be drawn as a straight line, which can be extended to find the intercept on the Y-axis and then find the critical temperature of the virgin binder.

Blending charts for high, intermediate, and low temperatures are developed. **Figure 2-5** shows the blending chart for high temperature.

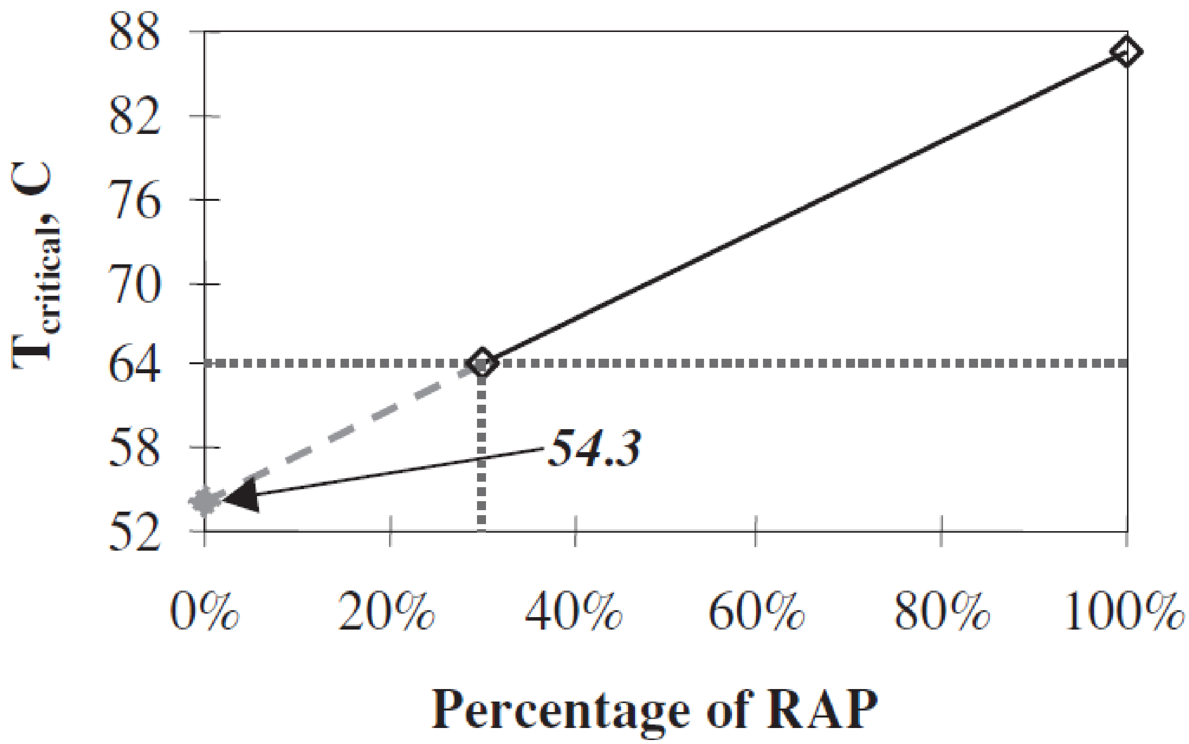

Figure 2-5. High-Temperature Blending Chart for Known RAP Percentage

Estimated critical temperature of virgin asphalt binder could be tabulated as shown in **table 2-6**. In this example, a virgin binder with true grade of PG 54.3-26 is required to obtain a final blended binder PG grade of 64-xx. In practice, a virgin binder of PG 58-28 would need to be used since asphalt binder is graded at intervals of 6°C and would result in a slightly higher final blended binder grade.

Table 2-5. Estimated Critical Temperature of Asphalt Binder

Aging	Property	Critical Temperature, °C	
Original	DSR $G^*/\sin\delta$	High	**54.3**
RTFO	DSR $G^*/\sin\delta$	High	53.4
PAV	DSR $G^*\sin\delta$	Intermediate	**22.6**
	BBR S-value	Low	–15.2
	BBR m-value	Low	**–16.4**
	PG	Actual	PG 54-26
		MP1	PG 58-28

2.7.4 Determination of Percentage of RAP

The procedure for the design of a blending chart to determine the percentage of RAP is similar to Case 1. In this case, a straight line in the blending chart is drawn with known critical temperatures of virgin and RAP binder and the percentage of RAP for the target critical temperature can be interpolated as shown in **figure 2-6**.

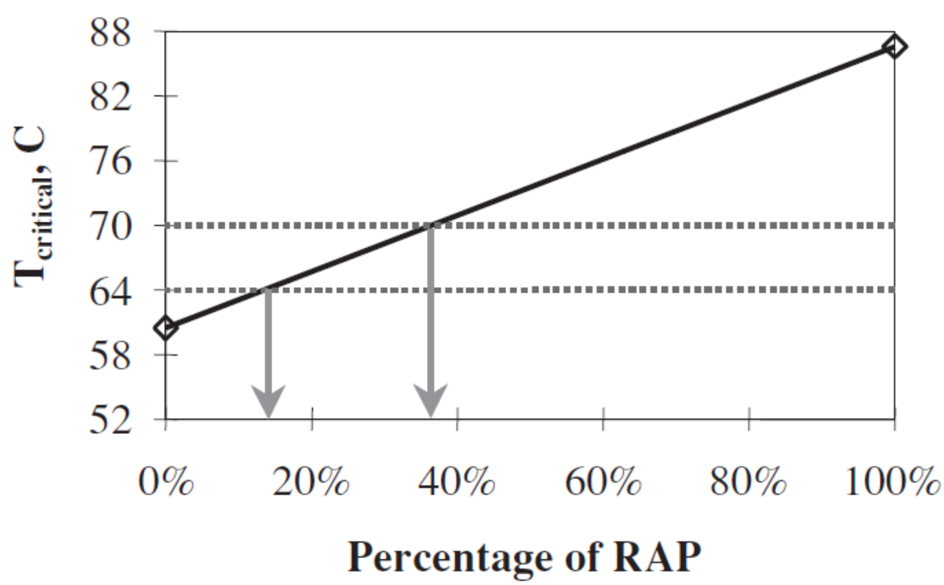

Figure 2-6. High Temperature Blending Chart for Unknown RAP Percentage

Asphalt binder is graded at 6^{o}C intervals, which gives a range of percentage of binder. The blending chart is defined by a linear relationship between properties of virgin and RAP binder (as shown in **figure 2-6**). Through this linear relationship, a maximum percentage of RAP can be determined with respect to the desired final binder grade of the mixture. This maximum percentage should be lower than the percentage of RAP obtained by the intermediate blending chart. **Table 2-7** shows example of the method of tabulation of estimated percentage of RAP to achieve the final blending grade.

Table 2-6. Estimated Percentage of RAP to Achieve Final Blending Grade

			Percentage of RAP to Achieve	
Aging	**Property**	**Temperature**	**PG 64-22**	**PG 70-28**
Original	DSR $G^*/\sin\delta$	High	**13.4%**	**36.4%**
RTFO	DSR $G^*/\sin\delta$	High	10.8%	32.5%
PAV	DSR $G^*\sin\delta$	Intermediate	**66.3%**	—
	BBR *S*-value	Low	57.6%	23.7%
	BBR *m*-value	Low	**40.5%**	**5.8%**

Once the percentage of RAP and virgin binder grade are known, the remaining Superpave mix design procedures are followed as normal. McDaniel et al [49] also recommended the computation of bulk specific gravity by assuming the percentage of binder absorption of the aggregate, deduction of RAP binder content from total asphalt content, and accounting for the weight of binder in RAP while batching the aggregates.

Even though McDaniel et al's [49] recommendations have been verified and accepted by most researchers, there have been efforts to simplify the procedure of the mix design.

Bautista et al. [50] conducted the research at University of Wisconsin to eliminate the complicated extraction-recovery method and to find out the low temperature rheological properties of RAP binder with a much simpler ignition method and a modified BBR test. Detailed investigation and testing is required to adopt this method in practice, its procedure explained in the following paragraph.

In this method, stiffness of aged binder is determined by testing two types of binder samples and two types of mortar samples. The two types of binder samples tested are virgin binder in its original state and virgin binder after it has undergone two PAV cycles. The two types of mortar samples are fresh and artificial. The fresh mortar sample is prepared by mixing RAP aggregates and virgin binder in its original state and artificial mortar is prepared by mixing RAP aggregates and virgin binder that has undergone two full PAV cycle to simulate aging of in-service pavement. Additional virgin binder (15 percent of RAP binder) is added to both mortal samples. The relationship between binder and mortar stiffness is plotted to determine RAP binder stiffness which is used to plot a blending chart of stiffness versus virgin binder content. By also taking into account the PG grade limit on stiffness, the percentage of RAP and virgin binder can be determined.

Al Qadi et al. [17] investigated double bumping (i.e. low and high grade softer than that of standard binder grade) of high RAP (40 percent) to reduce low temperature thermal cracking by comparing complex modulus and fracture energy. The use of a softer binder has potential to reduce brittleness and premature cracking problems in HMA with high RAP. Complex modulus results indicate that high temperature bumping significantly affects the stiffness of mix, however the effect of low temperature bumping is difficult to isolate by the complex modulus test. Double bumping tested with semi circular bending (SCB) specimen at 0^0C and -12^0C indicated that a fracture energy of a 40 percent RAP sample (1365 J/m2) is higher than that of the 20 percent RAP sample (1243 J/m2) with standard binder grade (without bumping). Double bumping offsets the effect of RAP at intermediate temperatures but at low temperatures it is not that effective as the viscoelastic nature of binder reduces below glassy transition temperature and the binder becomes brittle. More fracture energy tests are required to conclude the requirement of double or single bumping at low temperature (-30^0C and -24^0C).

2.8 Performance of the mixtures of unmodified binder with RAP

2.8.1 Laboratory Performance

Various researchers have investigated the proper methods of utilizing RAP and the associated performance of HMA incorporating RAP. The laboratory and the field performance of the RAP have been explained below.

2.8.1.1 Laboratory performance of RAP mixture at High Temperatures

In the past, many researchers have evaluated the effect of RAP content in the controlled mixtures in the laboratory. Rutting is one of the major problems in pavement and the effect of RAP on the laboratory rutting performance has been evaluated by various researchers.

Researchers have observed that for the mixtures having similar binder content and binder grade, higher content of RAP in the mixture results in higher rutting resistance. This is clearly seen in the following **figure 2-7** displays the rut depths calculated for different RAP mixtures by using APA by West. [9]

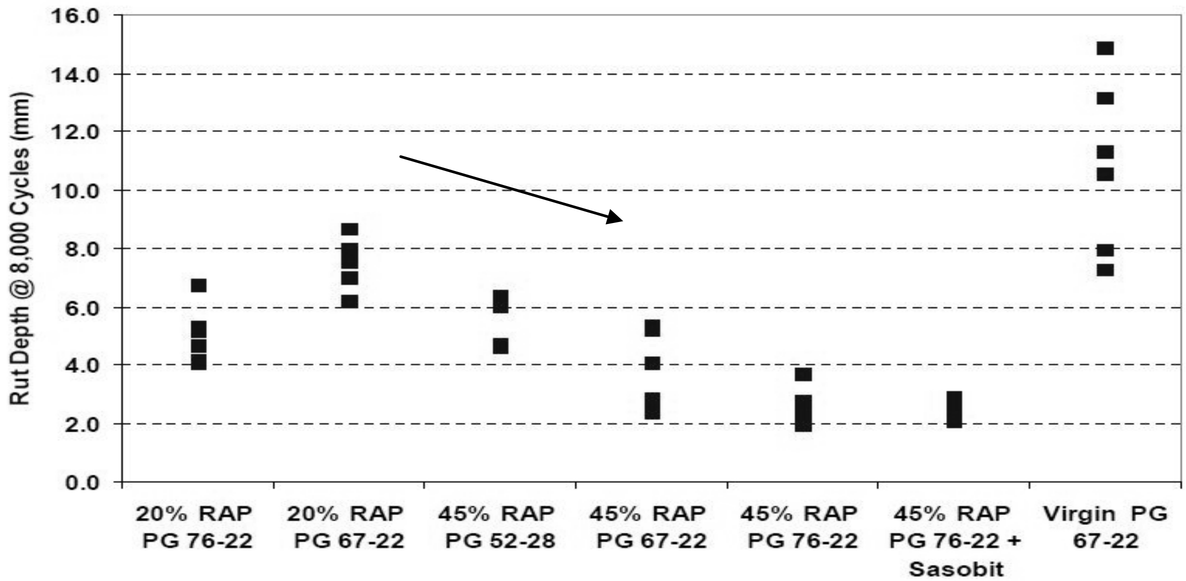

Figure 2-7. APA Test Results for the RAP Experimental Sections [(9)]

The above phenomenon discussed was observed by many previous researchers. Huang et al [15] observed similar results using the Superpave Shear Tester. According to Nukunya et al (2002) and Villiers (2004) [54]-[55], the phenomenon of higher rutting resistance is due to the lower content of virgin binder in the RAP mix. However, when rutting tests were performed by G.W. Maupin et al [21] using APA, it was observed that on an average there was no significant difference in rutting between mixtures with high (> 20 percent) and the low (<=20 percent) usage of RAP. The above phenomenon may be because of high variability of results in field core samples.

2.8.1.2 Laboratory performance of RAP mixture at intermediate and low Temperatures

According to most of the research that has been previously conducted, fatigue is the critical issue observed when high percentages of RAP are used in the mixture. No significant trend was observed by all the researchers and the discrepancies are outlined below.

When tests were performed using the Superpave Shear Tester, and in the indirect tensile test mode, it was observed that as the percentage of RAP increased from zero percent to 45 percent, the fatigue life decreased. Testing conducted for the NCHRP 9-12 study also confirmed that when RAP content was greater than 20 percent, lower fatigue life was observed.

It was discovered that as the RAP content increased from zero percent to 30 percent its fatigue life was improved when tested with the indirect tensile strength test, semi-circular bending test and the four-point beam fatigue test. Al-Qadi et al [17] commented that the results for fatigue cracking are very unpredictable for higher percentage of RAP. The fatigue life measured using the constant strain testing method increased with the increase in RAP percentage however no consistent level of increase in the fatigue life is observed. Moreover, when beam fatigue tests were performed at different strain limits; (low, high and intermediate strain levels) no significant difference between average test result values for high (30 percent RAP) and control (zero percent RAP) samples was observed. From the above observations, it is not certain that fatigue life always decreases with the increase in the RAP content.

Based on numerous laboratory studies, mixtures containing RAP exhibited significant increase in stiffness and even improved fatigue resistance. According to Huang [56], the RAP modified asphalt mix is a particulate-filled composite material. Based on Eshelby's equivalent medium theorem, this type of composite materials can be assumed as a virgin asphalt mastic layer coated "black rock" aggregates dispersed in an equivalent virgin asphalt mix. "Black rock" aggregates are aggregates with two layers present, the inner layer being the aggregate particle and the outer layer being an aged asphalt mastic film covering the particle. With the help of previous studies by Li, G., Zhao (2000) and by composite analyses it was indicated that the tested aged asphalt mastic layer was acting as a cushion layer between the hard aggregate and the soft asphalt mastic layers. It was also observed that the stiffness changed more gradually in the test samples avoiding a sudden change in stiffness and reducing the stiffness mismatch, thus reducing the stress and strain concentration. It was concluded that the layered system in RAP helped to reduce the stress concentration of HMA mixtures. It was also suggested from the reduced stress or strain concentration that the strength or ultimate strain of asphalt could be increased with the RAP acting as "black rock" thus increasing its fatigue resistance. (56) This conclusion was in agreement with the test results by Huang [15] and Sargious & Mushule (1991). [20]

2.8.2 Moisture Susceptibility

The percent of TSR is defined as the Indirect Tensile Strength in wet state divided by that in the dry state. As per Superpave specification it should be higher than 80 percent but some states have different specifications as per its weather condition. For instance, the South Carolina Department of Transportation (SCDOT) has a specification of 85 percent. Moisture resistance of mixture appears to increase with increase in RAP content, but when tested for TSR, results showed that TSR increases from zero percent to 20 percent RAP and decreases from 20 percent to 40 percent RAP. According to Al-Qadi et al [17], improved moisture resistance of RAP may be due to selective absorption of binder into aggregates that produces a bond and helps in resisting stripping and the possibility of incomplete blending of binders and formed double coating around the RAP aggregate. On the contrary, when Sondag et al [22] evaluated TSR for 18 mixtures, he found that all mixtures had a TSR more than 95 percent. No relationships were found with RAP content or binder grade within the TSR results. According to that study, addition of the RAP to the mixture had no positive or negative influence on the moisture susceptibility. Maupin [21] also found that there was no significant relation between the average TSR results and RAP when it used from zero to 30 percent RAP content. Laboratory tests were performed on cores collected from the field which could be one of the reasons for not getting consistent results. TSR ratio of mixtures containing a rejuvenator was lower than that of mixtures containing lower virgin binder. Also, there was no visual sign of stripping seen even for highest percentage of RAP (40 percent, 48 percent) from two different sources of aggregates. When Xiao [58] estimated TSR of hot mix asphalt with varying rubber content (zero, five, ten, and 15) percent and 25 percent of RAP, he observed that all samples satisfied Superpave specification for SCDOT (TSR = 85 percent) except for the mixture containing 15 percent of rubber.

2.8.3 Field Performance

When Kandhal et al [59] in his analysis compared ten to 45 percent of RAP mixtures with the virgin mixtures where the monitoring period was from one to three and a half years, there was no significant difference in the performance of virgin and RAP mix sections. However, he believed that one to three and a half years is not long enough to make a definitive evaluation of field performance of virgin and RAP mix sections. West [9] also conducted a field performance test on the NCAT test track under heavy loading and it showed good rutting performance except for one of the section which included 20 percent of RAP and lower PG virgin binder.

Figure 2-8 shows the average rut depth results for seven test sections. Each test section was loaded with 9.4 million ESALs of traffic. As shown in the figure, all test sections yield low rutting depths regardless of some mixes having low air voids and high VFA values. The section with the greatest rutting depth was the section with 20 percent of RAP and PG 67-22 virgin binder. It was stated in the study that the 20 percent RAP section saw larger rutting depths when compared with higher percentage of RAP sections because of its lower RAP percentage and lower amount of aged binder in the mix. However, it was even observed that only two of the eighteen sections had shown longitudinal cracking. West [9] then compared 18 sections all over the United States for rutting and fatigue cracking and he observed that 33 percent of the Virgin mixtures significantly performed better than the RAP mixture with 30 percent RAP content. He also observed that 29 percent of RAP mixtures performed better than the virgin mixtures and there was no significant difference between the virgin and the RAP mixtures for the remaining 38 percent. Similarly, he observed the same sections for fatigue cracking and saw that 29 percent of virgin mixtures performed better than the 30 percent RAP content mixtures and only ten percent of RAP mixtures performed better than the virgin mixtures. The remaining 61 percent had no significant difference between virgin and RAP mixtures.

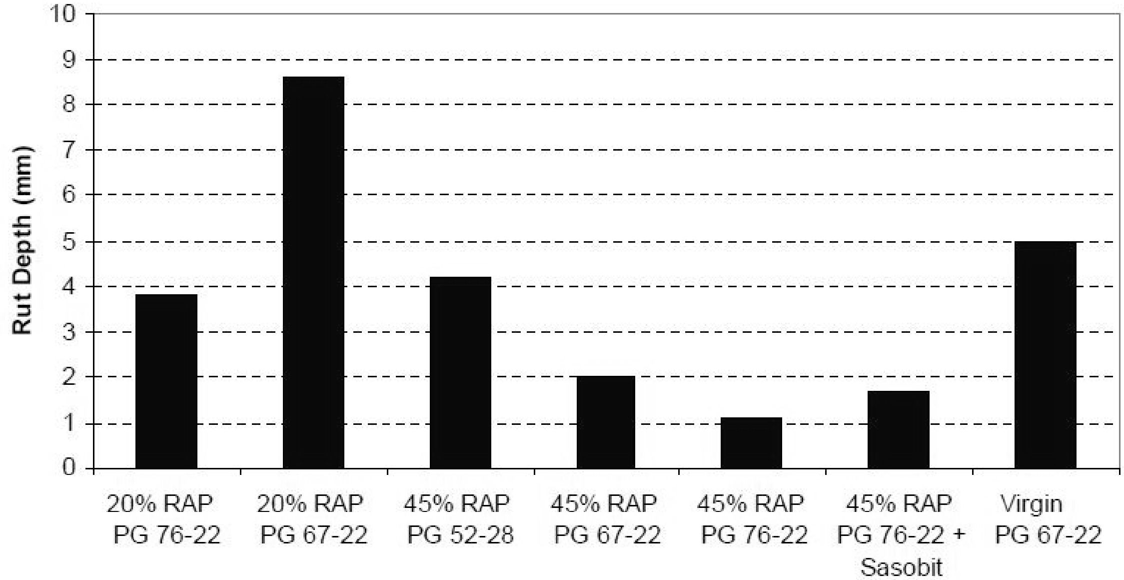

Figure 2-8. Field Rut Depths at 9.4 Million ESALs for the RAP Experimental Sections

2.9 Performance of the mixtures of modified Binder with RAP

2.9.1 Laboratory Performance

As discussed in the previous section, using high percentages of RAP in HMA improves rutting resistance and reduces the fatigue life. There were various studies conducted to improve the overall performance of the mixture by modifying the mixture. This modification was done by adding materials such as polymer (SBS), rubber, and Sasobit. The effects of these modifications are discussed below.

2.9.1.1 Laboratory Performance at Higher Temperatures:

The analysis done by Kim [60] consisted of a rutting test using an Asphalt Pavement Analyzer (APA). For this study, 35 percent of RAP, along with, three percent of Styrene Butadiene Styrene (SBS) was used in the asphalt mixes. **Figure 2-9** below shows the Rut depth comparison for different percentages of RAP from the APA test.

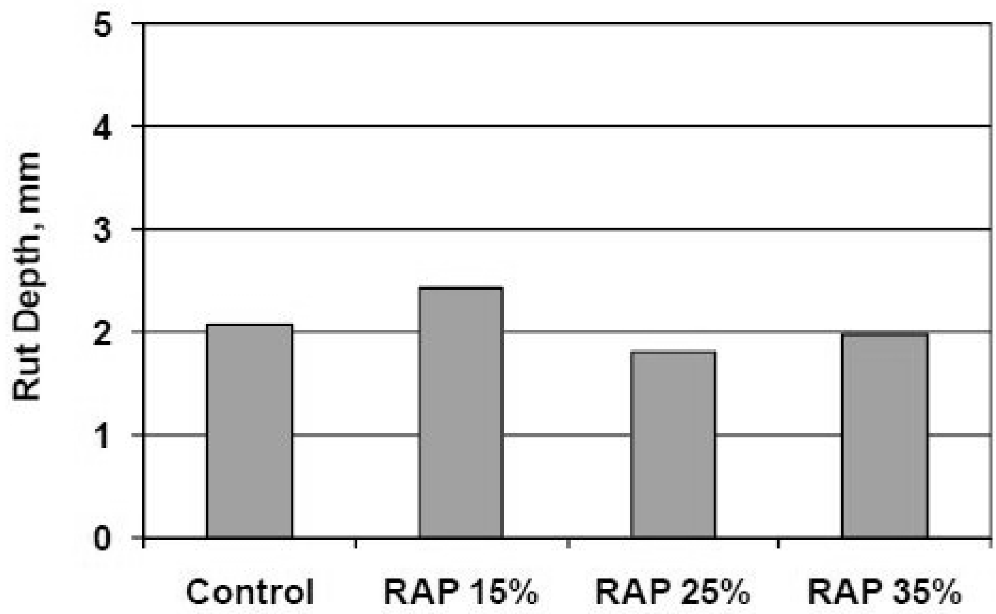

Figure 2-9. Rut Depth From APA Test

The 15 percent RAP mixture showed slightly higher rutting than average and the 25 percent RAP mixture showed slightly lower rutting than average. The results showed that adding RAP to mixtures with modified binder had little effect on rutting resistance. Another study conducted by West [61] showed that adding Sasobit to 45 percent RAP mixtures increased rutting resistance.

2.9.1.2 Laboratory Performance at Lower and Intermediate Temperatures:

SBS modifiers have become increasingly popular because of their ability to mitigate cracking. The addition of the polymers and rubber in HMA help with cracking performance. According to Huang et al [15], an increase in the fatigue life trend was seen for mixes using up to 30 percent RAP. The above phenomena must be due to the increase in the elasticity of the mixture by adding polymers. For higher content of RAP, it was found that the fatigue resistance is varied and the results obtained are inconsistent.

2.10 Laboratory Tests

2.10.1 Disc Shaped Compacted Tension Testing. (DCT)

The DCT test method determines the fracture energy (G_f) of asphalt-aggregate mixtures using disc shaped compact tension geometry. Fracture energy is the energy required to crack a compacted HMA sample. This energy is used to compare the fracture resistance of HMA samples due to thermal cracking. The test method is valid for specimens that are tested at -10°C below the lower end of the binder PG grade used. ASTM D7313-07a defines the test procedure for running a DCT test on HMA samples. **Figure 2-10** shows a typical curve of DCT test output. The curve in **figure 2-10** is the Cracked Mouth Open Displacement (CMOD) displacement versus the tensile force applied to the specimen. The area under curve is directly proportional to the fracture energy the specimen can withstand before it fails.

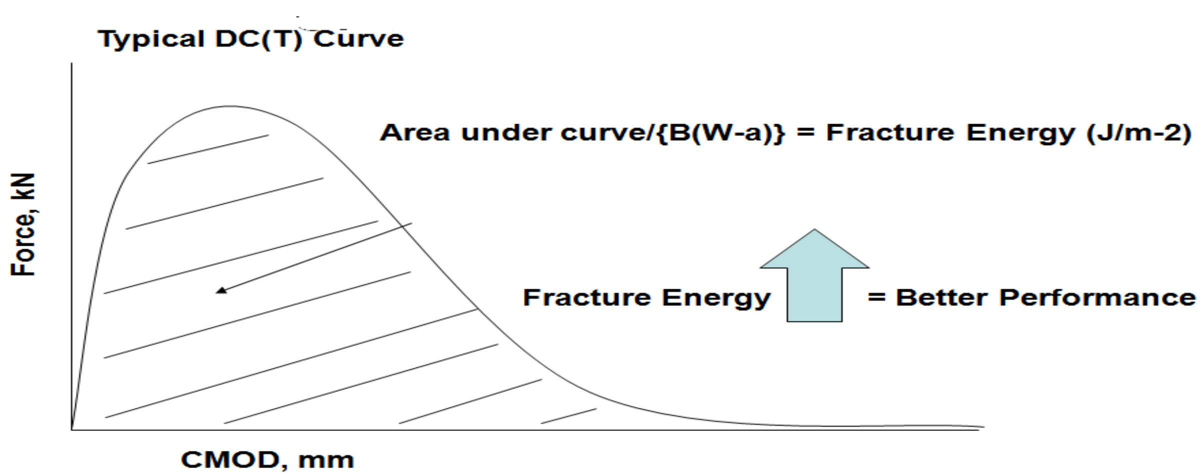

Figure 2-10. A Typical Force Versus CMOD Curve

Braham et al [65] had conducted the DCT test to compare the fracture energy of virgin mixtures and 30 percent RAP mixtures. The results revealed a significant decrease in the fracture energy for mixtures with 30 percent RAP and PG 58-28 binder tested at -12^{0}C as compared to the virgin PG 58-28 reference mixture tested at the same temperature. A reduction of fracture energy of approximately 70 percent was observed with 30 percent addition of RAP. However, the more important comparison is between the RAP mixtures and the mixture produced with virgin materials at the target binder grade, or PG 64-22. It was observed that the average fracture energies of the mixtures containing 30 percent RAP and PG 58-28 binder were greater than those of the virgin mixture manufactured with PG64-22 binder by about 50 percent on average. In this study the mixtures containing RAP with adjusted lower binder grade have even better fracture resistance than virgin PG64-22 mixture. **Figure 2-11** shows the average fracture energy for four different RAP mixes at 30 percent of RAP with PG 58-28 virgin binder, zero percent of RAP with PG 58-28 virgin binder and zero percent of RAP with PG 64-22 virgin binder.

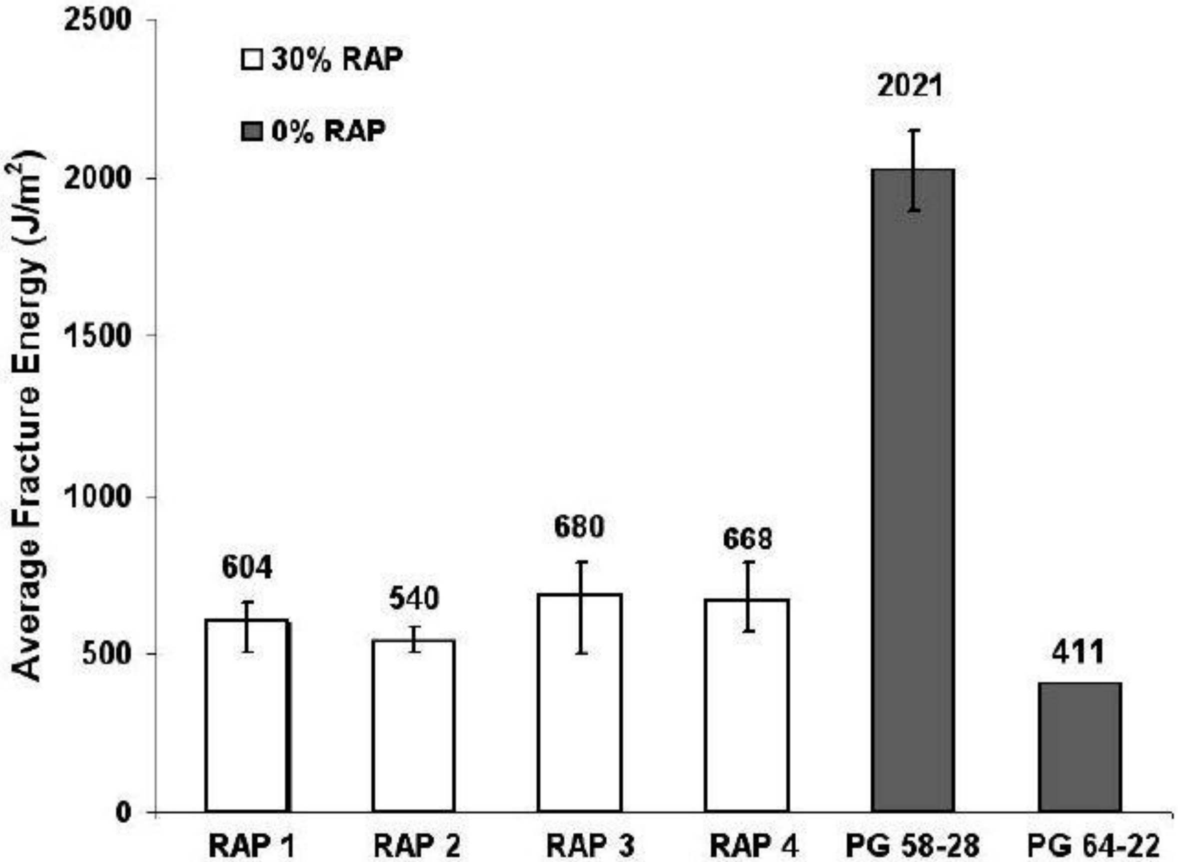

Figure 2-11. Average Fracture Energy for Zero Percent RAP and 30 Percent RAP Mixture.

2.10.2 Modified BBR

It has been shown that the addition of RAP aggregates in asphalt mixtures have a positive effect on rutting resistance, but a negative effect on cracking resistance, especially for low temperature cracking. Marasteanu et al [67] had compared the modified BBR creep stiffness with the well known method IDT creep stiffness NCHRP133. IDT were performed according to AASHTO T 322-07 and BBR mixture tests were performed according to AASHTO T313-08. It was observed that a simple linear relationship was obtained between the IDT creep stiffness and the BBR creep stiffness obtained at the intermediate and high temperature levels. IDT creep stiffness was approximately equal to 86.5 percent of the BBR creep stiffness. The IDT experimental data at the lowest temperature level is not always reliable due to the formation of ice around extensometers and very small deformations, and was not included in the model. A similar relation could not be identified for the field samples, most likely due to the aging gradient in field cores.

2.10.3 Moisture Susceptibility

Moisture susceptibility is generally the cause of poor mixture durability. It may be caused by the loss of cohesive bond between binder and aggregate, usually due to moisture intrusion. This is called stripping, and it often starts at the top of the pavement and progresses downward, resulting in raveling. It is primarily a function of aggregate type, although it can be caused by other factors such as poor drainage or inadequate compaction. Moisture susceptibility can be evaluated in the laboratory by performing stability, resilient modulus, or tensile strength testing on unconditioned and moisture conditioned samples.

Epps et al. [69] did Marshall stability testing on mixtures containing RAP. The conditioned samples were subjected to 2 hours of vacuum saturation followed by 7 days of soaking at 24°C. Many of the samples tested retained about the same stability before and after conditioning, and some stabilities increased, leading Epps et al. to question whether the recycling process may make RAP mixtures less moisture susceptible. Brownie et al. [70] also used Marshall stability testing to evaluate the stripping potential of RAP mixtures. They obtained RAP samples from 3 airfields and two civilian airports. The RAP mixtures were combined with varying degrees of Paxole recycling agent.

Original Marshall stabilities were obtained and samples were immersed in a 60°C (140°F) water bath for 24 hours. The retained stabilities ranged from 66 to 100 percent. According to the authors, 75 percent is the minimum recommended retained stability. The material which did not pass this criterion was from the Fallon airfield in Nevada. Samples of this mixture were tested with an anti-stripping agent, but the 75 percent retention was still not achieved. Brownie et al. [70] theorized that the anti-stripping agent could not cover efficiently and chemically alter the RAP aggregate surfaces. From this study, it was recommended that additional research was needed in order to effectively treat hydrophilic aggregates during recycling operations.

Moisture sensitivity testing by Stroup-Gardiner and Wagner [71] showed that the tensile strength retained ratio (TSR) for Minnesota and Georgia RAP mixtures was similar to the TSR of the virgin control mixture, with all three retaining near 50 percent. Superpave recommends a minimum TSR of 80 percent, so the RAP mixtures and the control mixture examined in this project had stripping potential.

2.11 Blending of RAP binder and virgin binder

The percentage of RAP, binder content, or rejuvenating agent is determined by testing performance related properties of binder. Performance related properties of RAP mix or binder properties within the RAP mix depend on the blending between RAP binder and virgin binder. Blending charts for RAP have been a critical research subject for a long time because of their huge benefit in RAP mix designs. Blending charts use four variables; the percentage of RAP in the mix, the grade of the RAP binder, the grade of the virgin binder, and the amount of virgin binder to be placed in the mix. Depending on which variables you find beforehand, these blending charts can be used to find any of these four variables.

The following blending cases are compared for conducting performance related tests: Black rock effect (BR), total blending (TB), partial blending (PB) and actual practice (AP). In the black rock case, it is assume that RAP binder does not contribute to the total binder content and acts as an aggregate, whereas in the total or partial blending case, aged (stiff) binder is assumed to be contributing completely or partially. The amount of partial blending occurring within a mixture is also known as the DOB. Overall gradation and total asphalt content of the mix are kept constant for all blending cases to compare the effect of blending on volumetric properties and stiffness. If the mix design is done by assuming BR effect but TB or PB effects occur, the total asphalt content and stiffness of mix will be more than expected.

McDaniel et al have recommended the use of the three-tier system based on the assumption of full-blending between virgin and RAP binder, which was later modified to incorporate the low temperature grade. The new three-tier system allows a maximum of 20 percent RAP without a change in the binder selection and up to 30 percent RAP with one grade softer at both ends. For mixes using more than 30 percent RAP, a blending chart is recommended in order to adjust the binder grade accordingly. In this blending chart, the percentage of RAP can be determined by linear interpolation between the grades of virgin and RAP binder, if the target grade of blended binder for the mix is known. Three such blending charts are developed for required high, intermediate, and low temperatures. The lowest percentage of RAP determined from these blending charts is assigned as allowable percentage RAP.

Kandhal and Foo [48] at NCAT confirmed the use of the three-tier system developed by McDaniel et al and also developed a blending chart, known as the "sweep blending chart", to determine the percentage of new binder (virgin binder) needed to hit the required final grade of blended binder in the RAP HMA if a three-tier system was not used. The "sweep blending chart" requires the determination of $G^*/\sin(\delta)$ for 1 kPa and 2.2 kPa stiffness and $G^* \sin(\delta)$ for 5 MPa stiffness for different percentages of virgin binder at high and intermediate temperatures. The percentage of virgin binder determined using the high temperature "sweep blending chart" (average 82 percent) agrees with field experience with recycled HMA. Kandhal and Foo [48] recommended the use of a 1 kPa stiffness "sweep blending chart" to reduce the effort of running the rolling thin film oven (RTFO) test. The percentage of the virgin binder obtained by the intermediate temperature using the "sweep blending chart" (average 63 percent) was higher than the typical average practice of around 80 – 85 percent. To rectify the discrepancy between the calculated percentage of virgin binder and actual practice, they recommended the blending chart, which is referred to as "specific grade blending chart", which has reduced the effort of developing three "sweep blending charts".

To investigate the blending phenomenon, Huang [56] mechanically blended (dry blended) RAP with virgin aggregates without introducing new virgin asphalt binder into the mixture. The purpose was to find out the extent at which the aged asphalt from the RAP would blend with virgin aggregates. Since the virgin aggregates were greater than

No.4 size; and RAP particles were all screened by No.4 sieve. This initial sieving of the aggregates allowed for easy separation of RAP and virgin aggregates after mixing. Irrespective of the RAP proportions varying from 10 to 30 percent, when blended at 190°C temperatures and mixed for three minutes, it was observed that the asphalt content of RAP reduced from 6.8 percent to six percent, which accounted for about 11 percent binder loss due to pure mechanical blending. The pure mechanical blending results showed that the aged asphalt tended to adhere to the RAP aggregate. A very small portion (about 11 percent) of the aged binder was mobilized in above procedure.

In addition to above study, a RAP mix with 20 percent of RAP and virgin aggregates was prepared. Only fine particles of RAP were separated for use in the mixture. In order to determine how much virgin asphalt binder blended with aged asphalt coating RAP aggregates, staged extractions were carried out. **Figure 2-12** below presents a schematic flow chart for the staged extraction.

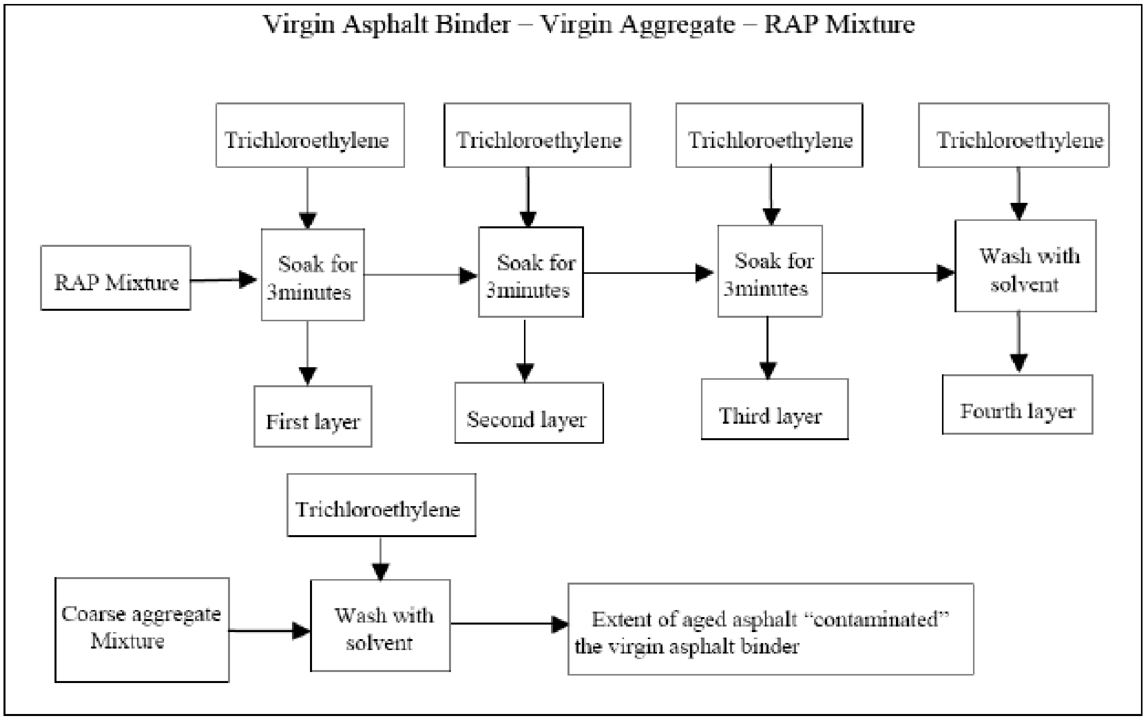

Figure 2-12. Staged Extraction-Recovery

The RAP mixture was first soaked in TCE solution for three minutes, and the solution was decanted. This batch of extracted binder was considered as the 1st (outermost) layer of RAP particles. The same mixture was soaked into TCE again for three minutes to obtain the asphalt binder of the 2nd layer, and so on. A total of four batches of staged extraction, representing four different layers of asphalt, were performed. The three minutes soaking time was determined through "trial and error". This was done in order to produce a similar amount of binder from each batch. The final batch was washed with solvent so that all of the remaining asphalt binder could be removed. The coarse (virgin) aggregate mixture was washed with TCE solution so that the level of contamination in the virgin asphalt binder, caused by the aged asphalt, could be determined.

Abson recovery was employed to recover the asphalt binder from the asphalt TCE solution. Rheological tests were conducted on the recovered asphalt binder so that the rheological properties of asphalt binders at different layers of RAP particles could be calculated. It was clear that asphalt viscosity increased as it went from outside layers to the inside layers. It was observed based on the staged extraction described above that about 60 percent of the total thickness, starting from the interior of the binder layer closest to the aggregate, had asphalt properties close to pure RAP aged binder. The asphalt properties of the remaining 40 percent showed blending between the RAP binder and virgin binder.

Recently Al Qadi et al. [17] has carried out extensive research study at University of Illinois at Urbana-Champaign in order to study the blending phenomenon of RAP and virgin binder. For this study, the dynamic complex modulus of two different RAP contents (20 percent and 40 percent) from two different sources was obtained. RAP mixture samples (AP samples) were compared with asphalt samples simulating BR effect, TB effect and 50 percent blending. Results indicated that at low RAP content (20 percent), there was no difference in dynamic complex modulus for all four set of sample; however, for high RAP (40 percent), the dynamic complex modulus of the AP sample was higher than the samples simulating BR, TB or 50 percent blending. In Al Qadi's [17] study, higher complex modulus of AP samples indicated higher stiffness. The researchers suggest that this is due to either the selective absorption of lighter fractions in the aggregate surface over time or the change in gradation caused by partial blending (whose extent is unknown). Gradation change is caused either by the formation of a mastic layer or the release of fine particles in RAP binder.

Also, an Environmental Scanning Electron Microscope Analysis (ESEM) was carried out to study the RAP particle mastic bonding and blending. The microstructure of the HMA sample was investigated by taking different type of images such as secondary electron (SE) and backscattered electron (BSE) imagery. In these images, aggregate, air void, and binder structures were differentiable; however, RAP and virgin binder were not differentiable. Hence an alternate method was adopted in which titanium was added to virgin binder and Scanning Electron Microscope images, along with Energy Dispersive X-Ray spectroscopy scans were taken. This method was previously used by Lee et al. [72] who showed micro scale interaction between virgin binder and RAP material. Detailed investigation of this method is under further study.

Al-Qadi et al. [17] made three mixes consisting of zero percent, 20 percent, and 40 percent RAP. In all three cases, the overall gradation was kept the same. The Superpave mixture design of the above three mixes indicated that the binder content was the same as shown in **table 2-8**. The surface area of the aggregates was similar for all the three mixes due to their similar gradations. Due to similar surface area and binder content, Al-Qadi et al. [17] concluded that 100 percent RAP binder was mobilized in all the three cases.

Table 2-8. Summary of JMF for Specimen Sets

	D1-100	D1-20	D1-40	D4-00	D4-20	D4-40
Optimum Binder (percent) (PG64-22)	5.7	5.7	5.7	5.9	6.0	6.0
RAP AC (percent)	4.7	4.7	4.7	5.1	5.1	5.1
Sieve Size (mm)	**Percent Passing**	**Percent Passing**	**Percent Passing**	**Percent Passing**	**Percent Passing**	**Percent Passing**
12.5	100.0	100.0	100.0	99.3	99.4	99.5
9.5	98.3	98.1	98.0	91.9	92.8	93.7
4.75	57.9	57.4	59.4	59.1	58.9	59.5
2.36	40.0	38.2	39.2	34.5	33.3	33.0
1.18	27.0	26.4	28.1	24.6	24.1	23.6
0.600	20.5	20.4	22.0	18.0	18.3	18.7
0.300	11.8	13.1	15.1	10.2	10.4	12.9
0.150	6.9	8.2	9.6	6.1	6.3	8.2
0.075	4.5	5.8	7.1	2.9	4.1	6.0

Another study to evaluate the interaction between virgin and RAP binder was carried out by Bennert et al. [73] Bennert et al. [73] developed an analytical procedure, using backcalculation methodology along with analytical methods developed by Bonaquist [74] and Rowe [75] to determine "effective" asphalt properties of HMA containing RAP. The term "effective" asphalt properties is used to described degree of interaction between virgin and RAP binder in RAP HMA. The concept of the procedure is as follows: If backcalculated asphalt binder properties of RAP HMA differ from extracted and recovered binder, which completely blends during the extraction and recovery process, then DOB is less than 100 percent. Results show that the DOB for the 15 percent and 20 percent RAP mixtures was lower than 100 percent. The 25 percent RAP mixture results yield a DOB very close to 100 percent. This method of backcalculation for asphalt binder properties is also useful in determining pavement performance of different RAP contents using MEPDG and comparing DOB of RAP binder for different percentage of RAP. The data collected within the Bennert et al. study for the evaluation of DOB between RAP and virgin binder is shown below in **figure 2-13**.

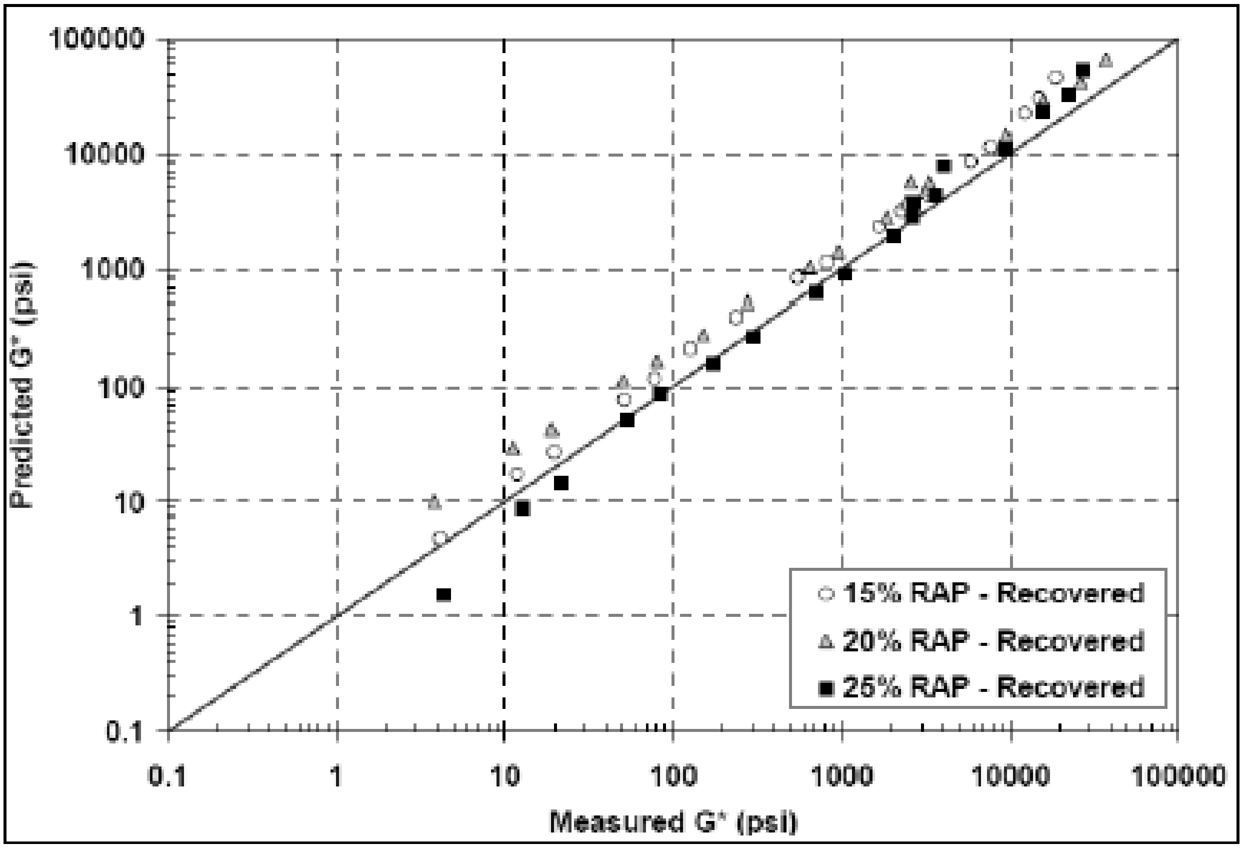

Figure 2-13. Evaluation of Degree of Blending Between Rap and Virgin Binder

2.12 Film thickness

One of the major factors contributing to the durability of the HMA is the film thickness of asphalt binder around the aggregates. Kandhal et. al. [76] recommended the use of a minimum average asphalt film thickness of 8 micron to help with mix durability. The concept of "average asphalt film thickness" assumes a similar film thickness for a particular asphalt content and gradation rather a different film thickness around each individual aggregate. One method to calculate average film thickness uses the total surface area of the aggregates within the mixture. The total surface area of the aggregates is the sum of the product of the percent passing and surface area factor for each sieve size. **Table 2-9** below gives the surface area factor for each sieve size as stated in the Asphalt Institute Manual Series 2. [44]

Table 2-9. Surface Area Factor Given in Asphalt Institute Manual Series (1993)

Sieve Size, (mm)	**Surface Area Factor (m2/kg)**
37.5	
25	0.41
19	
12.5	
9.5	
4.75	0.41
2.36	0.82
1.18	1.64
0.6	2.87
0.3	6.14
0.15	12.29
0.075	32.77

Average asphalt film thickness of HMA is calculated using **equations 2.1** and **2.2**;

Weight of effective asphalt binder around the aggregate = AC / (100 – AC) (2.1)

Film Thickness = Weight of effective asphalt binder around the aggregate /

(1000 * Specific gravity of Asphalt * Total Surface Area)

(2.2)

Here:

- Weight of effective asphalt binder around the aggregate is calculated in kg/kg of aggregates.

- AC is asphalt content determined by extraction recovery method AASTHO T319 and expressed as a percentage.
- Specific gravity of asphalt is assumed as 1.02.
- Total surface area is determined as per Bailey's method. It is sum of product of surface area factor and gradation (percent passing) of extracted aggregates and expressed in m2/kg.

2.13 Fractionation of RAP Aggregates

Fractionation is the process in which RAP aggregates are separated into at least two different sizes. In practice, fractionation sizes of 3/4 inch or 1/2 inch are typically used. Special fractionation machines can allow for more fine sieve sizes such as No. 4 and No. 8. Aggregates are sieved through these fractionation sizes and separated into two piles, one pile containing the aggregates above the fractionation size and one below. This process repeats if needed in order to produce stockpiles with the desired fractionation. Fractionation is required to raise the RAP percentage used in mixtures for six states and allows for an increase of 5 percent binder replacement for surface mixes in ten states. This increase for allowance of RAP is possible with fractionation due to its ability to eliminate a majority of the variability in aggregate size in large RAP stockpiles. It should be recognized that this process does not eliminate all RAP stockpile variability and that good quality control procedures should be used along with fractionation.

Crushing of RAP aggregates is required for stockpiles that contain large chunks of RAP. This process can be used in conjunction with fractionation in order to eliminate unusable aggregate sizes and decrease aggregate size variability within stockpiles. When crushing is used, it is important to carefully select a top size. A top size in crushing is the max size aggregates can be after the crushing process is completed. Lowering this size allows for the crushed RAP aggregates to be more versatile; however, lower top sizes create a lot of dust which may throw off VMA and DB ratios.

Chapter 3

Materials and Experimental Methods

3.1 Materials used in Degree of Blending and RAP Mixture Performance Studies

The RAP and virgin aggregates were collected from a local plant in the state of New Jersey. The gradation test for virgin aggregates and extracted RAP aggregates were performed according to AASHTO T27. The specific gravity for the virgin aggregates was given by the plant source. The extracted RAP aggregate specific gravity was calculated by separating RAP aggregates into two fractions; below No.8 sieve (fines) and above No.4 sieve (coarse). The specific gravity for both of the fractions was calculated in accordance with AASHTO T84 and AASHTO T85 for fines and coarse aggregates respectively. The virgin aggregates represented by bin 1, bin 2, bin 3, bin 4, bin 5 are sand, #10, 3/8th inch, 1/2 inch and 3/4th inch respectively. The RAP used was from a single RAP stockpile. Binder PG 70-28 and PG 58-28 were used for 25 percent and 35 percent RAP mixtures respectively as requested by the NJDOT. The control mixtures using no RAP were mixed using PG 76-22 obtained from Nu-Star. Plant mixtures were obtained from two Delaware plants in order to compare their performance with the performance of the New Jersey laboratory samples. **Figure 3-1** shows all the gradations used within the study.

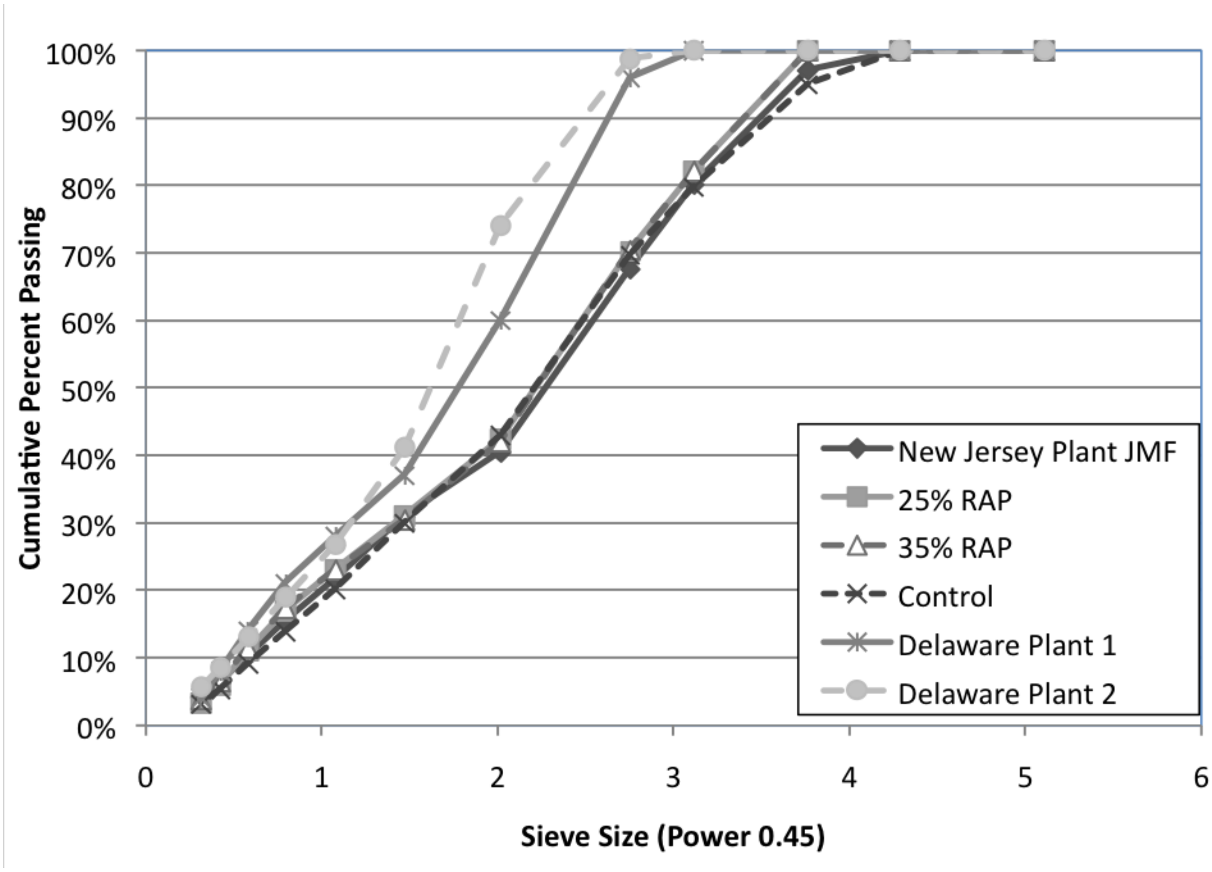

Figure 3-1 Plant and Laboratory Gradations Used in Study

3.2 Variability Study

3.2.1 Materials and Experimental Methods

The RAP sample was collected from one of the plants from the state of New Jersey. This RAP was evaluated for comparing the effects of different extraction and recovery procedures on binder content and the aggregate gradation. The five combinations of extraction and recovery procedures are compared and described in **table 3-1**. All samples were extracted using n-bromopropane solvent, also known as n-propyl bromide.

Table 3-1. Experimental Design and Different Combinations

	Combin. 1	Combin. 2	Combin. 3	Combin. 4	Combin. 5
Method of Extraction	T164	T164	T164	T164	T319
Method of Recovery	T319	T319	D5404	D5404	T319
Type of Solvent	New	Reused	New	Reused	Reused
Number of Replicates	2	2	2	2	2

RAP from four different plants in the state of New Jersey were evaluated for the variability study. For each plant, the variability of the binder content, the aggregate gradation, and binder properties within a stockpile were measured. Two different methods were used: Solvent Extraction and Recovery by AASHTO T319 and the Ignition Oven Method (IO). **Table 3-2** explains the experimental design for the variability study.

Table 3-2. Experimental Design of Variability Study

Asphalt Content and Gradation								
Plants	**Plant 1**		**Plant 2**		**Plant 3**		**Plant 4**	
Buckets	*T 319*	*T 308*	*T 319*	*T 308*	*T 319*	*T 308*	*T319*	*T308*
Bucket 1	1	1	1	1	1	1	1	1
Bucket 2	1	1	1	1	1	1	1	1
Bucket 3	1	1	1	1	1	1	1	1
Bucket 4	1	1	1	1	1	1	1	1

[1]Numbers represent number of replicates

The variability of the RAP is captured by the standard deviation calculated for gradation and asphalt content as stated by NCHRP, Project 9-33.

3.3 Superpave Mix Design

3.3.1 Materials and experimental methods

A step by step mix design process for recycled mixtures is presented in NCHRP Report No 452. The total asphalt content was reduced to compensate for the binder from the RAP. The mixing temperatures used in this study for each mixture are shown in **table 3-3** below.

Table 3-3. Mixing Temperatures of Laboratory Mixtures

Mix	RAP Percentage	Virgin Binder Grade	Mix Temperature (°C)	Compaction Temperature (°C)
1	25	PG 70-28	149-154	144-149
2	25	PG 70-28	149-154	144-149
3	25	PG 70-28	149-154	144-149
4	35	PG 58-28	148-154	136-141
5	0	PG 76-22	157-163	152-157

The virgin aggregates and binder were heated 30^0C and 10^0C above the mixing temperatures respectively. The RAP was heated for two hours at 110^0C prior to mixing. The heating served two purposes, to remove the moisture within the RAP and to pre-heat the RAP before mixing. The number of gyrations used for compaction is based on traffic level. For this study, the number of gyrations selected was 75 gyrations. **Table 3-4** shows the list of tests conducted on the materials, RAP, and mixtures. The other virgin material properties needed to conduct Superpave mix design were obtained directly from the plants. **Table 3-5** outlines the experimental design for the Superpave samples at different degrees of blending and percentages of RAP. For each mix design conducted, the total binder content that yielded four percent air voids was required to be found. Once this binder content was obtained, it was then used to make samples at seven percent air voids. Samples prepared for testing were made at seven percent air voids to represent field conditions.

Table 3-4. Tests for Virgin Material Properties to Perform Superpave Mix Design

Material	Source	Parameters Measured	Test Performed	Test Specification
Virgin Aggregates				
3/4th	Fanwood Quarry, NJ	Gradation Curve	Sieve Analysis	AASHTO T27
1/2nd	Fanwood Quarry, NJ	Gradation Curve	Sieve Analysis	AASHTO T27
3/8th	Fanwood Quarry, NJ	Gradation Curve	Sieve Analysis	AASHTO T27
#10	Fanwood Quarry, NJ	Gradation Curve	Sieve Analysis	AASHTO T27
Sand	Mt. Hope, NJ	Gradation Curve	Sieve Analysis	AASHTO T27
RAP Aggregates				
Extracted Agg.		Gradation Curve	Sieve Analysis	AASHTO T27
Extracted RAP Agg. below #4 Sieve	Plant of New Jersey	Bulk Specific Gravity	Fine Specific Gravity	AASHTO T84
Extracted RAP Agg. above #4 Sieve	Plant of New Jersey	Bulk Specific Gravity	Coarse Specific Gravity	AASHTO T85
RAP				
RAP	Plant of New Jersey	Gradation Curve	Sieve Analysis	AASHTO T27
Mix (25 Percent and 35 Percent RAP)				
Mix	Mixed in lab	Maximum specific gravity	Theoretical maximum specific gravity and density	AASHTO T209
		Short Term Aging	Standard practice for mixture / Conditioning of hot mix asphalt	AASHTO R30
		Compaction	Superpave Gyratory Compactor	AASHTO T312
		Bulk Specific gravity	Bulk specific gravity of compacted mixture	AASHTO T166
		Total Binder Content		Superpave Mix Design
		Voids filled with asphalt, VFA		
		Voids in mineral aggregate, VMA		
		Air voids in compacted mixture, V_a		
		Dust-Binder Ratio		

Table 3-5. Experimental Design for Comparing Superpave Parameters of Different Mixtures

Sr. No	Mixtures	25 Percent RAP (Minimum Replicates)	35 Percent RAP (Minimum Replicates)
1	Design binder content to meet all Superpave Mix design criterions	2	2
2	Full blending mixtures (100 percent blending)	2	2
3	Partial blending mixtures (Approximated DOB), the DOB value is assumed	2	2

3.4 Performance Test

3.4.1 Disc Shaped Compact Tension Test

The DCT test set up, the CMOD gage, and the loading fixture are shown in **figure 3-2**. A typical DCT specimen upon completion of the test is shown in **figure 3-3**. In accordance with the ASTM D7313-07 test procedure, the testing was conducted at -10°C above the low-end PG grade of the binder (-18 ºC for both PG 58-28 and PG 70-28 binder).

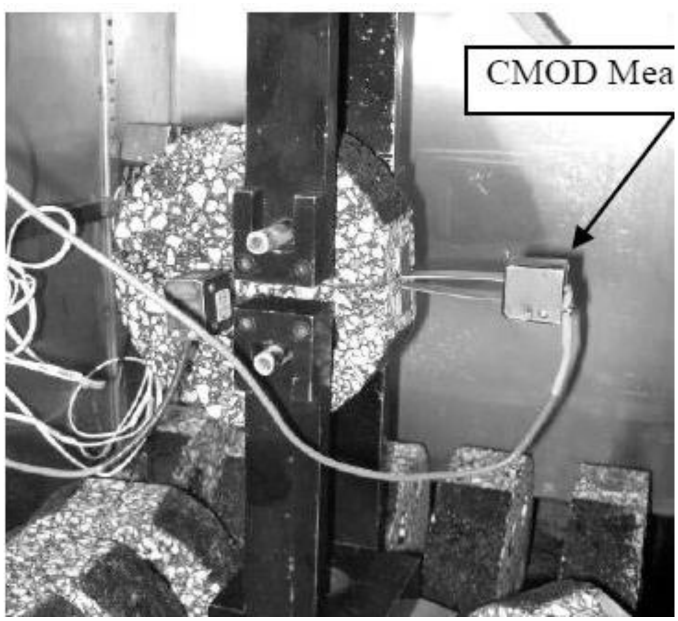

Figure 3-2. DCT Test Set Up

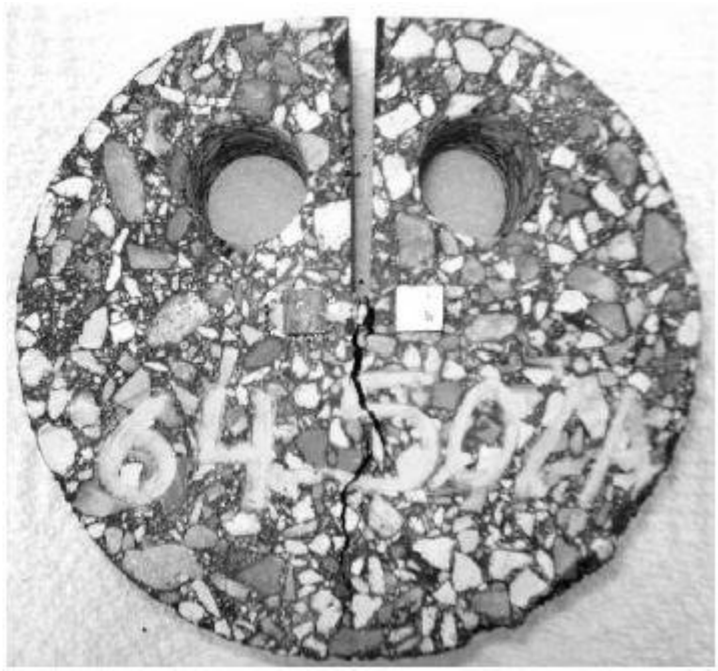

Figure 3-3. DCT Test Specimen after Test

3.4.2 Modified BBR Test

The bending beam rheometer measures the mid-point deflection of a simply supported asphalt beam subjected to a constant load applied at the mid-point. The device operates only in the loading mode which means that recovery measurements are not obtained. A test beam is placed in a controlled temperature fluid bath and loaded with a constant load for 1000 seconds. The test load (1961 ±50 mN or 4413 ±50 mN) and the midpoint deflection of the beam are monitored versus time using a computerized data acquisition system. Three-point bending creep tests were performed on specimens with the following size specification: Width = 6.35 mm (0.25 in), Height = 12.7 mm (0.50 in), Length = 127 mm (5.00 in). This size specification represents the standard size of a BBR specimen. Tests were performed at 22ºC above the low grade of the binder as required by the chosen loading level of 1961 mN. The BBR mixture sample is shown in **figure 3-4.**

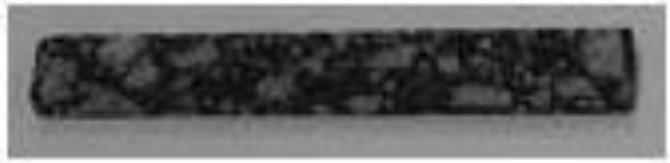

Figure 3-4. BBR Mixture Sample

The test temperature for this test is related to the temperature experienced by the pavement in the geographical area for which the asphalt binder is intended. The flexural creep stiffness, or flexural creep compliance, determined from this test describes the stress-strain-time response of asphalt mixtures at the test temperature within the linear viscoelastic response range. The low-temperature thermal cracking performance of paving mixtures is related to the creep stiffness and the slope of the logarithm of the creep stiffness versus the logarithm of the time curve of the asphalt mixture. This relationship is used as performance-based specification criteria for asphalt binders in accordance with AASHTO M 320.

3.4.3 Moisture Susceptibility

The test is performed according to AASHTO T 283. The test is performed by compacting specimens to an air void level of seven percent (±one percent). Three specimens are selected as a control (without moisture conditioning), and three more specimens are selected to be conditioned by saturating with water undergoing a freeze-thaw cycle. The specimens are then tested for indirect tensile strength by loading the specimens at a constant rate and measuring the force required to break the specimen. The tensile strength of the conditioned specimens is compared to the control specimens to determine the TSR.

Table 3-6 describes the performance test experimental design for the performance test for different Superpave mixtures compacted to for seven percent air voids. This is because seven percent air voids represents the on field conditions of the pavement for the first few years of the construction.

Table 3-6. Experimental Design for Performance Test for 25 Percent and 35 Percent RAP Mixtures Each

Performance Samples @ 7 Percent Air Voids	**DCT Test (Minimum Replicates)**	**Modified BBR (Minimum Replicates)**	**TSR (Minimum Replicates)**
Full blending mixture	2	2	2
Partial blending	2	2	2

3.5 Determination of degree of partial blending

Determination of degree of partial blending involved two tasks: The first is to determine percentage binder transfer through a coating study and the other is to determine the exact degree of partial blending through a blending study. **Table 3-7** gives the detailed experimental program used for this study. In this experimental program, two different binders, two different percentage of RAP, and one source of RAP are considered. PG 70-28 and PG 58-28 from NuStar refineries were selected in consensus with NJDOT personnel considering future applications of binder in New Jersey.

An approved JMF with RAP mixture as shown in **table 3-8** has been modified to conduct the study. RAP and virgin aggregates are obtained from a local asphalt plant. **Table 3-9** shows the individual gradations for Bin 3, 4, 5, and RAP aggregates obtained from this plant.

Table 3-7. Test Matrix to Determine Degree of Partial Blending in Different Percentage of RAP

Virgin Binder	Percent RAP by weight of aggregates (Minimum Replicates)	Coating Study (Minimum Replicates)	Superpave mixture design (12.5 mm nom. Max) Gyratory (4 percent air voids) or JMF (Minimum Replicates)	Extraction and recovery (Minimum Replicates)	Binder characterization (M320) (Minimum Replicates)
PG 70-28	25	2	2	6	16
PG 58-28	35	2	2	6	16

Table 3-8. Detailed JMF of HMA 19H76

Bin #	HMA 19H76
1	8.3
2	8.2
3	24.6
4	12.7
5	12.1
Filler	0.6
RAP	30
Percent Virgin Binder	3.5

Table 3-9. Individual Gradation for Bin 3, 4, 5, and RAP Aggregates

Sieves size	Sieves size	Bin 3	Bin 4	Bin 5	RAP
	(mm)	*(percent)*	*(percent)*	*(percent)*	*(percent)*
1 - 1/2	37.5	100	100	100	100
1	25.4	100	100	100	100
3/4	19	100	100	89	100
1/2	12.5	100	79	37	100
3/8	9.5	93	37	13	100
#4	4.75	0	0	0	100
#8	2.36	0	0	0	100
#16	1.18	0	0	0	59
#30	0.6	0	0	0	47
#50	0.3	0	0	0	31
#100	0.15	0	0	0	20
#200	0.075	0	0	0	14

3.6 Development of blending chart

Once the degree of partial blending is determined, a blending chart for partial blending needed to be created. A blending chart for different degrees of blending was developed by testing proportioned RAP and virgin binder. **Table 3-10** shows the test used to develop blending chart. **Figure 3-5** illustrates the detail of replicates.

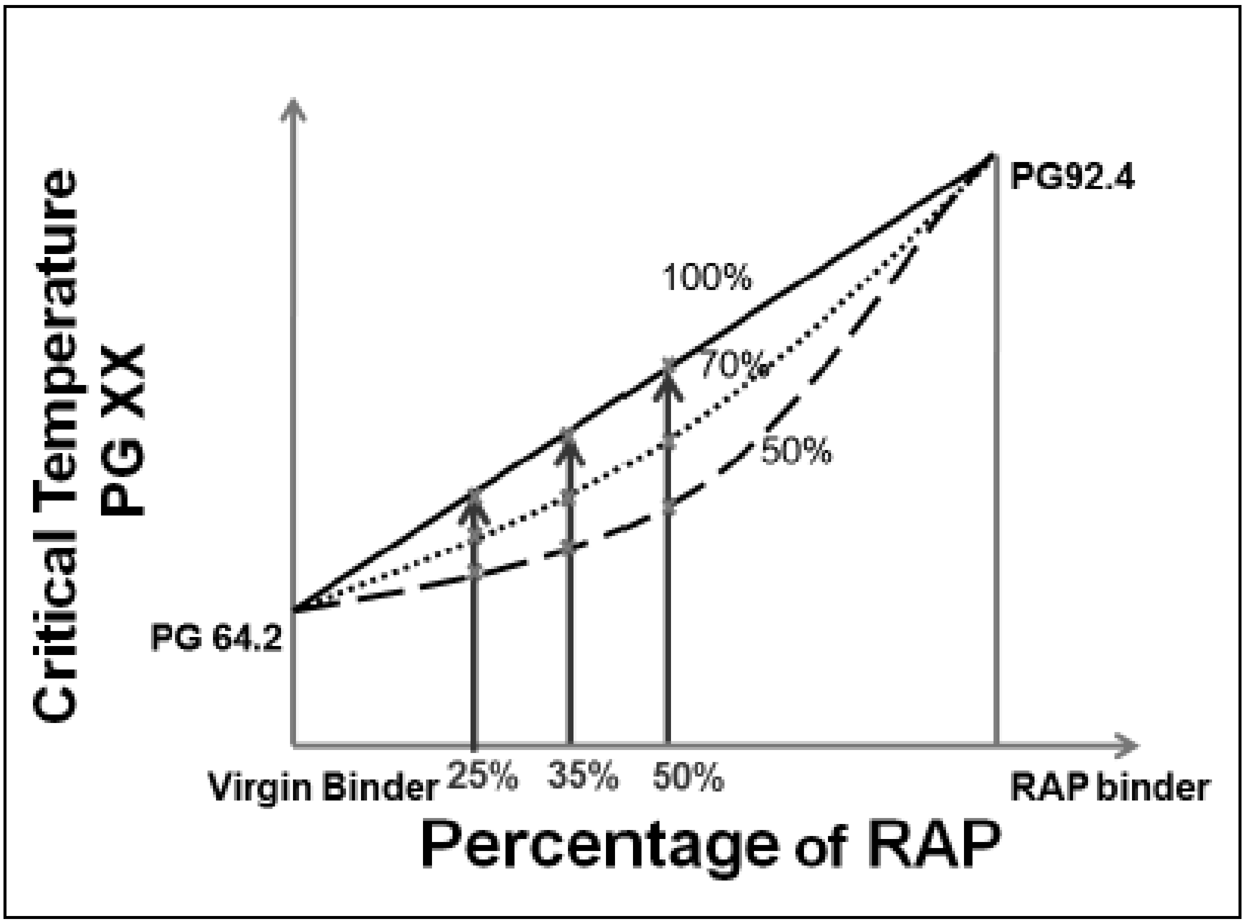

Figure 3-5. Graph Illustrating Details of Replicates Required to Develop Blending Chart for Different Degree of Blending

Table 3-10. Test Matrix to Evaluate a Blending Chart to Evaluate Degree of Blending

		Binder Classification (M320) for Various DOB		
Virgin Binder	**Extraction and Recovery (T319)**	**50 Percent (Minimum Replicates)**	**70 Percent (Minimum Replicates)**	**100 Percent (Minimum Replicates)**
PG 70-28	2	6	6	6
PG 58-28		6	6	6

Chapter 4

Coating Study

4.1 Introduction

To determine degree of partial blending of RAP HMA, it was essential to keep the mixing procedure, mixing duration and temperature of virgin aggregates, and RAP methodology the same as how it is conducted in an asphalt plant or as per New Jersey Department of Transportation (NJDOT) practice. In addition to that, it was essential to assume approximate virgin binder content to prepare the mix. Based on the literature review, a method to determine approximate RAP binder transfer was developed. This method is primarily based on study carried out by Huang et al. [56] The detailed experimental procedure and results are given in the following section.

4.2 Experiment and results

4.2.1 Initial procedure

In order to determine approximate RAP binder transfer, coarse aggregates and fine RAP aggregates are mixed together where the increase in weight of virgin aggregates is noted as RAP binder transfer. Initially mixing duration was unknown; the following procedure was used to evaluate the effect of mixing duration on percentage RAP binder transfer. The schematic representation of the coating study procedure is shown below:

1. Sieve the virgin aggregate above the #4 (4.75 mm) sieve as per the procedure described above.
2. Wash the aggregate to remove any fines that would pass the #4.
3. Dry the aggregate in the oven.

4. Sieve the RAP to be less than #4 sieve (4.75 mm).
5. Measure a total of 2000 grams of aggregate and RAP according to the gradation determined in the above paragraph.
6. Heat the aggregates, bucket and mixing arm to 350ºF in the oven.
7. Mix the RAP and virgin aggregates for 1, 2 and 3 minutes in the oven with a mechanical mixer.
8. Put the mix in the oven for 2 and ½ hours at 350ºF.
9. Remove the mix from the oven; allow the aggregate mix to cool until it is ready to be handled.
10. Separate the aggregates and the RAP from the aggregate/RAP mix through sieving (be sure to remove the entire RAP from the aggregate as some of it will be attached).
11. Weigh the aggregates and the RAP that has been separated from the mix.

To evaluate the effect of mixing time on the percentage RAP binder transfer, three percentages of RAP were studied for three different mixing durations. The three percentage of RAP used to represent low, intermediate and high percentages of RAP were 10, 25 and 40 percent. The three mixing durations were one, two and three minutes. The increase in weight of the virgin aggregates is due to the coating by the RAP binder, however, the reduction in weight of the RAP aggregates may be due to four things a) loss of moisture content; b) RAP binder lost to bucket and arm c) loss of fine particles of RAP during mixing and d) transfer of RAP binder to virgin aggregates. Therefore, the loss of RAP weight will be greater than the increase in the weight of virgin aggregates. The approximate RAP binder transfer is calculated using the following equation below.

Approximate RAP binder transfer (percent) = 100 x (Weight of RAP binder coating the virgin aggregates after mixing/ weight of binder around the RAP before mixing) (4.1)

Table 4-1 shows the results of the initial coating study. From the results, it could be observed that the percentage of RAP binder transfer was almost the same for 2 and 3 minute mixing durations. Hence the mixing duration could be kept above 2 minutes. Also, it could be seen that the percentage of binder transfer for 40 percent RAP was lower than that of 25 percent RAP. This could be due to the fact that as the percentage of RAP increases, the ability to capture RAP binder transfer to the virgin aggregates decreases. This could be due the fact that RAP binder is transferring from some RAP aggregates to other RAP aggregates during the mixing and this phenomenon is more apparent for higher percentages of RAP.

Table 4-1. Evaluation of Effect of Mixing Time on Percentage RAP Binder Transfer in Coating Study. Percent of RAP Binder Transferred for Different Mixing Times

Percent RAP	1 min.	2 mins.	3 mins.
10	14	31	29
25	11	35	35
40	3.5	26	25

4.2.2 Modified procedure

Depending upon the above observations the procedure of the coating study was modified to suit the blending study. In this modified procedure the following three modifications are done:

1. Duration of mixing was kept as 10 minutes (which was greater than allowed 2 minutes duration). It was same as that for the blending study mixing duration.

2. The gap gradation used for the blending study was used for the coating study. Hence, all the virgin aggregates were above sieve #4 (4.75 mm) and all the RAP aggregates were below sieve No.8 (2.36 mm).
3. RAP aggregates were heated for 30 minutes before the mixing to avoid effect of moisture on the blending study.

The modified procedure is used to determine approximate RAP binder transfer for 25 percent and 35 percent RAP. The JMF given in **table 3-7** was modified to create a gap gradation for 25 percent and 35 percent RAP using RAP aggregates and Bin 3, 4 and 5. The modified gap gradation is shown in **figure 4-1**.

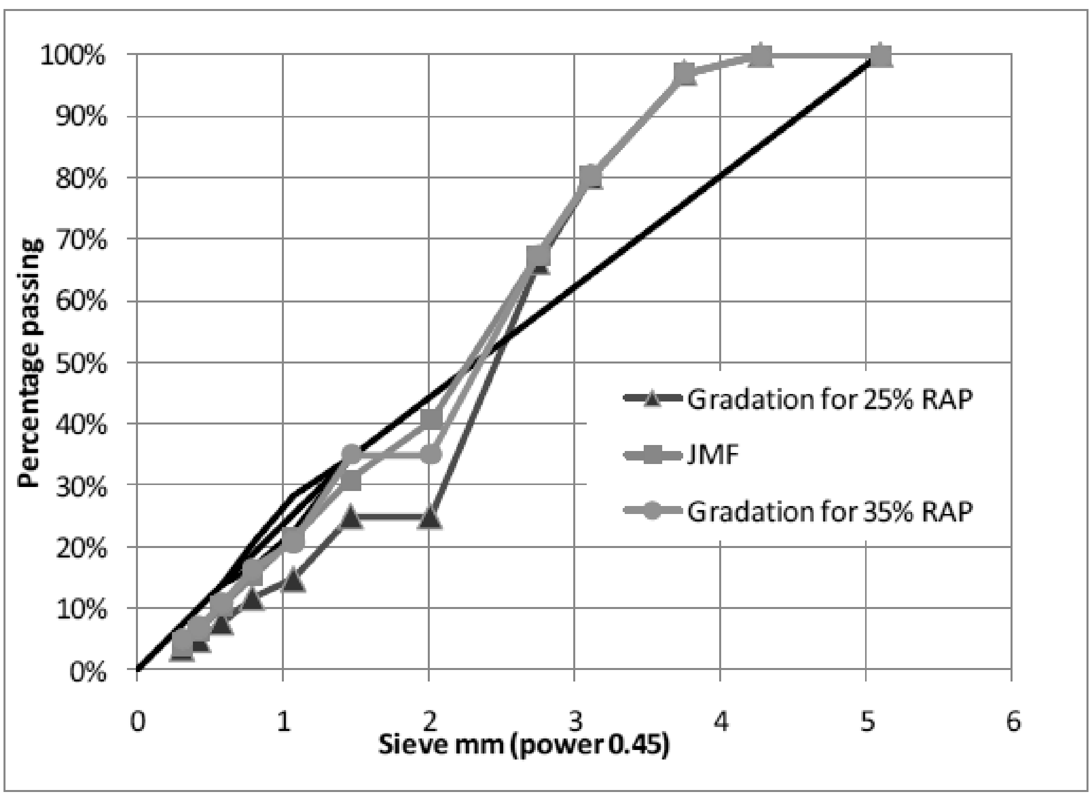

Figure 4-1. Gradation of the JMF and the Gap Gradation for 25 Percent and 35 Percent RAP

Table 4-2 shows the batch weight of different aggregate bins and results of the coating study. This coating study without the virgin binder only provides an estimate of the partial blending because some of the RAP working binder will also coat the RAP aggregates. Additionally, this cannot be measured in this process and the impact of the presence of hot virgin binder on the degree of partial blending cannot be captured.

Table 4-2. Material Used in Coating Study (Without Binder)

	Replicate 1			**Replicate 2**		
	Weight (percent)	**Batch 1 (g)**	**Batch 2 (g)**	**Weight (percent)**	**Batch 1 (g)**	**Batch 2 (g)**
Aggregate Bin 3	35.4	708.8	709	26.5	529.1	529.4
Aggregate Bin 4	12.6	253.1	253	11.6	232.5	232.4
Aggregate Bin 5	26.9	539.9	539	26.9	539.1	538.4
Initial weight of RAP	25	500.1	500.4	35	700.7	700.1
Total	100	2001.9	2001.4	100	2001.4	2000.3
Initial weight of virgin aggregates		1501.8	1501		1300.7	1300.2
Final weight of virgin aggregates		1508.9	1507.6		1305.7	1307
Approximate binder transfer (percent)		**25.2**	**23.4**		**12.7**	**17.3**

4.2.3 Approximate RAP binder transfer

The percentage of RAP binder in the RAP was obtained from the extraction and recovery process (AASHTO T319). The percentage of binder in the RAP was calculated to be 5.63 percent. The mass of binder in the RAP was determined from the weight of RAP aggregates and the RAP binder coating the coarse aggregates was determined from increase in weight of coarse virgin aggregates. The approximate RAP binder transferred was calculated using **equation 4.1**. **Table 4-2** shows the RAP binder transfer for 25 percent and 35 percent RAP was averaged to be 24 percent and 15 percent respectively. The free RAP binder that coats other RAP particles is not quantified by the binder transfer. Therefore, the total effective RAP binder would be higher than the binder transfer as determined by the coating study. This phenomenon becomes more significant as the percentage of RAP increases within the mix.

4.3 Summary

- The above chapter describes the detailed experimental procedure followed to determine approximate RAP binder transfer for 25 percent and 35 percent RAP mixes.
- The approximate binder transfer was considered as 24 percent and 15 percent for 25 percent and 35 percent RAP respectively.
- These percentages were used to determine the virgin binder content for the blending study.

Chapter 5

Blending Study

5.1 Introduction

A blending study was conducted to simulate plant mixing procedures. In this study, the gradation and materials are kept the same as that of the coating study but with the addition of virgin binder. Fundamental binder properties such as $G^*/\sin(\delta)$ of RAP HMA are evaluated to study the interaction between the RAP and virgin binders. The detailed experimental procedure and results for the blending study are given in the following section.

5.2 Experiment method

5.2.1 Materials

In this study, HMA mixtures with 25 percent and 35 percent RAP by weight of aggregates were tested. PG 70-28 and PG 58-28 obtained from NuStar Refineries were used for 25 percent and 35 percent RAP mixtures respectively. RAP was obtained from only one source in order to minimize variability.

5.2.2 Materials Procedure

The blending study was carried out using a modified JMF (**figure 4-1**) and the materials used in the coating study. The binder content from the JMF was used in the design. A full Superpave mix design was not deemed necessary because the gradation was modified with a sole intent to determine the degree of partial blending. The optimum binder content from the JMF supplied by the plant was 4.8 percent. The approximate RAP binder transfer from the above coating study was used to determine the amount of virgin binder content.

Table 5-1 shows the batch percentage and aggregate weights used for mixtures in the blending study. The weight of total mix was selected such that sufficient binder can be extracted for determining the binder properties.

Table 5-1. Materials Used in Blending Study (With Virgin Binder)

Material	**25 Percent RAP by weight Of aggregates (percent)**	**25 Percent RAP by weight of aggregates (g)**	**35 Percent RAP by weight of aggregates (percent)**	**35 Percent RAP by weight of aggregates (g)**
Aggregate bin 3	33.7	1685.0	25.2	1261.4
Aggregate bin 4	12.0	599.8	11.0	552.2
Aggregate bin 5	25.6	1280.4	25.6	1280.4
RAP	24.2	1210.40	33.7	1685.0
Virgin binder	4.4	219.6	4.4	221.0
Total batch weight	99.9	4995.2	99.9	5000.0
Total binder	4.8	240.0	4.8	240

5.2.3 Binder properties

After mixing, the virgin aggregates were separated manually from the RAP aggregates using minimal heat. Three 5000 gram batches were prepared and in order to minimize the heating duration while separating the mix, only small portions of the mix were heated in the oven. The binder from the separated mix was extracted and recovered using AASHTO T319. The RTFO $G^*/\sin(\delta)$ of the extracted binder was conducted at 76°C and 70°C. This temperature selection for 25 percent RAP with PG 70-28 virgin binder was chosen as the high PG-grade of the virgin binder. From the testing results it was found that binder testing temperature did not affect the determination of degree of partial blending. Hence further, all testing was carried out at the same temperatures (76^0C and 70^0C). The G*/sin (δ) of RTFO binder was selected for two reasons: The amount of binder required for a RTFO sample can be obtained with one single extraction and recovery using the AASHTO T319 procedure. The binder properties at high temperatures are generally more sensitive to blending than low temperature test results.

The concept behind DOB can be shown through the binder properties around RAP and virgin aggregates. For the zero percent blending condition, only the virgin binder would coat the aggregates and the residual binder around the RAP aggregates would not blend at all. This is known as black rock theory and states that the RAP aggregates would simply be "black rocks" as the residual binder only acts to change the appearance of the aggregates but has no effect on the properties of the mix. Since only the virgin binder is being used to coat, the properties of the binder around each virgin aggregate would be the same as the virgin binder. The RAP would have two layers, one of RAP binder and one of virgin binder on the outer layer. When 100 percent blending occurs, all the residual binder from the RAP will mobilize and become part of the mix, resulting in identical binder properties among the RAP and virgin aggregates due to the fact that they completely mix together. A partial DOB would then be when only some of the residual binder blends, meaning that the RAP aggregates would still retain some of their residual binder and therefore have different properties that fall somewhere in between the two aforementioned conditions.

In this study, the binder from the aggregates was extracted to be tested. The extraction process removes all of the residual and virgin binder coating the aggregates; therefore, in the zero percent blending condition, the resulting binder properties would be a mix of the virgin and RAP binder properties as a function of the proportion of the thickness of the two layers. The proportion of RAP binder and virgin binder can be calculated by determining the film thickness of RAP binder and virgin binder from Bailey's method. Bailey's method approximates the total surface area of aggregates within a mixture using surface area factors obtained from the overall gradation. This total surface area is then used in conjunction with the asphalt content of the mixture in order to determine the approximate film thickness around each aggregate. The film thickness is assumed to be the same for each aggregate in order to simplify calculations.

5.2.4 Methodology

The methodology of the blending study to determine the degree of partial blending is summarized as follows:

1. Determine the binder content of the RAP and the gradation of the extracted aggregates.
2. Determine the Superpave PG properties (from AASHTO M320) of the RAP binder and the virgin binder.
3. Create a Superpave gradation for a given percentage of RAP (i.e. 25 percent and 35 percent), such that all the fine aggregates (minus #8 -2.36 mm) are RAP and all coarse aggregates (greater than # 4 – 4.75 mm) are virgin aggregates. The Superpave gradation created in the lab will be similar to the JMF gradation for a given percentage of RAP. This gap gradation was created in order for the manual separation of virgin and RAP aggregates to be possible.
4. Consider design binder content from the JMF for the study. If the design binder

content is not known, determine the design binder content (DBC) based on the Superpave mixture design.

5. Coating study - Mix the RAP and the virgin aggregates. The mixing process was kept as close as possible to the practice followed by the plant in terms of the mixing time, the mixing process, and the temperatures of the virgin aggregates and the RAP. Calculate the increase in mass of virgin aggregates before and after mixing to determine the "the approximate" amount of RAP binder that coated the aggregates. This will help in determining the virgin binder content. Or assume initial binder transfer of around 50 percent.
6. Create the mixture at the virgin binder content (VBC) determined from the following equation:

$$Binder\ Content_{(virgin)} = JMF\ Binder\ Content\ (_{Design)} - RAP_{(Estimated\ Working\ Binder))} \quad (5\text{-}1)$$

   Where, the RAP working binder is obtained from coating study (step 5).
7. Separate the coated virgin and RAP aggregates after mixing by slight heating and manually separating into above #4 and below #8 sieves.
8. Extract and recover the binder separately from the coarse virgin aggregates (plus #4) and fine RAP aggregates (minus #8).
9. Determine the Superpave PG properties (from AASHTO M320) of the blended binder on the RAP and the virgin aggregates.
10. Determine the proportion of the virgin binder that would coat the RAP and the virgin aggregates under zero blending condition by estimating the surface area of the aggregates at each sieve size using Bailey's method.

11. Blend the RAP binder with the proportion of the virgin binder determined from step 10 above. Determine the Superpave PG properties (from AASHTO M320), such as G* / sin (δ).

12. Calculate the degree of partial blending from the following equations:

$$Blending\ Ratio = \frac{G^*/sin(\partial)_{blend\ binder\ virgin\ agg} - G^*/sin(\partial)_{blend\ binder\ RAP\ agg}}{G^*/sin(\partial)_{virgin\ binder} - G^*/\sin(\partial)_{RAP\ virgin\ binder\ o\ blend}} \quad (5\text{-}2)$$

$$Degree\ of\ Partial\ Blending\ (percent) = 100\,|1 - Blending\ Ratio| \quad (5\text{-}3)$$

Where:

(G*/sin(δ))blend binder virgin agg	-	RTFO G*/sin () of blended binder coating the virgin aggregates (determined from step 9)
(G*/sin(δ))blend binder RAP agg	-	RTFO G*/sin () of blended binder coating the RAP (determined from step 9)
(G*/sin(δ)) virgin binder	-	RTFO G*/sin () of the virgin binder (determined from step 2)
(G*/sin(δ))RAP virgin binder 0 blend	-	RTFO G*/sin () of the RAP and virgin binder that is coating the RAP aggregate assuming zero percent blending (determined from step 11)

G*/sin(δ) was chosen as the binder property to be tested for this study. Any binder property could be used in this equation.

13. Iteration - If the degree of partial blending (determined from step 12) is similar to the calculated value in step 5 then the degree of partial blending has been determined. However, if considerable difference exists between the two, the process will be repeated with the revised value of the RAP working binder that is obtained from step 12 and the steps will be repeated from step 6 onwards.

The detailed procedure used for the blending study with virgin binder is similar to the one followed in the coating study except that the weights changed and the virgin binder was also heated to mixing temperature. A schematic representation of the procedure is shown in **figure 5-1**.

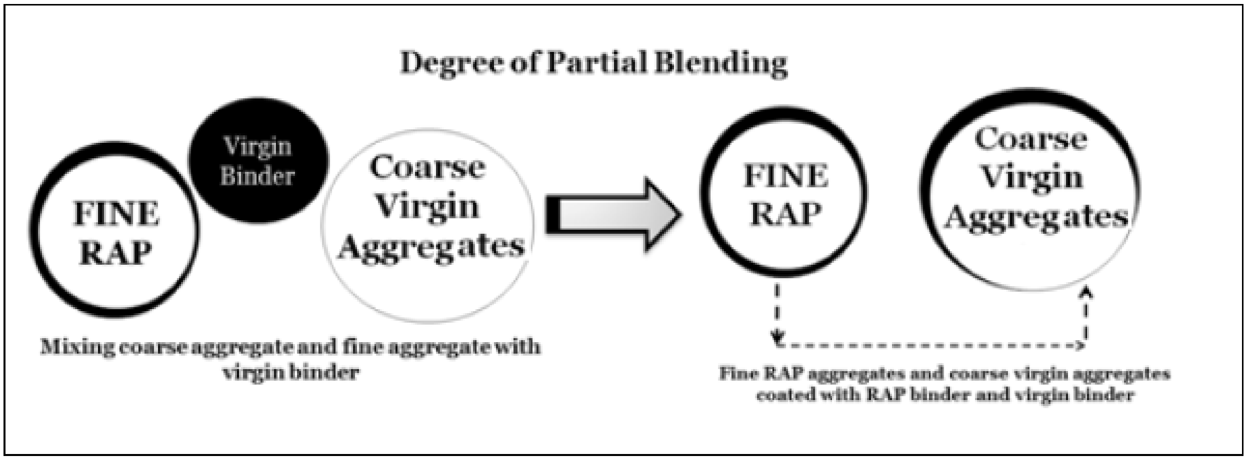

Figure 5-1. Schematic Representation of Procedure to Determine Degree of Partial Blending

5.2.5 Limitations

The limitations of the procedure are as follows:

- The process requires at least three extractions and recoveries of the binder; these include the RAP before the coating experiment, the virgin aggregates and the RAP after the coating experiment.
- To minimize the heating during separation, prepared sample should be large enough; heating should be done on portions of sample at a time which can be separated without cooling the sample. The sieving of the coated aggregates is very time consuming.

5.2.6 Determination of the degree of partial blending

If there is full blending, the properties of the binder around the virgin aggregates will be similar to that of the binder around the RAP. As the DOB decreases, the difference in the properties between the blended binder around the virgin aggregates and the RAP will approach that of the difference under the zero blending condition. After the properties of binder coating the virgin aggregates and the RAP aggregates under "black rock effect" or zero percent blending and full (100 percent) blending are identified, the degree of partial blending was determined from **equations 5-2** and **5-3** shown in the previous section.

The numerator of this equation is the difference of RTFO G*/sin (δ) of blended binder around virgin aggregates and RAP aggregates. The blended binder around the virgin and RAP aggregates is subjected to aging during mixing and heating (approximately 4.5 hr) carried out during separation process and therefore the blended binder is tested for RTFO DSR without subjecting to RTFO simulation.

The denominator is the maximum difference between virgin binder and proportioned virgin and RAP binder for zero blending. The original virgin binder is subjected to RTFO aging and tested for RTFO DSR. To obtain the RAP/Virgin binder stiffness for the zero DOB case, the proportion of the film thicknesses found for RAP and virgin binders must be calculated. This is determined through the use of Bailey's method. Aging conducted during mixing and conditioning (numerator) was assumed to be similar as aging conducted through the RTFO (denominator) because the coarse virgin aggregates and fine RAP were heated to 150°C during mixing with virgin binder.

5.3 Results and discussion

5.3.1 Results

The film thickness of RAP binder was calculated to be 10 microns using Bailey's method. **Table 5-2** gives the gradation, surface area factors, and calculation of total surface area for the mixtures used in this study.

Table 5-2. Surface Area Using Bailey's Method

Sieve Size, mm	Surface Area Factor (m2/kg)	Percent Passing	Surface Area (m2/kg)
37.5		100%	
25	0.41	100%	0.41
19		100%	0.00
12.5		100%	0.00
9.5		100%	0.00
4.75	0.41	100%	0.41
2.36	0.82	100%	0.82
1.18	1.64	37.6%	0.62
0.6	2.87	22.2%	0.64
0.3	6.14	14.0%	0.86
0.15	12.29	8.5%	1.04
0.075	32.77	3.2%	1.05
			0.00
Total		5.84	

Average film thickness of virgin binder around the RAP was assumed as 8 micron. This assumption was also cross checked using Bailey's Method with a RAP asphalt content of 4.4 percent. Hence, the ratio of the RAP binder and the virgin binder coating the RAP is 56:44. This higher number in this ration is reduced to ten for simplification. With this simplification, 56:44 is reduced to 10:8.

The RAP binder and the virgin binder were mixed according to the above ratio. This proportioned binder was subjected to short term conditioning using the RTFO. After short term aging was conducted, the Superpave PG properties (RTFO G*/sin (δ)) of the proportioned binder were calculated. **Figures 5-2**, **5-3**, and **5.4** show the Superpave PG properties for the binder coating the RAP and virgin aggregates as well as the degree of partial blending determined for the mixtures.

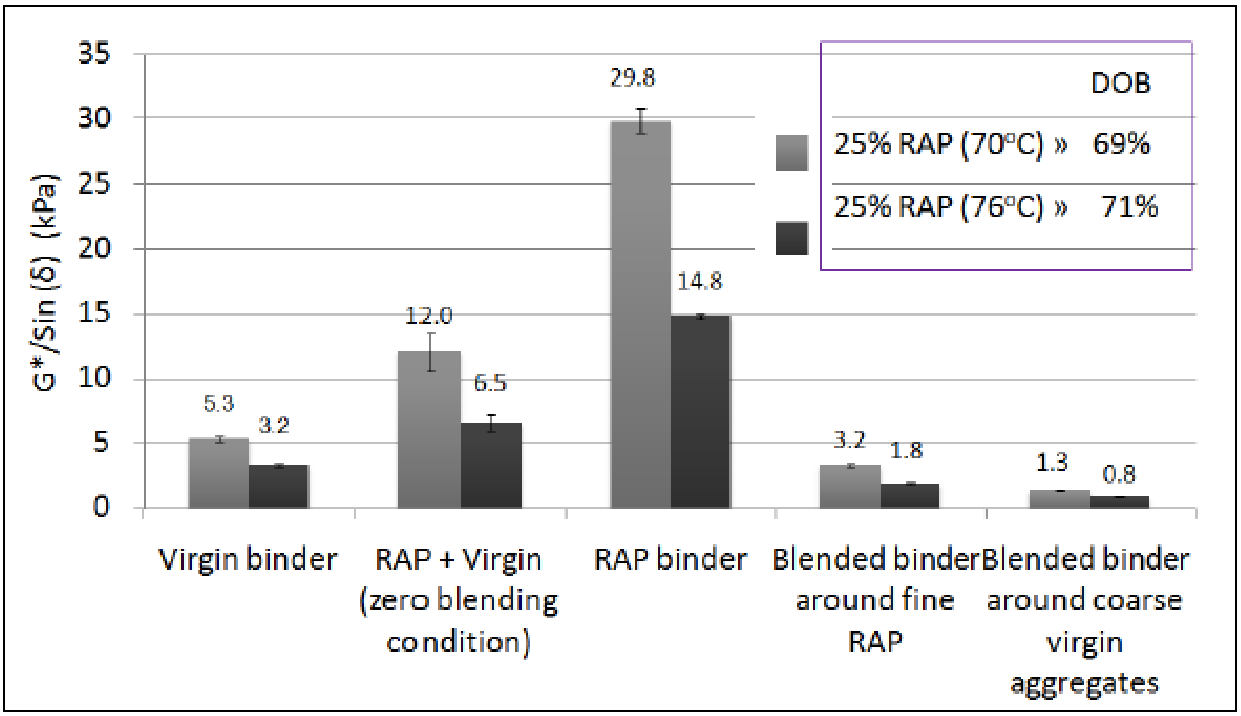

Figure 5-2. Comparison of RTFO G*/Sin(δ) at 76°C and 70°C For 25 Percent RAP.

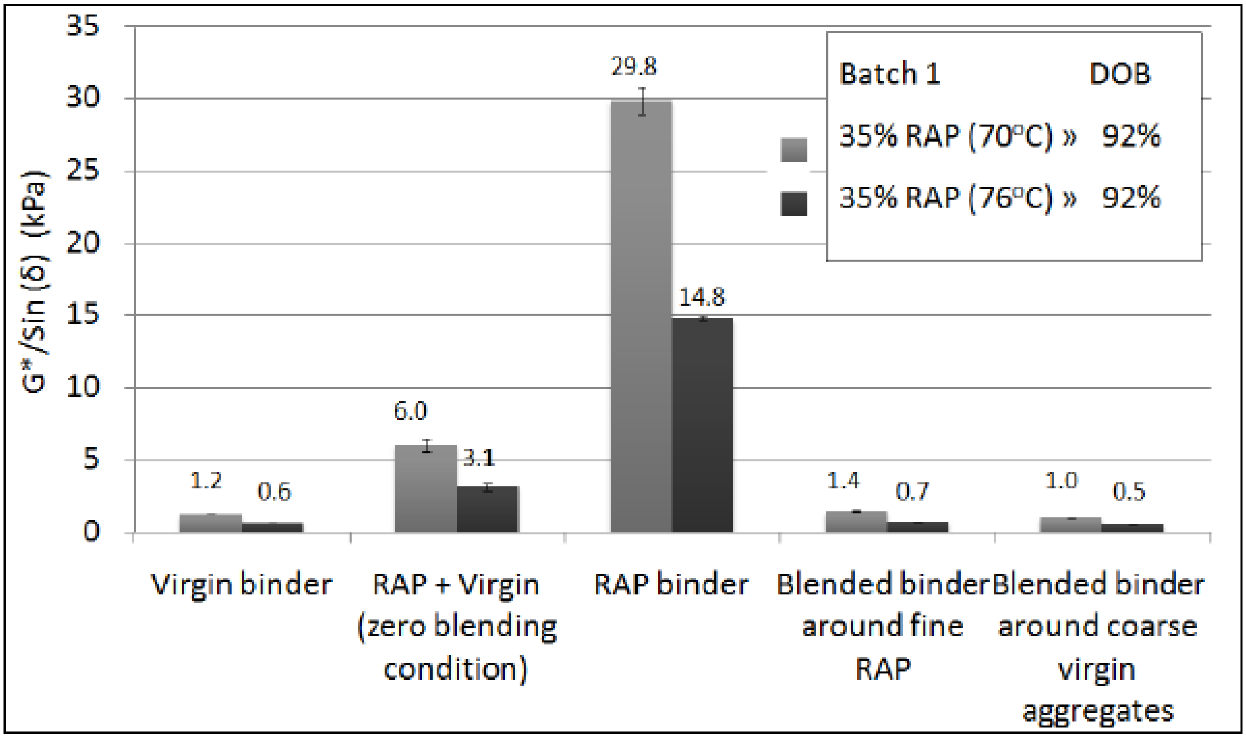

Figure 5-3. Comparison of RTFO G*/Sin(δ) at 76ºC and 70ºC For Batch 1 of 35 Percent RAP.

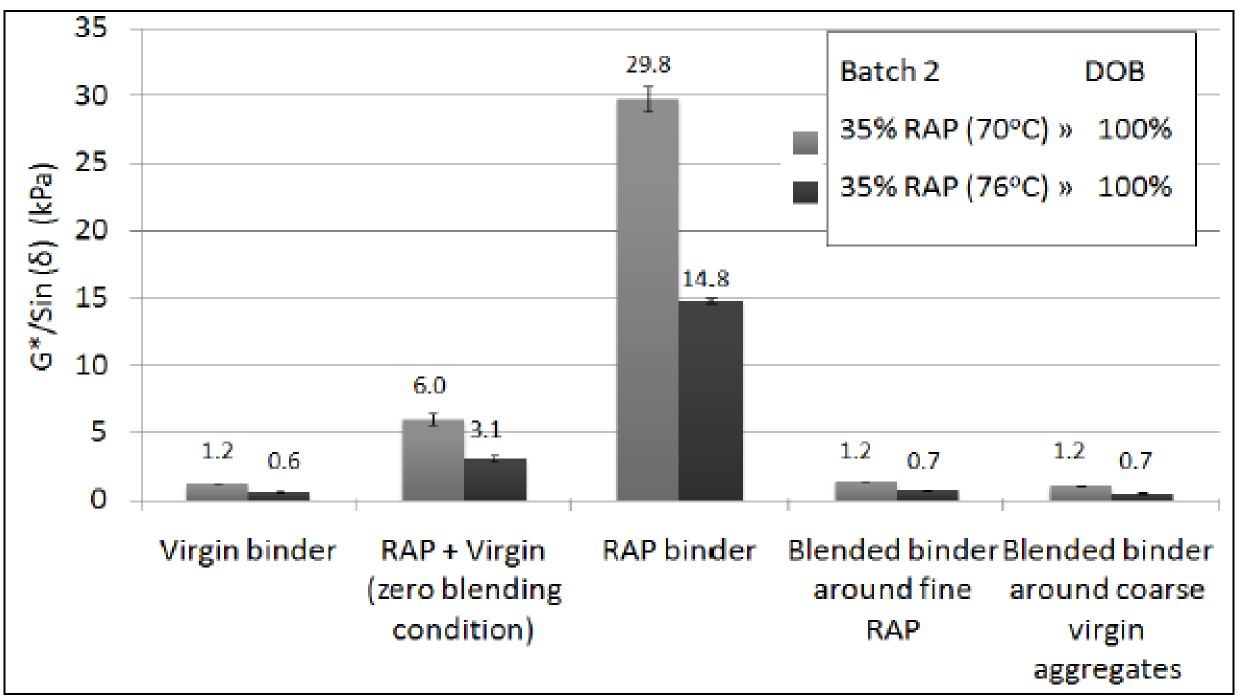

Figure 5-4. Comparison of RTFO G*/Sin(δ) at 76 ºC and 70ºC for Batch 2 of 35 Percent RAP.

5.3.2 Discussion

Degree of partial blending of RAP is dependent upon many factors like aggregate temperature during mixing, grade of binder, RAP binder properties, percentage of RAP, and virgin binder properties. From the above results, it can be seen that the degree of partial blending is higher for softer binders. Also, degrees of partial blending determined from different binder testing temperatures are similar. Hence, the degree of partial blending is independent of binder testing temperature. The calculation of the DOB was predicated by comparing the difference in binder properties between the coarse virgin aggregates and fine RAP at the zero blending condition. In some cases, the virgin binder values were higher than the blended binder values around the coarse aggregate; however, it is theoretically impossible for the virgin binder to be stiffer than the RAP binder. This phenomenon could have occurred in testing due to small errors and variability in the extraction recovery process. These errors become more significant as the stiffness of the virgin binder approaches that of the RAP binder at higher temperatures. The 70 percent DOB concluded from this testing was used in the 25 percent RAP mix design; however, this value was corrected through the use of the Superpave mixture design which will be explained in chapter 9.

5.3.3 Summary of findings

- The degree of partial blending for 25 percent RAP by weight of aggregates of chosen gradation and PG 70-28 virgin binder is 70 percent. This results used to make this conclusion were later found to be incorrect. This didn't affect the performance samples for 25 percent since 70 percent DOB was corrected to be 67 percent using Superpave.

- The degree of partial blending for 35 percent RAP by weight of aggregates of chosen gradation and PG 58-28 virgin binder is 96 percent.
- DOB determined by the blending study is much higher than that determined by the coating study. Hence, the step of determining of approximate binder could be skipped by assuming first approximate value of 50 percent for preparing mix.
- Degree of partial blending is independent of binder testing temperature.
- Degree of partial blending is higher for PG 58-28 as compare to PG 70-28.
- A new methodology of determining DOB was developed in this study.

5.4 Significance of study

The methodology proposed in this paper provides a systematic approach of determining the degree of partial blending in RAP. The ability to accurately determine the degree of partial blending will help in precisely determining the virgin binder content to be added in a mixture. It will also help in developing a blending chart to determine the properties of the final binder grade, the required virgin binder grade and the percentage of RAP based on the degree of partial blending measured from this procedure.

5.5 Summary

The above chapter describes the detailed experimental procedure followed to determine degree of partial blending using fundamental properties like $G^*/\sin(\delta)$ for 25 percent and 35 percent RAP mixes. The degree of partial blending for 25 percent and 35 percent RAP by weight of aggregates was determined as 70 percent and 96 percent, respectively. This percentage represents the amount of RAP binder that was effective in the mixture during and after mixing and aging. The following chapter discusses the attempt to determine degree of partial blending by evaluating film thickness of RAP HMA.

Chapter 6

Development of Blending Chart

6.1 Introduction

It has been shown that the demand to utilize higher percentages of RAP in the construction of HMA pavements has risen and still continues to rise today. In some states, including New Jersey, the mix is designed using virgin aggregates and virgin binder. After the design binder content is determined, the virgin binder content is established by giving full credit to the RAP binder, assuming 100 percent blending of virgin and RAP binder. However, research has shown that partial DOB occurs in RAP mixes.

In the previous section, a methodology to determine the degree of partial blending was discussed. The degree of partial blending between virgin binder PG 70-28 and RAP binder was determined to be 70 percent and between virgin binder PG 58-28 and RAP binder of the same source was determined to be 96 percent. This study explained that interactions between virgin and RAP binders depend upon the stiffness of virgin and RAP binders. This methodology used to determine the degree of partial blending is referred to as "Blending study". In order to study the effect of the degree of partial blending on PG grade of blended binder (mixture of virgin and RAP binder), a blending chart needs to be developed for partial DOB. A blending chart represents the relationship between percentage of RAP used in the mix and the corresponding critical temperature or PG grade of the blended binder. Researchers have consistently recommended the use of linear blending charts for determining the percentage of RAP binder or final grade of the blended binder for the full blending case.

6.2 Objectives

The objectives of this study are the following:

- Evaluate the effect of partial blending on higher critical grades of blended binder.
- Verify linearity of blending charts between virgin and RAP binder for full blending.
- To develop a suitable method to determine the critical grade of blended binder for different percentages of RAP binder using virgin and RAP binder for partial DOB.

6.3 Research Approach

The tasks conducted to achieve the objectives are as follows:

- Determine the higher critical temperature of blended binder by mixing RAP and virgin binders assuming for 100 percent, 70 percent and 50 percent DOB. It is referred to as "Method 1".
- Determine the higher critical temperature of blended binder by assuming linear relationship between the critical temperature of virgin and the RAP binder. This is called "Method 2".
- Determine the higher critical temperature of blended binder by assuming linear relationship between the critical temperature of virgin binder and a blend of 50 percent virgin and 50 percent RAP binder. This is called "Method 3".

6.4 Experimental procedure

6.4.1 Materials and Testing

In this study, two virgin binders, PG 70-28 and PG 58-28 were used. RAP binder is extracted and recovered from one source of RAP. The different degrees of blending considered in this study are 100 percent, 70 percent and 50 percent. The 100 percent and 70 percent degrees of blending were selected from the study discussed in the previous section. In addition to that, 50 percent DOB was chosen to evaluate effect of lower DOB on PG grade of blended binder. Critical temperature of the binder was determined based on G*/sin (δ) of un-aged binder by conducting Dynamic Shear Rheometer Tests DSR).[82] DSR testing on RTFO aged binder was not conducted because the trend of un-aged and RTFO aged binder is expected to be similar.

6.4.2 Method 1: Determination of Final Grade of the Blended Binder Made by Mixing Virgin and RAP Binder

The blending chart is developed by mixing RAP binder and virgin binder in different proportions by the total weight of binder. This will be referred to as "lab mixing" in this paper. Most of the researchers and HMA plants consider percentage of RAP binder from the RAP rather than percentage of RAP (mixture of RAP aggregates and binder). This percentage of RAP binder is based on RAP binder content of RAP which is determined by ignition oven method. Hence, there was no need to consider scenarios of different RAP content in this study. The values within the lab mixing test matrix, shown in table 6-1, were calculated using equations 6.1 and 6.2. Equation 6.1 gives the weight of RAP binder when total binder and DOB is known. Total amount of binder was approximately

10 grams, which is enough to carry out un-aged DSR testing. Equation 6.2 gives weight of virgin binder when weight of RAP binder and total binder is known.

Table 6-1. Actual Weight of RAP Binder and Virgin Binder Used in the development of blending chart

	Percentage of RAP Binder By Total Weight of Binder	**25**	**35**	**50**
100 Percent DOB	Weight of RAP binder (g)	2.6	3.7	5
	Weight of virgin binder (g)	7.7	6.8	5
	Total weight of binder (g)	10.3	10.5	10
70 Percent DOB	Weight of RAP binder (g)	1.8	2.6	3.7
	Weight of virgin binder (g)	8.2	7.7	6.8
	Total weight of binder (g)	10	10.3	10.5
50 Percent DOB	Weight of RAP binder (g)	1.2	1.8	2.6
	Weight of virgin binder (g)	8.8	8.2	7.7
	Total weight of binder (g)	10	10	10.3

$$W_{RAP\ binder} = (\text{percent of RAP} /100)\ X\ W_{Total\ binder}) * (\text{percent DOB}/100) \quad (6.1)$$

$$W_{Virgin\ binder} = (W_{Total\ binder}) - (W_{RAP\ binder}) \quad (6.2)$$

Where:

Percent of RAP = Percentage of RAP binder by total weight of binder

Percent DOB = Percentage of DOB between virgin and RAP binder

$W_{Total\ binder}$ = Total weight of virgin and RAP binder, g.

$W_{RAP\ binder}$ = Weight of RAP binder, g.

$W_{Virgin\ binder}$ = Weight of virgin binder, g.

In this study, three different degrees of blending were considered. It represents full (100 percent) and partial (70 percent and 50 percent) blending. The RAP binder and virgin binder were selected such that the percentage of RAP binder would be 25 percent, 35 percent and 50 percent of the total weight of binder. This represents the range of percentage of RAP binder which is most likely to be affected by degree of partial blending. **Table 6-1** gives the actual weight of binder used during the testing.

6.4.3 Method 2: Considering Linear Relationship between High Critical Grade of Virgin Binder and RAP Binder (NCHRP Report 452)

Method 2 is explained in NCHRP report 452. It assumes full blending between RAP binder and virgin binder. Higher critical grade of blended binder for different percentage of RAP binder is determined by considering a linear relationship between the critical grade of RAP binder (100 percent) and virgin binder. Critical grade of virgin and RAP binder is determined by conducting DSR testing on un-aged binder. **Equation 6.3** gives the formula to determine the critical grade of un-aged binder for different percentages of RAP binder.

$$T_{Blend} = T_{Virgin}\,(1 - (\text{percent of RAP}/100)) + ((\text{percent of RAP}/100) * T_{RAP}) \qquad (6.3)$$

Where:

T_{Blend} = Critical temperature of the blended asphalt binder, □C

T_{Virgin} = Critical temperature of the virgin asphalt binder, □C..

Percent of RAP = Percentage of RAP binder by total weight of binder.

T_{RAP} = Critical temperature of recovered RAP binder, □C.

An example to determine critical grade of blended binder in RAP HMA for 25 percent RAP by total weight of binder is shown below:

Here, T_{Virgin} = 72.3ºC

Percent of RAP = 25

T_{RAP} = 93.7ºC

Hence, T_{Blend} = 72.3 (1 – (25/100)) + ((25/100) * 93.7) = 77.6ºC

6.4.4 Method 3: Considering Linear Relationship between Virgin Binder Only and a Blend of 50 Percent RAP Binder and 50 Percent Virgin Binder Mixed in the Laboratory

This method also assumes a linear relationship between the critical temperature of RAP and virgin binder. This linear relationship is shown in figure 6-1 below. In this method, to avoid error due to linear interpolation between virgin and 100 percent RAP binder, 50 percent RAP binder is used as an end point instead of 100 percent RAP binder. Critical temperatures of virgin and 50 percent RAP binder are determined by testing the sample for un-aged DSR. The equation to obtain final grade of the blended binder in the RAP HMA is derived as follows:

$$T_{Blend} = T_{Virgin} + (\text{percent of RAP}/100) * (T_{50\ percentRAP} - T_{Virgin}) / ((50 - 0)/100)$$

$$T_{Blend} = T_{Virgin} + 2 * (\text{percent of RAP}/100) * (T_{50\ percentRAP} - T_{Virgin}) \qquad (6.4)$$

Where:

T_{Blend} = Critical temperature of the blended asphalt binder, □C

T_{Virgin} = Critical temperature of the virgin asphalt binder; □C

Percent of RAP = Percentage of RAP binder by total weight of binder; and

$T_{50\ percentRAP}$ = Critical temperature of 50 percent RAP binder, □C.

An example to determine critical grade of the blended binder in RAP HMA for 25 percent RAP by total weight of binder is shown below:

Here, T_{Virgin} = 72.3ºC

PercentRAP = 25 percent

$T_{50\ percentRAP}$ = 85.3ºC

Hence, T_{Blend} = 72.3 + 2*(25/100) (85.3 – 72.3) = 78.8ºC

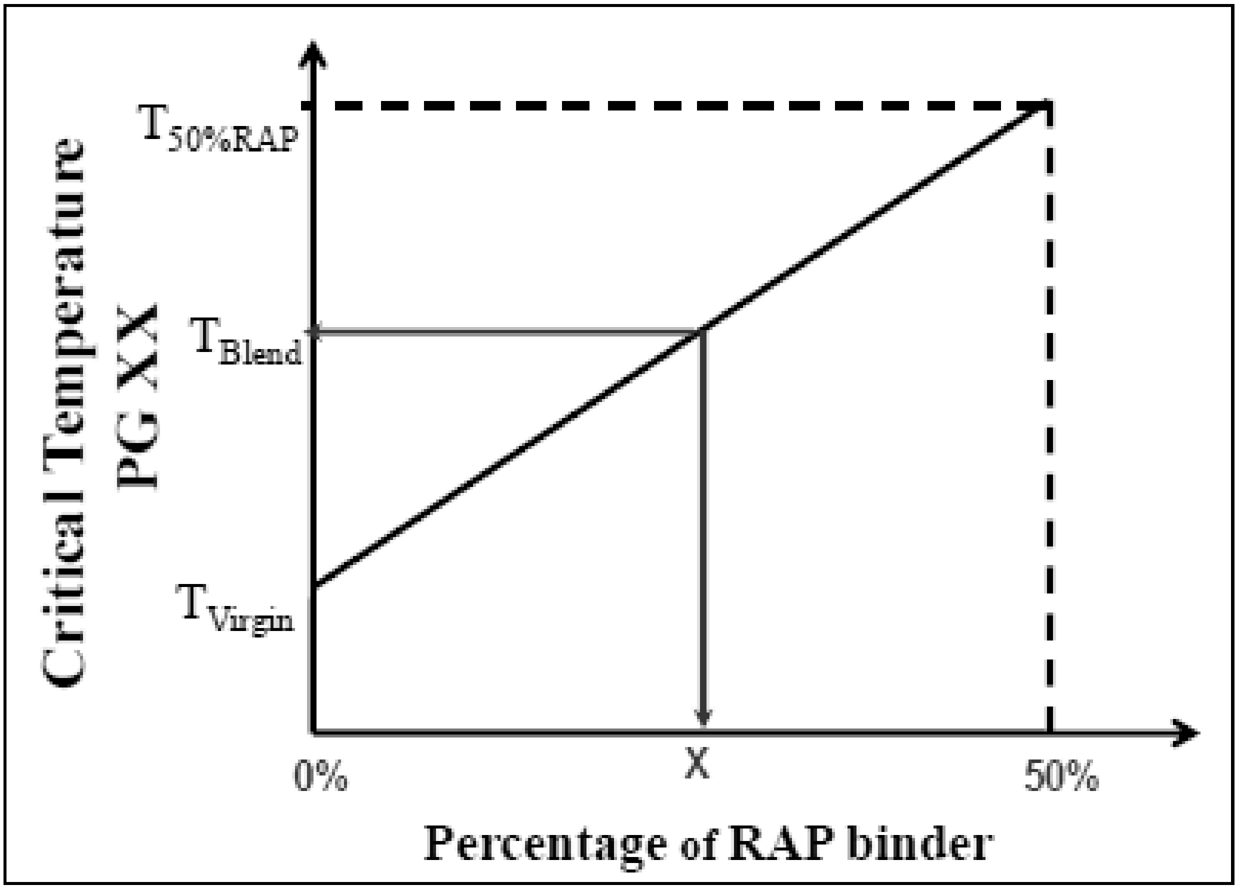

Figure 6-1. Method 3 Blending Chart to Determine Critical Temperature for Intermediate Percentage of RAP by Interpolating Virgin and 50 Percent RAP Binder

6.5 Results and Discussion

6.5.1 Comparison of Different Grades of Binder for Various Degrees of Blending Determined by Actual Mixing of Binders in the Laboratory

Figure 6-2 and figure 6-3 show the plots for different degrees of blending for PG 70-28 and PG 58-28, respectively. Table 6-2 and table 6-3 show the final critical temperature for 100 percent, 70 percent, and 50 percent DOB and the difference between full blending

(100 percent) and partial blending (70 percent, 50 percent) for PG 70-28 and PG 58-28, respectively.

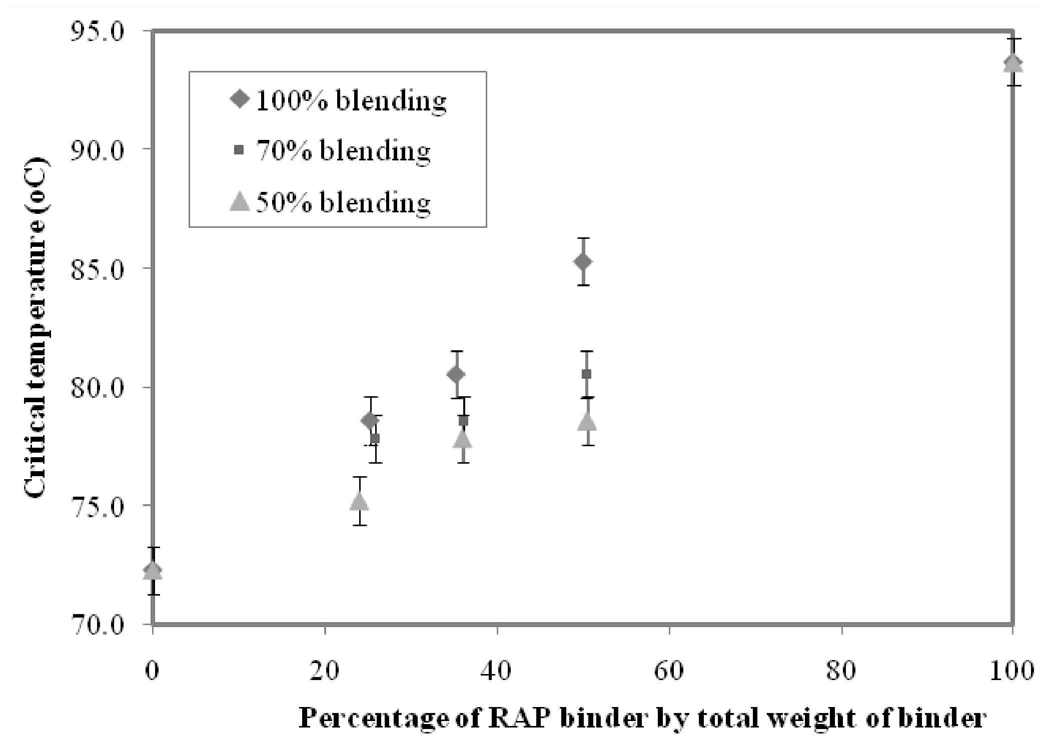

Figure 6-2. Blending Chart for PG 70-28

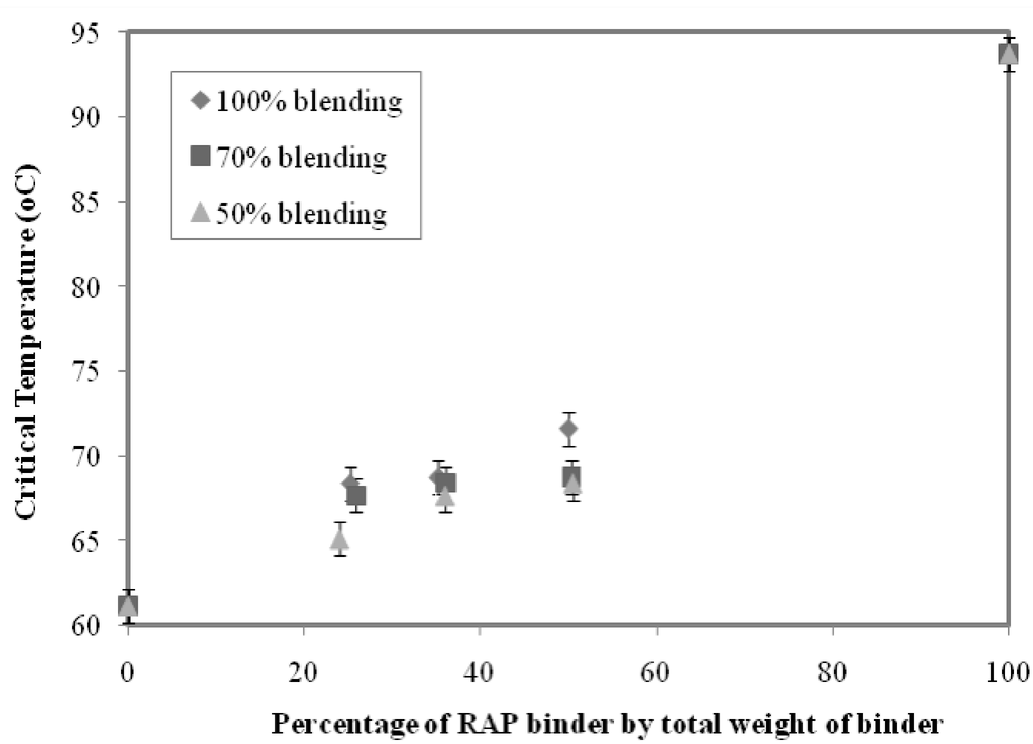

Figure 6-3. Blending Chart for PG 58-28

Table 6-2. Final Critical Binder Grade Determined For Different Degrees of Blending For PG 70-28

Percentage of RAP binder by total weight of binder	100 Percent DOB (ºC)	70 Percent DOB (ºC)	50 Percent DOB (ºC)	Difference between 100 percent and 70 percent DOB (ºC)	Difference between 100 percent and 50 percent DOB (ºC)
100%	93.7			-	-
50%	85.3	80.5	78.6	4.8	6.7
35%	80.5	78.6	77.8	1.9	2.7
25%	78.6	77.8	75.2	0.8	3.4
0%	72.3			-	-

Table 6-3. Final Critical Binder Grade Determined For Different Degrees of Blending For PG 58-28

Percentage of RAP binder by total weight of binder	100 Percent DOB (ºC)	70 Percent DOB (ºC)	50 Percent DOB (ºC)	Difference between 100 percent and 70 percent DOB (ºC)	Difference between 100 percent and 50 percent DOB (ºC)
100%		93.7		-	-
50%	71.6	68.7	68.4	2.9	3.2
35%	68.7	68.4	67.6	0.4	1.1
25%	68.4	67.6	65.1	0.7	3.3
0%		61.1		-	-

6.5.2 Validation of Linear Relationship in Full Blending

Figure 6-4 and figure 6-5 shows the comparison of the final critical temperature determined for 100 percent blending by Method 1, Method 2 and Method 3. Also, table 6-4 found in the following section shows the equation of a trend line. The equation of that line is in the form of $Y = m X + C$, where m is the slope of line, C is the intercept, X (percentage of RAP binder) is the independent variable and Y (critical temperature) is the dependent variable. The discussion of the results is in the following section.

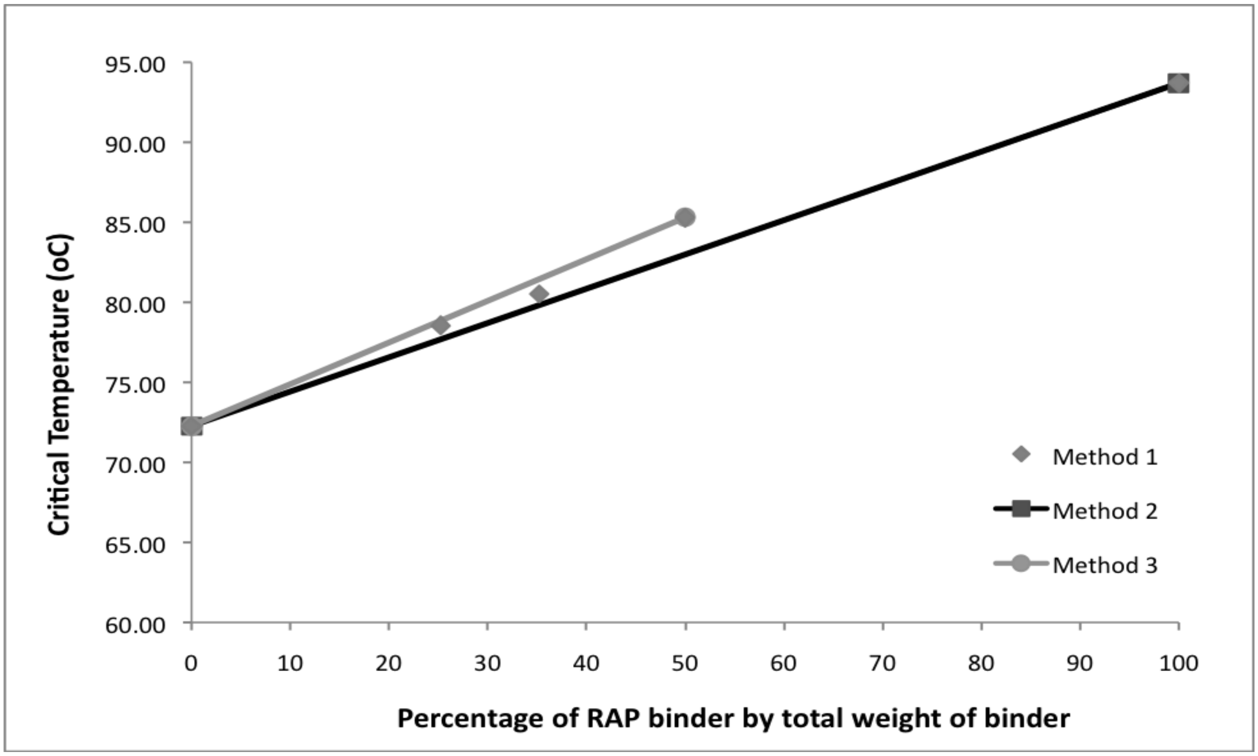

Figure 6-4. Blending Chart for PG 70-28 for 100 Percent DOB

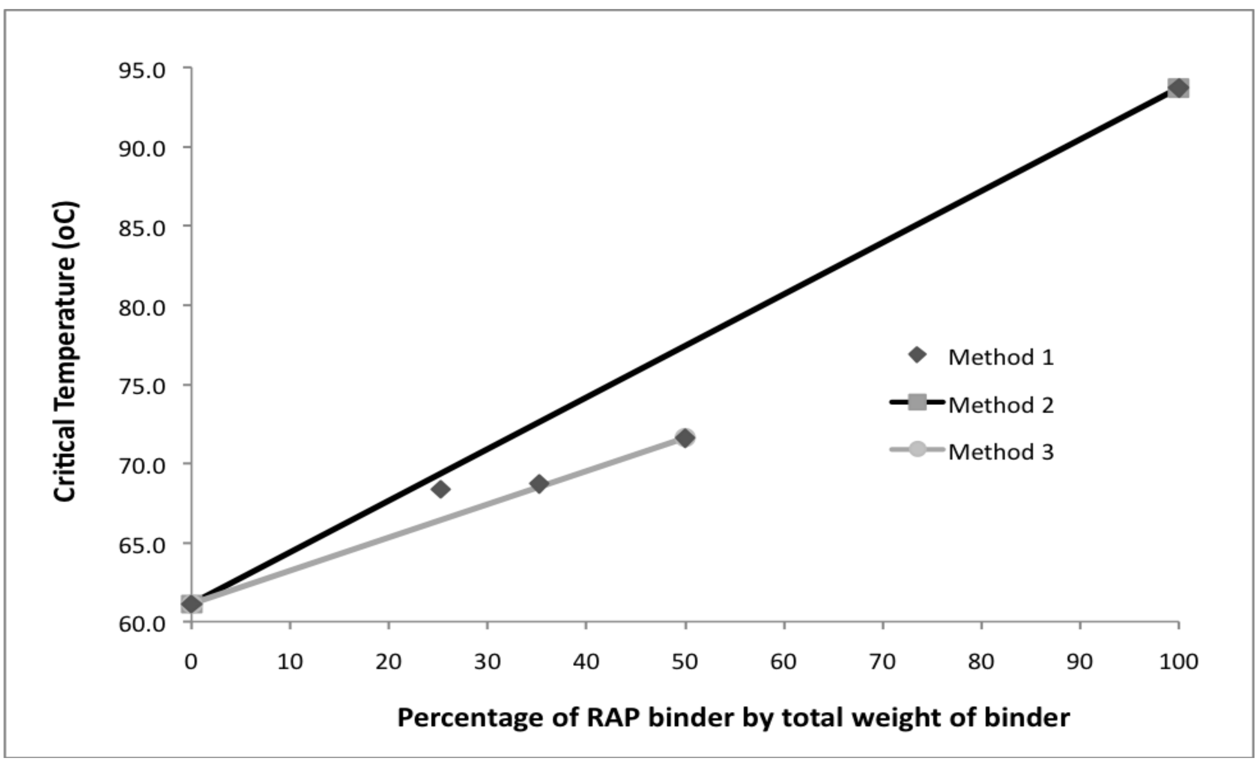

Figure 6-5. Blending Chart for PG 58-28 for 100 Percent DOB

6.5.3 Discussion

Based on experimental results, the comparison of full (100 percent) and partial (70 percent and 50 percent) blending determined by the mixing of binders in the laboratory indicate that the change in grade is not significant at lower percentages of RAP binder (25 percent and 35 percent) with PG 70-28. However, at high percentages of RAP binder with 50 percent DOB and PG 70-28 virgin binder, the change in grade is higher than six degrees, which will cause a grade change.

The difference of the grade of the blended binder between full (100 percent) and partial (70 percent and 50 percent) blending is within six degrees for different percentages of RAP binder for PG 58-28 virgin binder. Overall, the change in grade is sensitive to both the grade of the virgin and RAP binders. With PG 70-28 virgin binder and 50 percent RAP binder, at 50 percent DOB, the critical grade of the blended binder was lower than that for full blending.

Table 6-4 shows that the critical temperature determined by actual mixing has R square values of 0.98 and 0.94. The regression analysis gave a significance value, $P = 0.00$ for both the binders. The significance value ($P < 0.05$) indicates that with 95 percent confidence, it can be stated that the percentage of RAP binder is sufficient in predicting the critical binder grade of the binder.

A high R-squared indicates that the independent variable is useful in predicting the dependent variable. This validates the assumption of a linear relationship for full blending condition. A comparison of Method 2, which is given in NCHRP report 452 with actual mixing (Method 1) shows that the final grade predicted by Method 2 is within six degrees to that of actual mixing, except for 50 percent RAP binder with PG 70-28 virgin binder. This prediction could be made more accurate by considering the grade of 50 percent RAP binder (Method 3) instead of 100 percent RAP binder.

Table 6-4. Comparison of Results of Actual Mixing (Method 1) with Method 2 and Method 3

	PG 70-28		
Percentage of RAP binder by total weight of binder	Method 2 (NCHRP 452) (ºC)	Method 1 100 Percent DOB (Based on actual mixing) (ºC)	Method 3 (assuming linear relationship between zero percent and 50 percent RAP binder) (ºC)
100%	93.7		
50%	83.0	85.3	85.3
35%	79.8	80.5	81.4
25%	77.6	78.6	78.8
0%	72.3		
Blending chart	y = 0.21x + 72.3	y = 0.23x + 72.3	y = 0.26x + 72.3
R^2	1	R^2 = 0.98	1
	PG 58-28		
Percentage of RAP binder by total weight of binder	Method 2 (NCHRP 452) (ºC)	Method 1 100 Percent DOB (Based on actual mixing) (ºC)	Method 3 (assuming linear relationship between 0 percent and 50 percent RAP binder) (ºC)
100%	93.7		
50%	77.4	71.6	71.6
35%	72.5	68.7	68.5
25%	69.3	68.4	66.4
0%	61.1		
Blending chart	y = 0.33x + 61.1	y = 0.29x + 61.1	y = 0.21x + 61.1
R^2	1	R^2 = 0.94	1

6.6 Summary of Findings

A summary of findings of the study is shown below:

- A detailed procedure to determine the blending chart for different degrees of partial blending was developed.
- The difference in critical grade of binder between 100 percent and 50 percent DOB for 50 percent RAP binder with PG 70-28 is above 6ºC. All others were within 6ºC.
- The comparison of the critical temperature determined by actual mixing, Method 1, as well as Method 2 and Method 3 shows that as the difference between critical temperature of RAP binder and virgin binder increases (21.4ºC for PG 70-28 and 32.6ºC for PG 58-28), the prediction of the final grade by Method 2 would be higher than that of the actual. In such cases, determination of the final grade by Method 3 would be closer to that determined by actual mixing.

Chapter 7

Variability of RAP in Stockpiles

7.1 Introduction

Reclaimed asphalt pavement (RAP) is milled from the old pavement and stored as either single or mixed stockpiles. RAP material may be obtained from either different layers or private sector works, which may or may not be built as per state standards, and placed into a single stockpile. This introduces variability within the RAP resulting in an increase in variability within any HMA mixtures using RAP. This variability ultimately decreases the overall amount of RAP that can be placed in HMA. In order to increase the amount of RAP in HMA, it is essential to measure the material variability of RAP. A varying asphalt content and extracted aggregate gradation leads to RAP variability within the stockpile. The determination of the accurate asphalt content is very essential to account for RAP variability. Of the two commonly used extraction and recovery methods, Solvent extraction method (AASHTO T319) is a cumbersome process and is highly variable as compared to Ignition Oven method (IO). However, since the percentage of asphalt content in the RAP is not known, the process of determining IO correction factor is difficult to determine accurately. Since plants regularly use IO as a standard method of determining Asphalt content, an incorrect IO may have significant impact in the volumetric properties of asphalt concrete. There is a need to determine a methodology of determining an accurate IO correction factor for RAP stockpiles. With this accurate IO correction factor, correct allowable percentages of RAP can be concluded for a given plant.

7.2 Objective of Study

- To determine the correction factor for Ignition Oven to calculate accurate asphalt content.
    - (An elaborated step by step procedure to calculate the correction factor for Ignition Oven is discussed in the paper)
- To show the magnitude of variability within RAP stockpiles
- To determine the maximum amount of RAP that can be added to the mixture for different plants in the state of New Jersey.

7.3 Sampling protocol

RAP samples were collected from the different plants in the following manner. Three RAP samples were collected at the base of the stockpile. An effort was made to have the samples equidistant from each other. The fourth sample was the mixture of the three samples. A schematic showing this sampling method is can be seen below in **figure 7-1**.

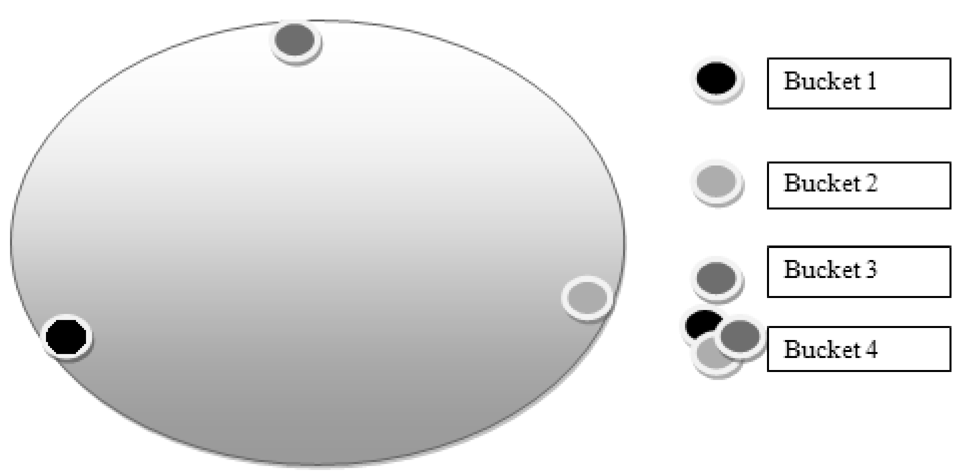

Figure 7-1. Stockpile Sampling Schematic

The aforementioned sampling protocol was selected to capture the variability of the RAP samples within the stock-pile. The experimental design to capture the RAP variability is explained in the following section.

7.4 Materials Used In Study

RAP was obtained from four different plants in New Jersey. Gradations of the RAP aggregate for the different combination of ER procedures is presented in **figure 7-2**.

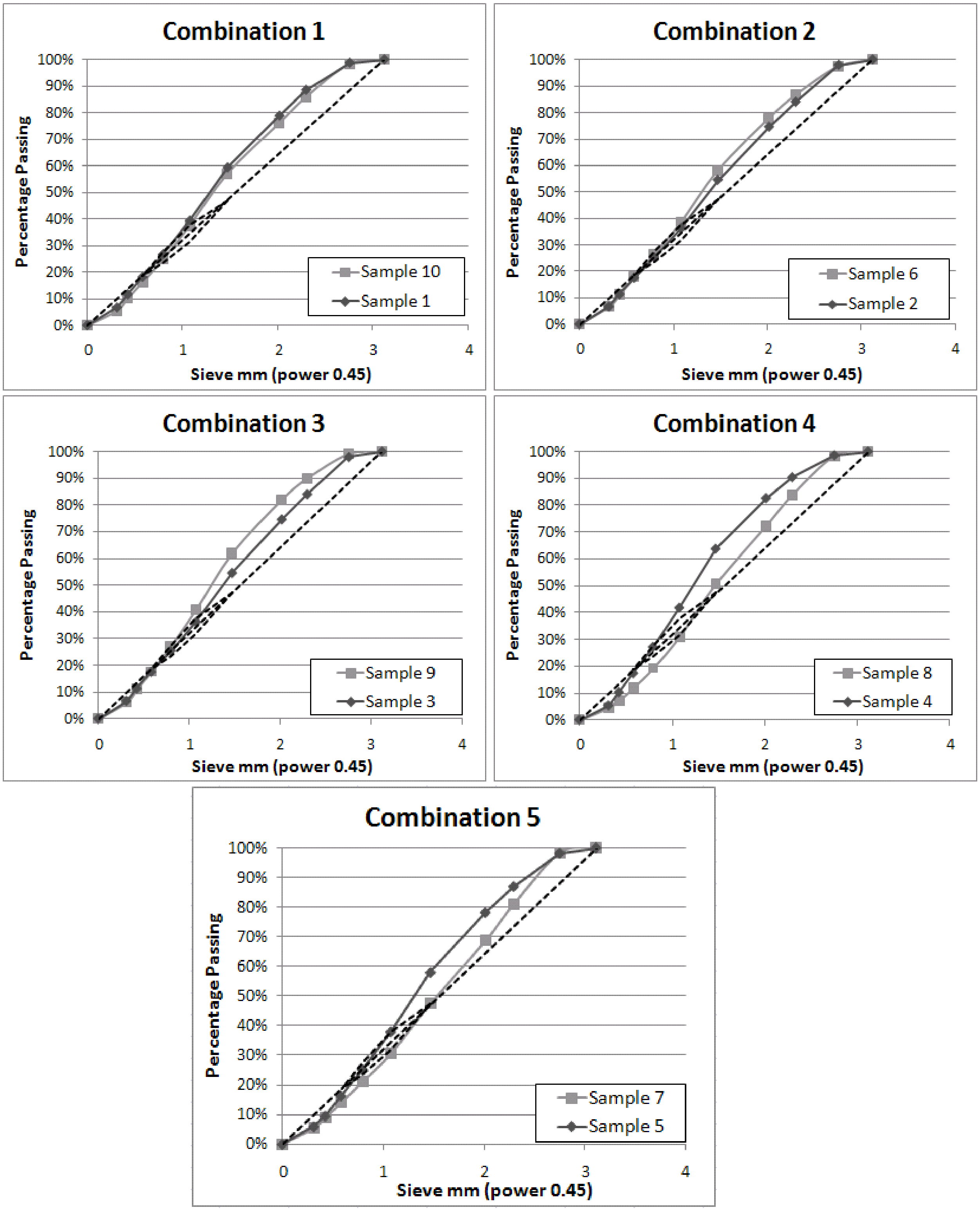

Figure 7-2. Gradation of RAP Aggregates for Different Combination of Extraction and Recovery Procedure

7.5 Experimental Design

The variability of the RAP is captured by standard deviation in gradation and asphalt content based on NCHRP, Project 9-33. For each plant, the binder content and the aggregate gradation from all the buckets were measured and compared with respect to each other. Two different methods were used: Solvent Extraction and Recovery by AASHTO T319 and the Ignition Oven Method (IO). **Table 7-1** explains the experimental design for the study.

Table 7-1. Experimental Design for Study

	Plant 1		**Plant 2**		**Plant 3**		**Plant 4**	
	Asphalt Content and Gradation (Number of Replicates)							
	T319	IO	T319	IO	T319	IO	T319	IO
Bucket 1	1	1	1	1	1	1	1	1
Bucket 2	1	1	1	1	1	1	1	1
Bucket 3	1	1	1	1	1	1	1	1
Bucket 4	1	1	1	1	1	1	1	1

7.6 Determination of Correction Factor for the Ignition Oven

The following steps were used to determine the correction factor for the ignition oven.

1. The comparison of asphalt content by Ignition oven method and Solvent extraction method (AASHTO T319) is shown in **figure 7-3**.

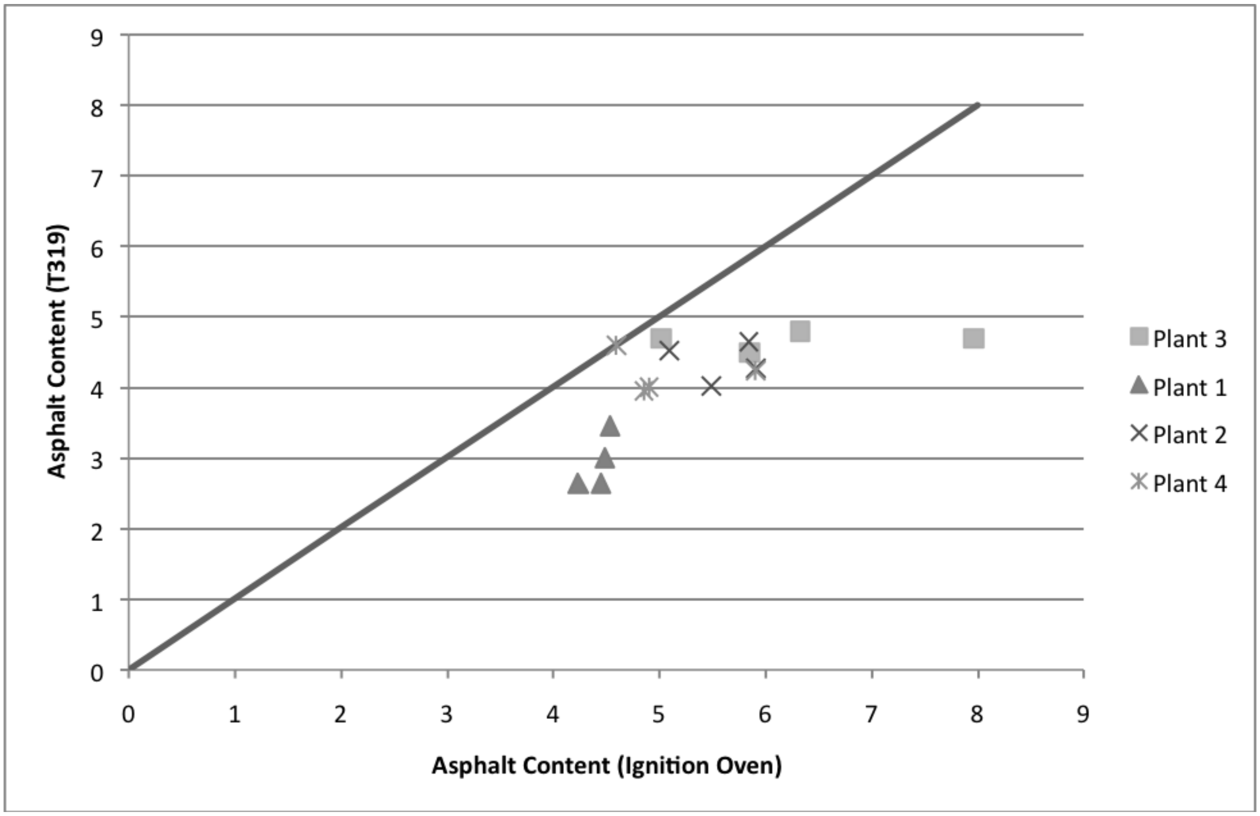

Figure 7-3. Comparison of AC for Ignition Oven and Extraction and Recovery

Figure 7-3 shows ignition test asphalt content plotted versus asphalt content by extraction and recovery by AASHTO T319. The asphalt content measured by Ignition Oven appears to be higher than that measured by the centrifuge extraction and recovery test.

The results gathered in this experiment were as expected with the research that was conducted. The portions of the aggregate break down during exposure to the high temperatures in the ignition oven, which is measured as weight loss and equated to asphalt content in this test. However, a part of weight loss is due to the loss of fines. This can be clearly seen when the extracted aggregate from AASHTO T319 method is burned in the Ignition Oven. The gradation of the extracted aggregate from the AASHTO T319 (termed as **before** in the graph) and burning the same aggregate in the Ignition oven (termed as **after** in the graph) is shown in the following **figure 7-4**.

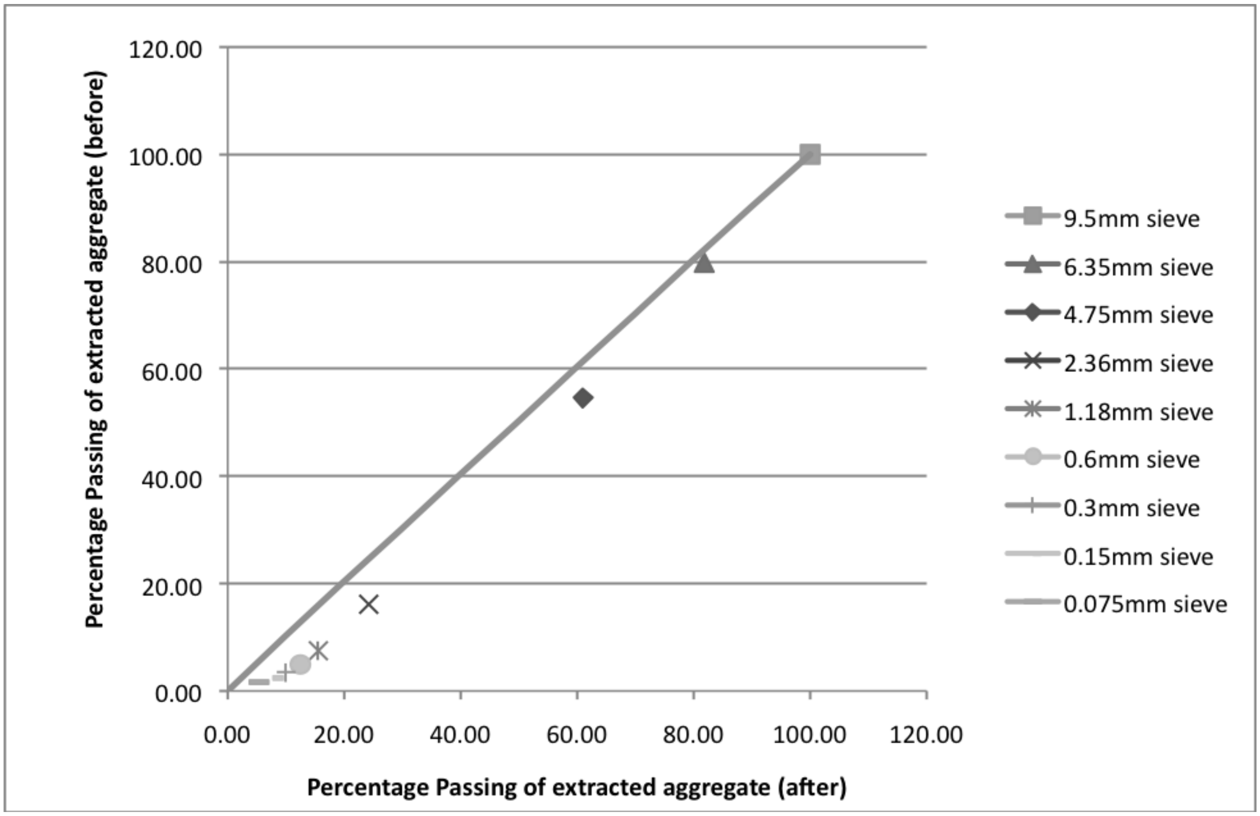

Figure 7-4. Comparison of Percentage Passing on Each Sieve for Extracted Aggregate by T319 (before) and Same Aggregate Sample Burned in Ignition Oven (after)

2. The extracted aggregate from the solvent extraction method (AASHTO T319) is burned in Ignition oven. The Comparison of percentage passing on each sieve for extracted aggregate by AASHTO T319 (before) and same aggregate sample burned in Ignition Oven (after) is evaluated and shown for one of the samples from Plant 1.

From the above **figure 7-4** it is clearly seen that the gradation of the extracted aggregate sample becomes finer after burning in the ignition oven. This clearly indicates that Ignition oven burns of a portion of aggregate particles other than the asphalt content.

3. Calculation

   A) Let A be the percent Asphalt Content measured from Ignition Oven (IO).

   B) Let B be the percent Asphalt Content measured from Extraction and Recovery by AASHTO T319.

   C) Let C be the percent of difference in the weight when extracted aggregate from the AASHTO T319 method is burned in the Ignition oven.

   Correction factor percent = A-B-C

***Example*:**

1. Percent Asphalt content measured from IO=A= 4.48 percent
2. Percent Asphalt content measured from T319=B= 3 percent
3. Percent weight difference after extracted aggregate burned in the ignition oven = C = 0.540 percent
4. Therefore the correction factor = A-B-C

   i. = 4.48 percent - 3.00 percent - 0.54 percent

   ii. = 0.944 percent

5. The corrected percent asphalt content = A - correction factor

   i. = 4.48 percent - 0.944 percent

   ii. = 3.54 percent

Tables 7-2 and **7-3** show the loss of fines and corrected asphalt content for all four plants tested respectively.

Table 7-2. Loss of Fines for All Four Plants

Loss of fines (percent) of RAP aggregates in IO after Extraction and Recovery				
Plants	*1*	*2*	*3*	*4*
Replicate 1	0.54	0.66	1.43	0.96
Replicate 2	0.65	0.75	1.22	1.22
Average	0.60	0.71	1.33	1.09
Standard Deviation	0.08	0.06	0.15	0.18
Coefficient of Variance Percent	13	9	11	17

Table 7-3. Corrected Asphalt Content for All Four Plants

Plants	**1**	**2**	**3**	**4**
Percent Asphalt Content (IO)	4.48	5.49	6.32	5.62
Loss of fines	0.60	0.71	1.33	1.09
Corrected Percent Asphalt Content (IO)	3.88	4.78	5.00	4.53

The corrected asphalt content for each plant is shown in the above tables. It was observed that the loss of fines varies from 0.60 to 1.33 percent for different plants.

7.7 Determination of Variability Allowable Percentage of RAP

7.7.1 Variability in Gradation

Table 7-4 below shows the five combinations of extraction and recovery procedures used in this variability study.

Table 7-4. Combinations Used in Variability Study

	Comb. 1	**Comb. 2**	**Comb. 3**	**Comb. 4**	**Comb. 5**
Method of Extraction	T164	T164	T164	T164	T319
Method of Recovery	T319	T319	D5404	D5404	T319
Type of Solvent	New	Reused	New	Reused	Reused
Number of Replicates	2	2	2	2	2

Table 7-5 below shows the Coefficient of Variance (COV) of the RAP aggregate gradations for the extraction and recovery procedures.

Table 7-5. COV of RAP Aggregate Gradation for Different Extraction and Recovery Procedures

Sieve Size		**COV**				
(in)	*(mm)*	***1***	***2***	***3***	***4***	***5***
½	**12.5**	0	0	0	0	0
3/8	**9.5**	0	0	0	0	0
¼	**6.35**	2	2	1	5	5
#4	**4.75**	2	3	2	9	9
#8	**3.36**	3	5	3	16	14
#16	**1.18**	3	5	3	21	15
#30	**0.6**	5	4	1	24	13
#50	**0.3**	8	2	6	25	11
#100	**0.15**	10	0	9	24	4
#200	**0.075**	14	2	13	13	7

From the above **table 7-5** it is observed that the COV values of RAP gradation are higher for the ER combinations four and five as compared to combinations one through three.

<u>7.7.2 Variability in Binder Content and Binder Stiffness</u>

The binder content for the different combination of extraction and recovery procedures shown in **figure 7-5** indicate that binder content determined by combination four and five is closer compared to combinations one through three.

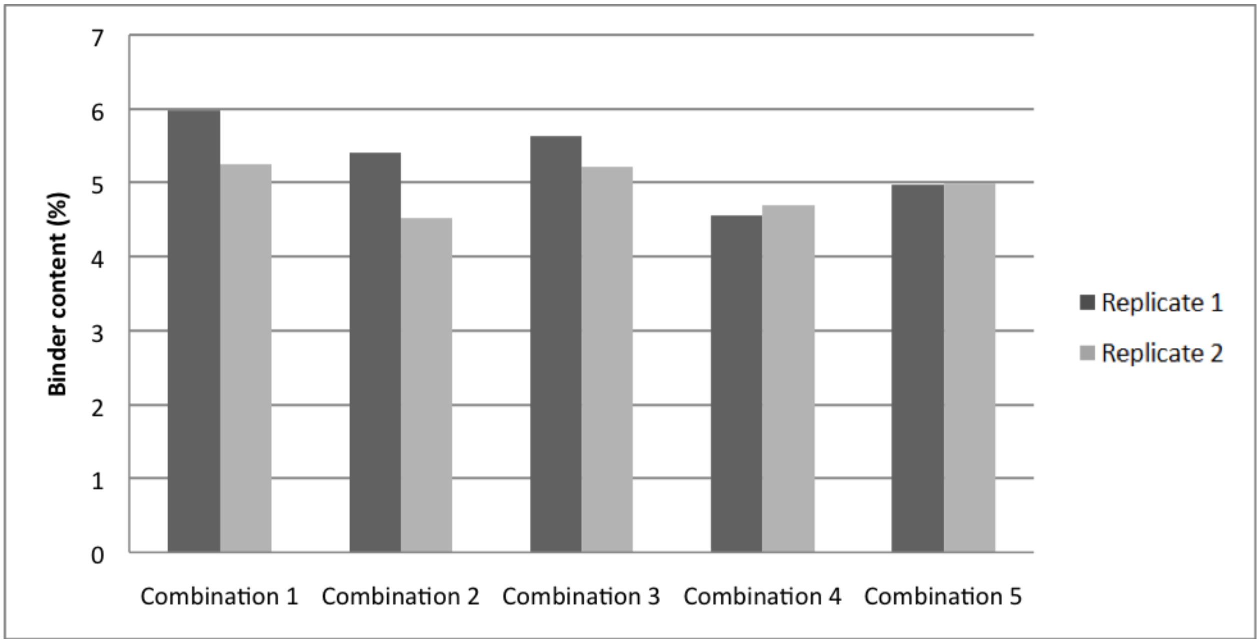

Figure 7-5. Binder Content of RAP for Different Combinations of Extraction and Recovery Procedure.

The RAP binder property (un-aged G*/Sin δ) for the different combinations of extraction and recovery methods determined by combinations 4 and 5 (0.3, 0.1), shown in **figure 7-6,** has a low standard deviation compared to combinations 1 through 3 (3.7, 1.3 and 1.6). Both replicates done for each combination are shown with this figure.

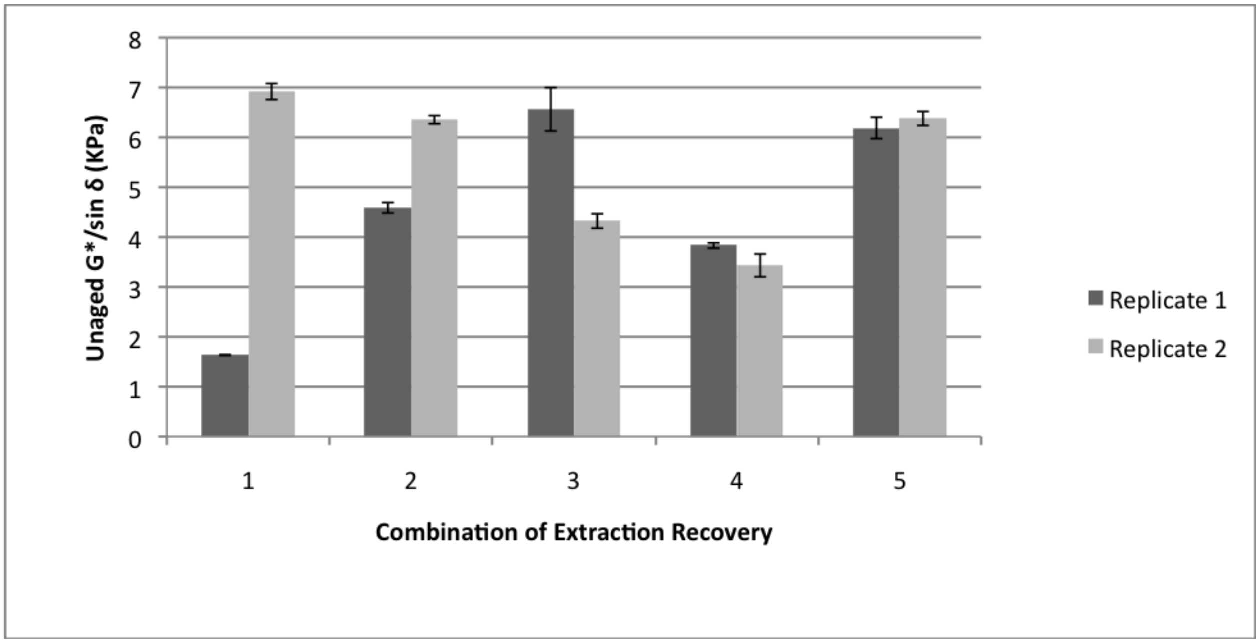

Figure 7-6. Comparison of Un-aged G*/Sin δ for Different Combination of Extraction and Recovery Procedure.

Determination of properties of RAP aggregate and binder is necessary for moderate and high percentages of RAP (above 15 percent). Some researchers have consistently shown that when RAP is mixed with virgin binder and aggregates partial blending occurs. It is seen that the standard deviation of RAP binder content and RAP binder properties (G*/Sin δ) of combination 4 and 5 is lower than that of combination 1, 2, and 3.

7.7.3 Allowable Percentage of RAP

NCHRP, Project 9-33 has compiled *A Mix Design Manual for Hot-Mix Asphalt*. Methods mentioned in this manual to design RAP mix are based primarily on the NCHRP report 452. As per this manual, the maximum amount of RAP that can be added to the mixture is governed by the amount of dust (below 0.075 sieve) and the variability of the RAP. The variability of the RAP is captured by standard deviation in the gradation and asphalt content. This standard deviation is used to determine allowable percentage of

RAP, as shown in **table 7-6**. In this paper, *HMA Tools* developed during the NCHRP 9-33 is used to determined allowable percentage of the RAP.

Table 7-6. Standard Deviation for the Critical Sieve Sizes of the Four Plants

Ignition Oven	**Standard Deviation**			
Sieve Size, mm	**Plant 1**	**Plant 2**	**Plant 3**	**Plant 4**
50	0	0	0	0
37	0	0	0	0
25	0	0	0	0
12.5	0	0	0	0
9.5	0.3	4.3	1.8	2.0
6.35	4.1	5.2	9.8	6.0
4.75	4.5	5.1	13.8	6.3
2.36	1.7	4.4	18.5	7.2
1.18	0.7	3.1	11.5	5.0
0.06	0.5	2.3	7.5	0.9
0.03	0.2	1.7	4.3	1.6
0.150	0.3	1.4	2.6	1.3
0.075	0.3	0.9	1.3	0.7
Asphalt Content	0.1	0.4	0.4	0.5
Allowable Percent RAP	22	8	0	6

It is seen from the above table that for plant 1, the standard deviation value was the least for the asphalt content and all three critical sieve 9.5mm, 2.36mm and 0.075mm. Therefore the allowable percentage of RAP is highest for plant 1; whereas for plant 3, the standard deviation values are higher resulting in the least allowable percentage of RAP. It is not suggested to calculate the allowable percentages of RAP considering only 4 sets of replicates. For an accurate calculation of the allowable percentage of RAP, a minimum of 10-15 replicates need to be evaluated. The above allowable percentage of RAP is used only to explain the concept of the critical sieve sizes standard deviation affecting the allowable percentage of RAP.

7.8 Summary of Findings

- COV of RAP gradation is higher for the ER combinations 4 and 5 as compared to 1 to 3.
- Standard deviation in RAP binder content is lower in the ER combination 4 and 5 as compared to the combination 1 to 3.
- Standard deviation of the RAP binder property (un-aged $G^*/\sin\delta$) is lower in the extraction recovery combination 4 and 5 as compared to the combination 1 to 3.
- A procedure of determining the correction factor of the Ignition oven for RAP samples was developed.
- Standard deviation of the critical sieve sizes 9.5mm, 2.36mm and 0.075mm of plant 1 were observed to be the least from all the plants; therefore, the allowable percentage of RAP is highest for plant 1; whereas for plant 3, the standard deviation values are higher resulting in the least allowable percentage of RAP. These results were based on data obtained from four plants.

Chapter 8

Comparison of the Performance of 25 Percent and 35 Percent RAP HMA

8.1 Introduction

The use of high percentages of RAP in New Jersey roadways is only justified if the performance of RAP HMA is equal to, or better than, the performance of HMA with no RAP. In this study, HMA mixtures using 25 percent and 35 percent RAP were tested and compared to control samples with no RAP added. Since the addition of RAP increases the stiffness of a mixture, this would improve high temperature performance, but make these pavements more susceptible to freeze-thaw effects and low temperature cracking. Taking this into account, only low temperature testing was conducted for samples due to the fact that type of testing would best show any negative effects that RAP may cause in pavements. The following low temperature testing was done for each mixture: DCT, TSR, and BBR. The volumetric properties of different assumed degrees of blending were also compared to show the effects of under asphalting when the 100 percent of blending assumption is used. In the following sections, the methodology along with the results of this portion of the study will be discussed.

8.2 Research Approach

Table 8-1 represents the detail of all the mixes prepared using Superpave mix design along with their appropriate notations. Mix one was used in order to determine the amount of binder required to coat the virgin and RAP aggregates without the presence of RAP binder. The binder was removed from the RAP aggregates using an ignition oven. Mix two introduced RAP binder into the mixture of aggregates and virgin binder in order to determine the DOB occurring within the mix. Mix three was used to determine the amount of under asphalting occurring with the assumption of 100 percent DOB as well as the effect it had on the performance of the samples. Mix two and three used PG 70-28 as the virgin binder for each mixture. Mix four increase the RAP percentage to 35 percent in order to determine the effect this increase had on pavement performance and used PG 58-28 binder to compensate for there being more RAP binder. Mix five was the control mixture using no RAP aggregates and was used to help compare the effects of RAP on pavement performance. PG 76-22 was used as the virgin binder for this mixture. After the total binder content was determined for 25 percent RAP mixtures, the mixes were prepared for 70 percent and 100 percent assumed DOB for 25 percent RAP.

Table 8-1. Detailed List of All Mixtures Prepared with Superpave Mix Design

Notation	RAP (%)	Mixture
MIX 1	25	Superpave Mix design to calculate total binder content to match all Superpave Parameters (Virgin Aggregate + Ignited RAP aggregate +Virgin Binder to hit four percent air voids)
MIX 2	25	Measure Superpave Volumetric properties for mixtures Assuming Partial Blending i.e. 70 percent Blending (Virgin aggregate +RAP+ Total binder from MIX_1-(0.70*RAP binder))
MIX 3	25	Measure Superpave Volumetric properties for mixtures Assuming Full Blending i.e. 100 percent Blending (Virgin aggregate + RAP + Total binder from MIX_1-RAP binder)
MIX 4	35	Superpave Mix design to calculate total binder content to match all Superpave Parameters (Virgin Aggregate + RAP aggregate +Virgin Binder to hit four percent air voids)
MIX 5	Control (0% RAP)	Superpave Mix design to calculate total binder content to match all Superpave Parameters (Virgin Aggregate +Virgin Binder to hit four percent air voids)

8.3 Methodology

The following methodology was followed to obtain the performance results for each mixture in the study. An example is provided below in order to show how the binder content for 70 and 100 percent blending for 25 percent RAP was determined.

1. Remove the residual asphalt from the RAP aggregates using an ignition oven (AASHTO T308). This mix design was conducted using ignited RAP so that the asphalt content required to make four percent air void samples could be used to find the DOB occurring in the other mix designs. **ONLY FOR 25 PERCENT RAP (100 PERCENT DOB)**
2. Select a starting binder content to use for the Superpave mix design. Adjust the binder content to account for the residual binder from the RAP.
3. Mix batched aggregates and binder at temperature within the allowable range specified for given binder. Mix for approximately five minutes until aggregates and binder are uniformly mixed. This procedure follows AASHTO R30. **ONLY FOR 25 PERCENT RAP (70 Percent and 100 Percent DOB) & 35 PERCENT RAP**
    - Pre-heat RAP to 110^{0}C in order to minimize aging.
    - When adding aggregates, place half of the virgin aggregates in the mixing bucket followed by the batched RAP aggregates, followed by the rest of the virgin aggregates.
4. Condition the mixture for two hours at a temperature within the allowable compaction temperature range specified for each binder. This conditioning

simulates the aging that occurs at an asphalt plant. This process follows AASHTO R30.

5. Test volumetric properties (Maximum Specific Gravity – G_{mm} & Bulk Specific Gravity – G_{mb}) in order to find air void content, Voids in Mineral Aggregate (VMA), Voids Filled with Asphalt (VFA), and the Dust-to-Binder Ratio (DB).
6. Check volumetric properties against the limits given in the Superpave specifications. If the volumetrics pass, continue onto **Step 7**. The binder content used is then referred to as the optimum binder content. If the volumetrics do not pass, repeat **Steps 3-6** with a different binder content.
7. Using the Gmm value and sample mold properties, determine the mass required to obtain seven percent air voids in each sample. Samples are tested at seven percent air voids in order to represent field conditions. This percentage of air voids is typical for asphalt performance testing.
8. Using the mass obtained from **Step 7,** along with the optimum binder content, mix samples according to the process outlined in **Step 3**.
9. Condition the mixture for four hours at a temperature within the allowable compaction temperature range specified for each binder. This conditioning simulates the aging that occurs at an asphalt plant. This process follows AASHTO R30.
10. Fabricate and test seven percent air void specimens according to the test specifications given for DCT, TSR, and BBR testing.

***Example*:**

Given

- Total binder content based on Superpave mix design= 5.65 percent
- Binder content of RAP (calculated by ignition oven correction factor) = 4.88 percent

Analysis

1. The virgin binder added assuming 70 percent DOB: is given by **equation 8.1**:

$$\text{Virgin Binder Added (70 percent)} = 5.65 \text{ percent} - (0.70*4.88 \text{ percent} * (\text{percent RAP})) \quad (8.1)$$

2. The virgin binder added assuming 100 percent DOB: is given by **equation 8.2**:

$$\text{Virgin Binder Added (100 percent)} = 5.65 \text{ percent} - (1.00*4.88 \text{ percent} * (\text{percent RAP})) \quad (8.2)$$

8.4 Materials and Job Mix Formula

In this study, all aggregates were obtained from a single asphalt plant located in New Jersey and all binders were obtained from a local refinery. The job mix formula used to conduct Superpave mix designs for all HMA mixtures was obtained from the same asphalt plant where the aggregates were acquired. All HMA mixtures used the same gradation in order to minimize variability as well. The binder grades used in each mix design were specified by the NJDOT. Plant mixtures were obtained from two Delaware plants in order to compare their performance with the performance of the New Jersey laboratory samples. **Table 8-2** shows the batch percentages and binder used for each mix design in the study.

Table 8-2. Batch Percentages and Binder Grades for All Mix Designs in Study

Aggregate	Mix 1	Mix 2	Mix 3	Mix 4	Mix 5
3/4"	0%	0%	0%	0%	28%
1/2"	29%	29%	29%	29%	0%
3/8"	27%	27%	27%	25%	34%
Screening	3%	3%	3%	3%	20%
Sand	16%	16%	16%	8%	18%
RAP	25%	25%	25%	35%	0%
Binder Grade	PG 70-28	PG 70-28	PG 70-28	PG 58-28	PG 76-22

Figure 8-1 shows the plotted gradations of all the HMA mixtures referenced in table 8-2, the gradations of the Delaware mixtures used in the study, and the gradation of the local New Jersey asphalt plant where materials were obtained.

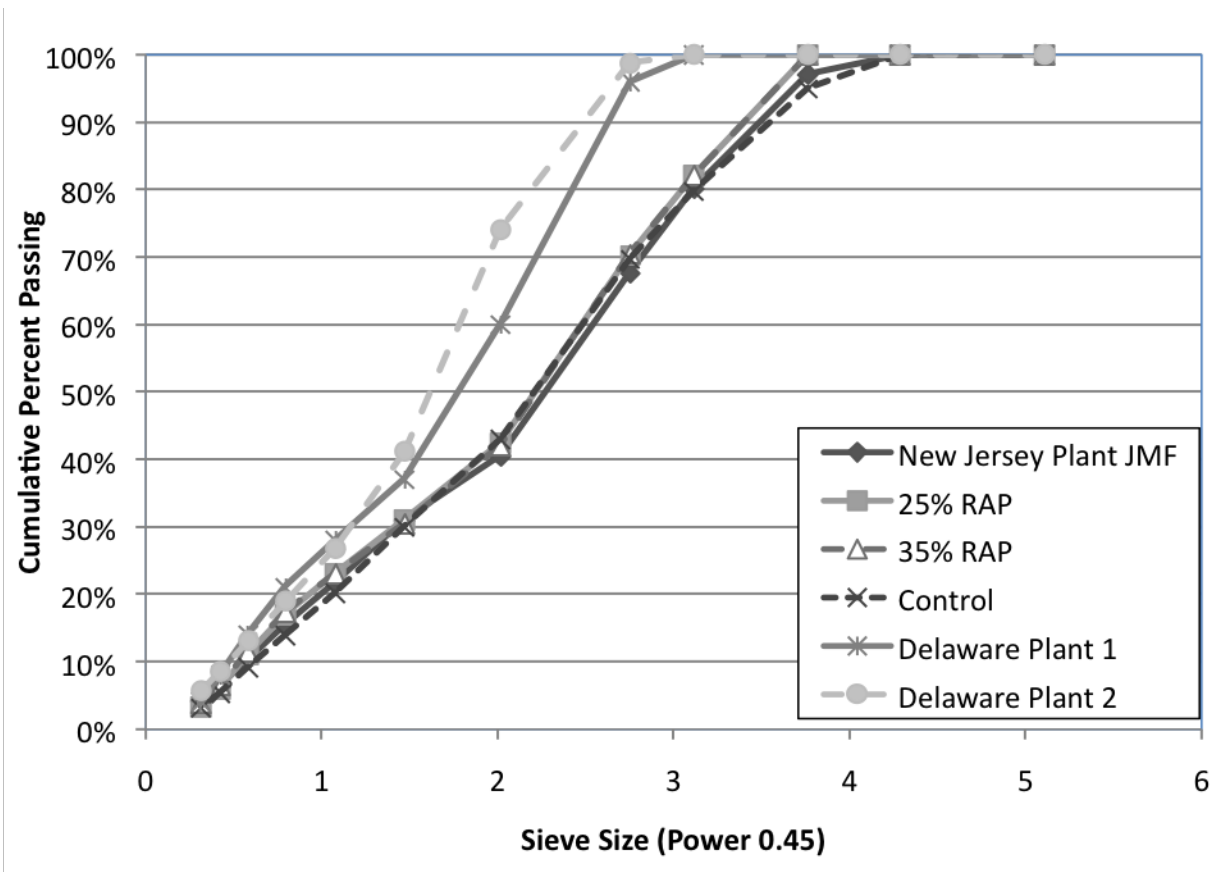

Figure 8-1 Plant and Laboratory Gradations Used in Study

8.5 Superpave Volumetrics and DOB Back Calculations for Mixtures

The volumetric properties obtained for each Superpave mix, along with the back calculations for DOB with the 25 percent RAP mixes are discussed in their respective sections below.

8.5.1 Superpave Volumetric Properties for Mixtures

The Superpave process of obtaining the optimum binder content was used to make the control mix sample at 4 percent air voids. The batch percentages that yielded the gradation in **figure 8-1** were used in the creation of these samples. The following data in **table 8-3** show the design binder content obtained from volumetric testing that passed VMA, VFA, and DB criteria set by the NJDOT. Mix one was not included in this table since VMA, VFA, and DB were not required to be checked with this mixture.

Table 8-3. VMA, VFA, and Dust to Binder Ratio for Mixes

	Mix 1	**Mix 2**	**Mix 3**	**Mix 4**	**Mix 5**	**Limits**
Design Binder Content	5.65	[redacted]			5.95	N/A
G_{mm}	2.571	2.588	2.592	2.459	2.567	N/A
G_{mb}	2.467	2.461	2.436	2.359	2.456	N/A
Air voids (%)	4.1	4.9	6.0%	4.1%	4.32%	3.5-4.5%
Virgin Binder added (%)	5.65	4.84	4.48	3.94	5.95	N/A
VMA (%)	16.2	16.2	16.9	15.3	17.0	> 13
VFA (%)	74.7	75.60	76.87	73.4	76.0	60-78
Dust to Binder Ratio	0.61	0.64	0.65	0.69	0.94	0.6-1.2

8.5.2 Calculations of DOB

The effective binder content is the key in determining the Superpave volumetric parameters. The DOB is accurately measured by comparing effective binder content rather than the total binder content. The design binder content for Mix 1 was 5.65%, and the effective binder content was 5.08%. If the assumed degree of blending is same as actual, the effective binder content would be the same for all cases. The difference in the effective binder content can be attributed to the difference between assumed and the actual DOB. Calculation of degree of partial blending from 70 percent DOB is elaborated below.

8.5.2.1 Determination of DOB for 25 Percent RAP Mixtures

The following process outlines the back calculation for the 25% RAP mix with 70 percent DOB (Mix 2).

1. Assume total binder content = estimated binder at 4% air voids for 70% blending, therefore $P_{b,estimated}$ = 5.65%. The absorbed asphalt was 0.61 based on the volumetrics shown in Table 4 for Mix 2.
2. The effective asphalt % by the total weight at 4% air voids = Total binder – absorbed asphalt

   = 5.65-0.61

   = 5.04
3. But the effective binder needed to hit 4% is 5.08%. Therefore, assuming 70% degree of blending is under asphalting the mix. The amount of under asphalting is determined by the difference in the effective binder content: (5.08-5.04) = 0.04%

4. Therefore, the corrected degree of blending = 70%-(0.04/(RAP binder content * percentage of RAP))

=70-(0.04/(4.88*0.25))

= 67%

The estimated degree of blending value is close to the calculated value which is consistent with the values obtained in Chapter 5 of this report. The DOB could not be back calculated from 100% DOB, because the air voids were significantly higher than 4%. From the volumetric properties and effective asphalt content, it appears that the DOB is slightly less than 70 percent, resulting in a value of 67 percent.

8.5.2.2 Determination of DOB for 35 Percent RAP Mixtures

Due to variability issues within the RAP for 35 percent RAP mixtures, the actual degree DOB at this percentage could not be calculated. For this study, it was assumed that 100 % DOB occurred in 35 % RAP mixtures based on information gathered from aforementioned blending study.

8.6 Discussion of Performance Results for Superpave Mixtures

All results obtained by the performance tests conducted for this study are discussed in their respective sections below. The blended binder performance grades shown in the tables below were calculated using linear blending charts in order to better conclude the effect of RAP on the performance criteria.

8.6.1 Disk Shaped Compact Tension Test

The fracture energy results shown in **table 8-4** and **figure 8-2** were obtained for both 25 percent and 35 percent RAP. The error bars shown in **figure 8-2** show the 5 percent statistical significance range for each data value.

Table 8-4. DCT Results for High RAP Percentage Mixes

Percent RAP	PG Grade of virgin binder	PG RAP binder grade	Source of Material	Degree of Blending (DOB)	Fracture Energy (lb-in/sq in)	Blended Binder
25%	PG 70-28	PG 91.7-19.8	New Jersey	70%	3.550	74-(28)-27
25%	PG 70-28	PG 91.7-19.8	New Jersey	100%	2.950	75-(29)-26
35%	PG 58-28	PG 91.7-19.8	New Jersey	100%	6.135	70-(27)-25
Control	PG 76-22	N/A	New Jersey	N/A	4.955	76-(31)-22
35%	PG 70-22	N/A	Delaware – Plant 1	100%	7.015	Info Not Provided
35%	PG 64-22	N/A	Delaware – Plant 2	100%	4.050	Info Not Provided

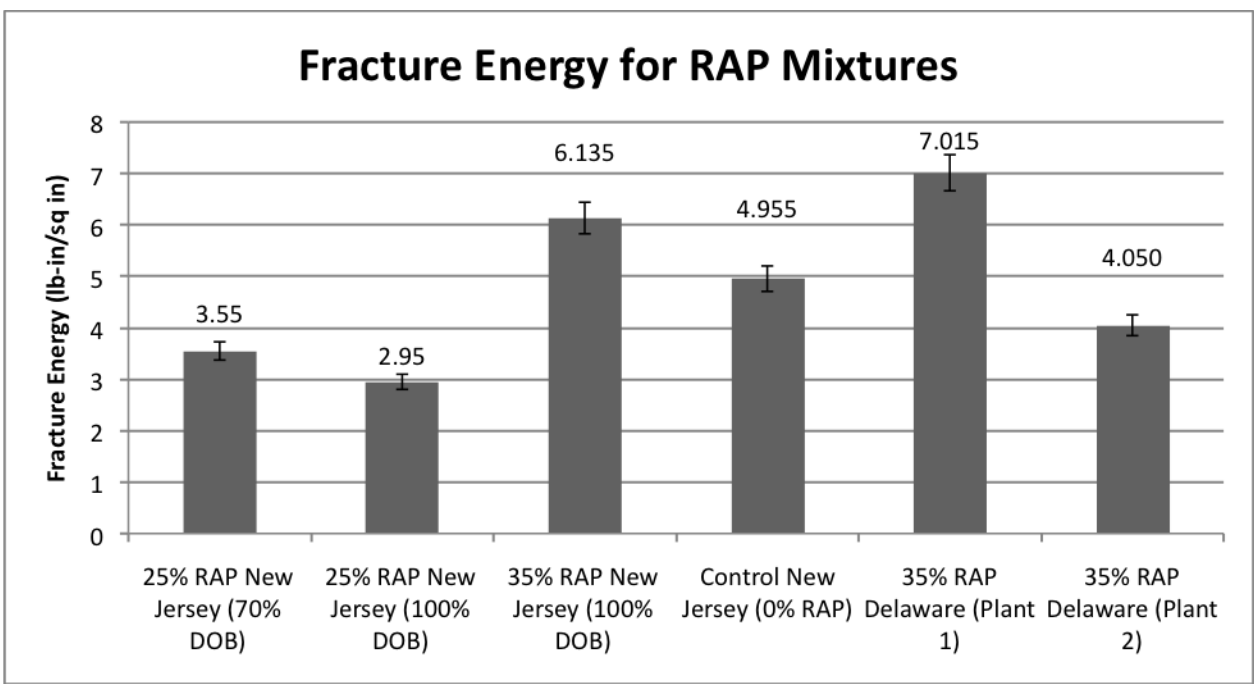

Figure 8-2. Fracture Energy for All RAP Mixtures

It was observed from the results in **table 8-4 and figure 8-2** that using the assumption of 100 percent DOB for 25 percent RAP yields a fracture energy value 17 percent lower than when using the assumption of 70 percent DOB. From this observation, it can be concluded that using a higher DOB assumption than what is actually occurring in the mix negatively affects the performance of 25 percent RAP asphalt samples. The results in the previous table conclude that an increase of RAP combined with a softer virgin binder grade increases the fracture energy by 73 percent. The 35 percent RAP samples showed a significantly larger tail section after the peak force of the fracture energy curve compared to the 25 percent samples. This increase was as expected since softer binders are more elastic that stiffer binders allowing them to control low temperature cracking more effectively. When the results of the RAP mixture were compared to the control mixture's performance, it was found that the control had 40 percent more than the 25 percent RAP mixtures and 19 percent less fracture energy than 35 percent RAP mixtures respectively. These results show that it is possible for asphalt samples with 35 percent RAP content to achieve a fracture energy similar to, or greater than, asphalt samples with no RAP content through the use of lower PG grade virgin binders. The addition of Delaware RAP performance data will help to show what fracture energies could be deemed acceptable. Plant one from Delaware yielded a fracture energy 14 percent greater than the 35 percent samples and 42 percent greater than the control samples. Plant two yielded a fracture energy 34 percent less than the 35 percent samples and 18 percent less than the control samples.

8.6.2 Moisture Susceptibility

The moisture susceptibility results shown in **table 8-5** were obtained for both 25 percent and 35 percent RAP. HMA mixes must have a TSR greater than or equal to 0.80 to pass NJDOT specifications.

Table 8-5. TSR Results for High RAP Percentage Mixes

Percent RAP	**Virgin binder grade**	**RAP binder grade**	**Source of Material**	**Degree of Blending (DOB)**	**Tensile Strength Ratio (TSR)**	**PASS/FAIL**
25%	PG 70-28	PG 91.7-19.8	New Jersey	70%	1.08	PASS
25%	PG 70-28	PG 91.7-19.8	New Jersey	100%	0.75	FAIL
35%	PG 58-28	PG 91.7-19.8	New Jersey	100%	0.99	PASS
Control	PG 76-22	N/A	New Jersey	N/A	1.04	PASS

From the results shown in **table 8-5**, it was determined that the under asphalting of 25 percent RAP samples due to the 100 percent DOB assumption caused the TSR value of that mix to decrease by 25 percent. The 100 percent DOB samples for 25 percent RAP failed to pass the criteria of 0.80 specified by the NJDOT. With these observations, it was concluded that under asphalting 25 percent RAP mixtures can cause a decrease in TSR and possibly cause the mixture to fail the criteria set by the NJDOT. It is shown in the previous table that all mixes with the correct DOB assumptions were not susceptible to moisture. In theory, TSR values that remain constant at an approximate ratio of 1 show that the samples perform the same whether or not they have been through moisture conditioning leading. Any TSR values that are over 1 would only occur due to variability of performance within the mixture. Due to the fact that the three New Jersey samples were all approximately one, it can be said that 25 percent and 35 percent RAP do not result in a decrease in TSR performance.

8.6.3 Modified Bending Beam Rheometer Test (BBR)

The results from the modified BBR tests conducted on mixtures for both 25 percent RAP and 35 percent RAP can be found in **table 8-6** and **figure 8-3.** The error bars shown in **figure 8-3** show the 5 percent statistical significance range for each data value.

Table 8-6. BBR Results for High RAP Percentage Mixes

Percent RAP	**Virgin binder grade**	**RAP binder grade**	**Source of Material**	**Degree of Blending (DOB)**	**Average Stiffness (MPa) at +22°C above the low PG virgin binder grade**	**Blended Binder**
25%	PG 70-28	PG 91.7-19.8	New Jersey	70%	3688	74-(28)-27
25%	PG 70-28	PG 91.7-19.8	New Jersey	100%	3714	75-(29)-26
35%	PG 58-28	PG 91.7-19.8	New Jersey	100%	2710	70-(27)-25
Control	PG 76-22	N/A	New Jersey	N/A	3138	76-(31)-22
35%	PG 70-22	N/A	Delaware – Plant 1	100%	4356	N/A
35%	PG 64-22	N/A	Delaware – Plant 2	100%	5054	N/A

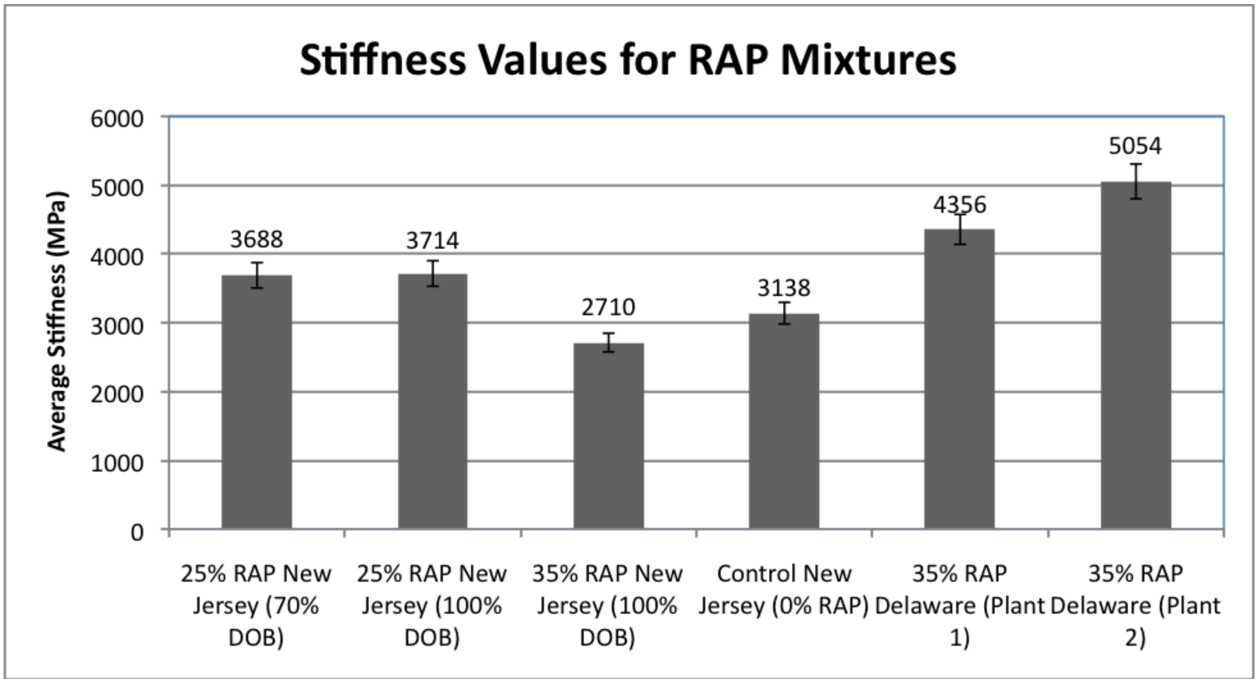

Figure 8-3. Stiffness Values for All RAP Mixtures

It is shown from **table 8-6** and **figure 8-3** that the difference in stiffness values for 70 percent DOB and 100 percent DOB was statistically insignificant. An increase of 0.7 percent was calculated for the change of 70 percent DOB to 100 percent DOB. This concluded that the assumption of 100 percent DOB as opposed to 70 percent DOB for 25 percent RAP does not significantly affect the stiffness of the material. The results showed that using 35 percent RAP lowered the stiffness of the samples by approximately 27 percent compared to the 25 percent RAP samples. This decrease in stiffness is most likely due to the fact that PG 58-28 is softer than PG 70-28. The control samples yielded stiffness values approximately 15 percent lower and 16 percent higher than the 25 percent and 35 percent samples respectively. Both 35 percent RAP plant mixes from Delaware yielded a higher stiffness than all the laboratory mixed samples which was expected. This is due to the Delaware mixes having more fine materials within the gradation as well as their binder choice for the mixture. It appears that the Delaware mix only lower the binder grade slightly to account for 35 percent RAP which would also lead to a higher stiffness value in BBR testing.

8.7 Effect of Variability of RAP on 35 Percent RAP mixtures

The RAP was used from a single stockpile. The gradation of five random set of the RAP aggregates burnt in the Ignition Oven are displayed in **table 8-7** followed by **table 8-8** that displays the maximum difference in the sieve sizes within the 5 sets of Ignition oven gradation.

Table 8-7. Gradation of RAP aggregates burnt in Ignition Oven (5 sets)

Sieve Size			**Percentage Passing**				
(in)	(mm)	(mm ^ 0.45)	1	2	3	4	5
1-1/2	37.5	5.108743	100.00%	100.00%	100.00%	100.00%	100.00%
1	25.4	4.287214	100.00%	100.00%	100.00%	100.00%	100.00%
¾	19	3.762176	100.00%	100.00%	100.00%	100.00%	100.00%
½	12.5	3.116087	100.00%	100.00%	100.00%	100.00%	99.60%
3/8	9.5	2.754074	100.00%	96.20%	97.10%	96.90%	98.20%
#4	4.75	2.0161	77.70%	62.40%	64.40%	63.60%	77.50%
#8	2.36	1.47167	60.60%	42.40%	42.70%	41.90%	57.90%
#16	1.18	1.077325	47.10%	32.60%	32.30%	31.50%	44.70%
#30	0.6	0.794636	36.40%	25.40%	25.10%	24.20%	34.00%
#50	0.3	0.581707	24.10%	16.20%	17.00%	16.00%	22.60%
#100	0.15	0.425835	13.60%	7.70%	9.20%	8.60%	13.00%
#200	0.075	0.311729	8.20%	4.20%	5.40%	5.10%	6.60%

Table 8-8. Maximum difference between the sieve sizes of 5 sets of burnt RAP aggregates

Sieve Size			**Maximum Difference**
(in)	*(mm)*	*(mm ^ 0.45)*	
1 - ½	37.5	5.108743	0.0%
1	25.4	4.287214	0.0%
3/4	19	3.762176	0.0%
1/2	12.5	3.116087	0.4%
3/8	9.5	2.754074	3.8%
#4	4.75	2.0161	15.4%
#8	2.36	1.47167	18.7%
#16	1.18	1.077325	15.6%
#30	0.6	0.794636	12.2%
#50	0.3	0.581707	8.1%
#100	0.15	0.425835	5.9%
#200	0.075	0.311729	4.0%

From the above **table 8-7** and **table 8-8** we can see that, the maximum difference between the burnt RAP aggregates is prominent for sieve sizes #4, #8, #16 and #30. The rest of the sieve sizes have differences less than 10 percent. This difference in the gradation did not affect the Superpave mix design for mixtures with 25 percent RAP. The 25 percent RAP mix volumetrics passed all Superpave volumetric criteria. On the other hand, when for a hot mix asphalt with 35 percent RAP was made, it was very hard to get the results within the allowable range and the results were not within the specification limits.

8.8 Summary of Findings

- The actual DOB calculated for 25 percent was 67 percent. The DOB for 35 percent could not be calculated due to variability issues within the RAP. The DOB assumed for 35 percent was assumed to be 100 percent.

- 25 percent RAP with 100 percent DOB had 17 percent lower fracture energy than 25 percent RAP with 70 percent DOB. This shows that under asphalting can negatively affects asphalt pavement performance.
- 35 percent RAP samples had 73 percent more fracture energy than 25 percent RAP samples with 70 percent DOB.
- Control samples had 40 percent more fracture energy than the 25 percent RAP samples and 19 percent less fracture energy than the 35 percent RAP samples.
- Plant one from Delaware yielded a fracture energy 14 percent greater than the 35 percent samples and 42 percent greater than the control samples. Plant two yielded a fracture energy 34 percent less than the 35 percent samples and 18 percent less than the control samples.
- 25 percent RAP with 100 percent DOB had a 25 percent lower TSR than 25 percent RAP with 70 percent DOB. The 25 percent RAP mixture with 100 percent DOB did not pass the criteria of 0.8 set for TSR by the NJDOT. This shows that under asphalting negatively affects asphalt pavement performance and possibly cause an asphalt mix to not pass NJDOT criteria.
- Moisture sensitivity was not significantly affected for 25 percent RAP with 100 percent DOB, 35 percent, and control samples.
- 25 percent RAP with 100 percent DOB had a 0.7 percent higher stiffness value than 25 percent RAP with 70 percent DOB. The stiffness of the 25 percent samples was not affected either positively or negatively for this particular under asphalting case.

- 35 percent RAP samples yielded a 27 percent decrease in stiffness compared to the 25 percent RAP samples.
- Control samples yielded stiffness values approximately 15 percent lower and 16 percent higher than the 25 percent and 35 percent samples respectively.
- Delaware mixtures yielded higher stiffness values than all laboratory tested samples (25 percent and 35 percent).
- For the burnt RAP aggregate gradation, the percent passing on the #4, #8, #16, and #30 sieves had differences greater than 10 percent. These differences did not affect the Superpave mix design for 25 percent RAP, but significantly affected the design for 35 percent RAP.

Chapter 9

Cost Analysis of Using RAP in Asphalt Pavements

9.1 Cost Analysis

A major benefit of using RAP in asphalt pavements is that RAP pavements are cheaper to produce than pavements with no RAP. The magnitude of this cost difference plays a significant role in the determination of whether the application of high percentage RAP pavements is practical or not. **Tables 9-1** and **9-2** show the cost analysis that was conducted in order to find the difference in cost between pavements created with and without RAP. For this cost analysis, numbers and prices were obtained from the NJDOT and a local asphalt plant. 25000 tons was an arbitrary value chosen to show the long term benefit of using RAP in multiple projects. Labor costs and construction costs were assumed similar for pavements with and without RAP. The DOB was assumed to be 100 percent with five percent RAP binder content. The final costs also assume that the largest aggregate cost possible with the RAP aggregates being a substitute for only fine aggregates.

Table 9-1. Basic Costs Associated With Roadway Pavements

Materials and Processes Need For Pavement	*$/ton*
BINDER	
Asphalt Cement Index	$ 545.00 *[April 2011]* (NJDOT)
AGGREGATES	
Coarse (Retained #8)	$ 22.00
Fine (Pass #8)	$ 12.00
Crushing & Screening	$ 5.50
MIX	
Coarse	80%
Fine	20%
Binder Content	5.00%
0 Percent RAP Amount Mix Needed (tons)	25000
25 Percent RAP Amount Mix Needed (tons)	18750
35 Percent RAP Amount Mix Needed (tons)	16250

Table 9-2. Cost Savings for Roadway Pavements Using RAP

	Total Cost	Price Reduction
No RAP	$ 1,181,250.00	N/A
25 Percent RAP[2]	$ 957,812.50	$ 223,437.50
35 Percent RAP[2]	$ 848,437.50	$ 332,812.50

It is shown through **table 9-2** that the cost savings from using high percentages of RAP are significant over time when used in multiple projects. These savings should be able to pay for any initial costs associated with better RAP stockpiling practices. These stockpiling practices will minimize RAP variability, allowing for higher RAP percentages to be used in asphalt plants. It is important to realize that the overall savings in **table 9-2** are based on an arbitrary weight of 25000 tons and that the overall savings would increase after this weight is surpassed.

9.2 Summary of Findings

- With an assumption of 25000 tons of roadway being paved, approximately $220,000 and $330,000 could be saved by using 25 percent and 35 percent of RAP by weight in the JMF respectively.

Chapter 10

RAP HMA Excel Sheet Design vs. Lab Data

10.1 Excel Sheet Design

A study was carried out to see if the RAP HMA Excel sheet used by the NJDOT for RAP mixture designs could be altered to account for DOB correctly. To accomplish this task, a DOB cell was added to alter the amount of binder the RAP would attribute to each trial mixture. This was done by increasing the absorption of the RAP aggregates. This was useful in estimating the virgin binder needed for the mixture design. The task of altering the RAP HMA Excel sheet was successfully completed. The comparison of results can be found in **figures 10-1 and figure 10-2.**

	RAP 1	RAP 2	RAP 3	RAP4
Description:	RSP No. 1			
Degree of blending	30			
Binder Content, Wt. %	5.00			
Binder Specific Gravity	1.030			
Maximum Theoretical Specific Gravity	2.599			
Estimated Binder Absorption of RAP aggregates, Wt. %	0.480			
Estimated Binder Absorption Accounting for Degree of blending, Wt. %	3.64			
Effective Binder Content	1.36			
Measured Fine Aggregate Bulk Specific Gravity	2.726			
Measured Coarse Aggregate Bulk Specific Gravity	2.723			
Measured Fine Aggregate Apparent Specific Gravity	2.742			
Measured Coarse Aggregate Apparent Specific Gravity	2.901			

RAP No./Description	Trial 1	Trial 2
RAP 1 / RSP No. 1	0.3	0.3
#N/A	0.0	0.0
#N/A	0.0	0.0
#N/A	0.0	0.0
TOTAL RAP BINDER CONTENT	0.3	0.3
TOTAL NEW BINDER CONTENT	5.2	5.3
BLENDED BINDER GRADE, PG-	52-(22)-16	52-(22)-16
NEW BINDER GRADE, PG-	58-(19)-28	58-(19)-28
NEW BINDER SPEC. GRAV.	1.030	1.030

Figure 10-1. Excel Sheet Results for 30 Percent DOB

Degree of blending	70
Binder Content, Wt. %	5.00
Binder Specific Gravity	1.030
Maximum Theoretical Specific Gravity	2.599
Estimated Binder Absorption of RAP aggregates, Wt. %	0.480
Estimated Binder Absorption Accounting for Degree of blending, Wt. %	1.84
Effective Binder Content	3.16
Measured Fine Aggregate Bulk Specific Gravity	2.726
Measured Coarse Aggregate Bulk Specific Gravity	2.723
Measured Fine Aggregate Apparent Specific Gravity	2.742
Measured Coarse Aggregate Apparent Specific Gravity	2.901

RAP No./Description	Trial 1	Trial 2
RAP 1 / RSP No. 1	0.8	0.8
#N/A	0.0	0.0
#N/A	0.0	0.0
#N/A	0.0	0.0
TOTAL RAP BINDER CONTENT	0.8	0.8
TOTAL NEW BINDER CONTENT	4.8	4.8
BLENDED BINDER GRADE, PG-	58-(22)-22	58-(22)-22
NEW BINDER GRADE, PG-	58-(19)-28	58-(19)-28
NEW BINDER SPEC. GRAV.	1.030	1.030

Figure 10-2. Excel Sheet Results for 70 Percent DOB

10.2 Summary of Findings

- The NCHRP 9-33 Excel sheet was modified to account for partial DOB of RAP binder.

Chapter 11

Summary, Conclusions, and Recommendations

11.1 Summary of Findings for Report

The summaries of each chapter are listed below:

- The approximate binder transfer was considered as 30 percent and 20 percent for 25 percent and 35 percent RAP, respectively. These percentages were used to determine the virgin binder content for the blending study.
- The degree of partial blending for 25 percent RAP by weight of aggregates of chosen gradation and PG 70-28 virgin binder is 70 percent. The results used to make this conclusion were later found to be incorrect. This didn't affect the performance samples for 25 percent since 70 percent DOB was corrected to be 67 percent using Superpave.
- The degree of partial blending for 35 percent RAP by weight of aggregates of chosen gradation and PG 58-28 virgin binder is 96 percent.
- DOB determined by the blending study is much higher than that determined by the coating study. Hence, the step of determining of approximate binder could be skipped by assuming first approximate value of 50 percent for preparing mix.
- Degree of partial blending is independent of binder testing temperature.
- Degree of partial blending is higher for PG 58-28 as compare to PG 70-28 as expected since it is a softer binder.
- A new methodology of determining DOB was developed as explained in Chapter 5 of this report

- A detailed procedure to determine the blending chart for different degrees of partial blending was developed.
- The difference in critical grade of binder between 100 percent and 50 percent DOB for 50 percent RAP binder with PG 70-28 is above 6ºC. All others were within 6ºC.
- The comparison of the critical temperature determined by actual mixing, Method 1, as well as Method 2 and Method 3 shows that as the difference between critical temperature of RAP binder and virgin binder increases (21.4ºC for PG 70-28 and 32.6ºC for PG 58-28), the prediction of the final grade by Method 2 would be higher than that of the actual. In such cases, determination of the final grade by Method 3 would be closer to that determined by actual mixing.
    - Method 1: Determine the higher critical temperature of blended binder by mixing RAP and virgin binders assuming for 100 percent, 70 percent and 50 percent DOB.
    - Method 2: Determine the higher critical temperature of blended binder by assuming a linear relationship between the critical temperature of virgin and the RAP binder.
    - Method 3: Determine the higher critical temperature of blended binder by assuming linear relationship between the critical temperature of virgin binder and a blend of 50 percent virgin and 50 percent RAP binder.
- COV of RAP gradation is higher for the ER combinations 4 and 5 as compared to 1 to 3. The standard deviation in the RAP binder content is lower in the ER combination 4 and 5 as compared to the combination 1 to 3.

- Combination 1: Extraction (T164), Recovery (T319), New Solvent
  - Combination 2: Extraction (T164), Recovery (T319), Reused Solvent
  - Combination 3: Extraction (T164), Recovery (D5404), New Solvent
  - Combination 4: Extraction (T164), Recovery (D5404), Reused Solvent
  - Combination 5: Extraction (T319), Recovery (T319), Reused Solvent
- Standard deviation of the RAP binder property (un-aged $G^*/\sin\delta$) is lower in the extraction recovery combination 4 and 5 as compared to the combination 1 to 3.
- A procedure of determining the correction factor of the Ignition oven for RAP samples was developed.
- Standard deviation of the critical sieve sizes 9.5mm, 2.36mm and 0.075mm of plant 1 were observed to be the least from all the plants; therefore, the allowable percentage of RAP is highest for plant 1; whereas for plant 3, the standard deviation values are higher resulting in the least allowable percentage of RAP. These results were based on data obtained from four plants.
- The actual DOB calculated for 25 percent was 67 percent. The DOB for 35 percent could not be calculated due to variability issues within the RAP. It was also found that using the softer binder with 35 percent RAP made the mixtures very unworkable making the volumetric tests very difficult to conduct. The DOB assumed for 35 percent was assumed to be 100 percent.

According to the DCT tests:

- 25 percent RAP with 100 percent DOB had 17 percent lower fracture energy than 25 percent RAP with 70 percent DOB. This shows that under asphalting can negatively affects asphalt pavement performance.
- 35 percent RAP samples had 73 percent more fracture energy than 25 percent RAP samples with 70 percent DOB. This would provide an incentive to increase the RAP content from the current 15 percent and 25 percent limits to 35 percent.
- Control samples had 40 percent more fracture energy than the 25 percent RAP samples and 19 percent less fracture energy than the 35 percent RAP samples.
- Plant one from Delaware yielded a fracture energy 14 percent greater than the 35 percent samples and 42 percent greater than the control samples. Plant two yielded a fracture energy 34 percent less than the 35 percent samples and 18 percent less than the control samples.

According to the TSR tests:

- 25 percent RAP with 100 percent DOB had a 25 percent lower TSR than 25 percent RAP with 70 percent DOB. The 25 percent RAP mixture with 100 percent DOB did not pass the criteria of 0.8 set for TSR by the NJDOT. This shows that under asphalting can negatively affects asphalt pavement performance and possibly cause an asphalt mix to not pass NJDOT criteria.
- Moisture sensitivity was not significantly affected for 25 percent RAP with 100 percent DOB, 35 percent, and control samples.

According to the modified BBR tests:

- 25 percent RAP with 100 percent DOB had a 0.7 percent higher stiffness value than 25 percent RAP with 70 percent DOB. The stiffness of the 25 percent samples was not affected either positively or negatively for this particular under asphalting case.
- 35 percent RAP samples yielded a 27 percent decrease in stiffness compared to the 25 percent RAP samples.
- Control samples yielded stiffness values approximately 15 percent lower and 16 percent higher than the 25 percent and 35 percent samples respectively.
- Delaware mixtures yielded higher stiffness values than all laboratory tested samples (25 percent and 35 percent).
- For the burnt RAP aggregate gradation, the percent passing on the #4, #8, #16, and #30 sieves had differences greater than 10 percent. These differences did not affect the Superpave mix design for 25 percent RAP, but significantly affected the design for 35 percent RAP.
- With an assumption of 25000 tons of roadway being paved, approximately $220,000 and $330,000 could be saved by using 25 percent and 35 percent of RAP by weight in the JMF respectively.
- The NCHRP 9-33 Excel sheet was modified to account for partial DOB of RAP binder.

11.2 Conclusions and Recommendations

The following conclusions were made based off of the results found from the studies discussed in this report:

- When attempting to determine the final PG grade of blended binders, determining the higher critical temperature of blended binder by assuming a linear relationship between the critical temperature of the virgin and RAP binder is more accurate than determining the higher critical temperature of the blended binder by mixing RAP and virgin binders assuming for 100 percent, 70 percent and 50 percent DOB.
- DOB is an important factor to consider when utilizing RAP percentages 25 or higher. All DOB values in this report are for a specific JMF with one RAP source. These DOB values are not valid for other mixtures done outside these conditions.
- The assumption of 100 percent DOB can lead to under asphalting of the mix. This could ultimately have a negative effect on the performance of the asphalt.
- Variability could cause severe problems in obtaining acceptable value for mix designs when utilizing RAP percentages 35 percent or higher
- Plants that practiced fractionation showed lower RAP variability and had a higher percentage of allowable RAP.
- Linear relationship for blending charts may cause an error in estimating the blended binder grade. This error may increase as the difference in grade between the RAP and virgin binder increases as well as when higher percentages of RAP are used.

- Partial DOB occurs in mixtures with RAP and virgin materials. The partial DOB depends on both RAP and virgin binder selection.
- The use of softer binders to compensate for higher percentages of RAP can raise the fracture energy of a given mixture with high percentages of RAP; however, it will decrease the stiffness of the mixture.
- The use of high percentages of RAP within the study did not show any negative effects towards moisture sensitivity.
- Results showed that using high percentages of RAP can negatively affect the fracture energy of a sample.
- Using high percentages of RAP will lead to significant long-term cost savings.

The following recommendations were made based on the results found from the studies discussed in this report:

- Better stockpiling practices of RAP aggregates are needed in order to minimize variability.
    - Fractionate RAP materials in order to minimize variability in gradation. This gives a better control over the amount of binder contributed by the RAP and is easier to achieve the target gradation.
- Develop an equation in order to estimate the DOB of a given asphalt mixture. The equation should be a function of RAP aggregate and binder properties.
    - DOB values obtained in the report cannot be assumed to be correct for mixtures outside the mixture specifications described in this report.

    - A study is underway in order to develop an equation that will approximate DOB for any given mixture.
- Use rejuvenating agents in order to soften binder in order to compensate for high percentages of RAP

Chapter 12

Executive Summary

When an old road has to be replaced, the existing pavement that is removed can be recycled for use in new asphalt mixes since it already contains the two main components of pavements; binder and aggregates. This substance is known as RAP and is a resource that can reduce the cost and environmental impact of constructing new roads. Currently, New Jersey state specifications limit the percentage of RAP that can be used to 15 percent for surface courses and 25 percent for the intermediate and base courses; however, other states have implemented much higher RAP percentages. While it would be clearly beneficial to use higher percentages of RAP, several factors can limit RAP usage. One issue with RAP usage is that the interaction between the residual (RAP) binder and the virgin binder is largely unknown, both in terms of the amount of residual binder that mobilizes to become part of the mix and the effect that said binder will have on mix performance. The amount of RAP binder that mobilizes is known as the DOB and there are two main theories associated with it, full blending and “black rock” theory. Full blending is what the current state specification use and assumes that 100 percent of the RAP binder will activate and become part of the new mix whereas “black rock” theory states that none of the binder will be active and that the recycled aggregates are simply “black rocks.” It is also possible that the DOB is somewhere in between, known as partial blending since the DOB can be affected by many factors such as heat, moisture content, binder grade etc. First a coating study was performed to estimate the DOB and it was found to be 24 percent and 15 percent for 25 percent and 35 percent RAP respectively. For the section of this report related to partial blending, it was found that 25 percent RAP along with a PG 70-28 binder yielded a DOB of 70 percent while 35 percent RAP with PG 58-28 binder yielded a DOB of 96 percent meaning that it is possible that roads are currently being under asphalted. The methodology for the blending study was adopted for determining the degree of partial blending. Variability is also an issue with RAP and was investigated in this report in terms of binder content and gradation. A procedure was developed for determining a correction factor for the ignition oven of RAP. Another issue with RAP is that as binder ages is becomes more stiff and stiffer binders have a tendency to be more susceptible to low temperature cracking so samples were created to determine the effect of higher percentages of RAP on low temperature laboratory performance. High temperature testing was not performed because it was assumed that stiffening from the RAP binder would not have a negative effect. Disc shaped compact tension test(DCT) samples were made for 25 percent RAP assuming both 70 and 100 percent DOB and it was found that the sample assuming 100 percent DOB had a 17 percent lower fracture energy, agreeing with the previous data and showing that roads may be under asphalted. The 35 percent RAP samples were found to have 73 percent higher fracture energy than 25 percent RAP. The control samples were found to have 40 percent higher fracture energy than 25 percent RAP samples and 19 less fracture energy than 35 percent RAP samples. Asphalt from two Delaware plants was obtained in order to compare to the laboratory samples and further understand what may be deemed as an acceptable fracture energy. It was found that plant one from Delaware yielded a fracture energy 14 percent greater than the 35 percent samples and 42 percent greater than the control samples. Plant two yielded a fracture energy 34 percent less than the 35 percent samples, and 18 percent less than the control sample. A TSR test(TSR) was performed to determine moisture susceptibility and it was determined that for 25 percent RAP assuming 100 percent DOB, the sample did not pass the required value of 0.8 set by the NJDOT, but the 70 percent DOB samples did, showing that the under asphalting may lead to negative pavement performance. It was also found that the 35 percent RAP and control samples passed the TSR requirement of 0.8. With respect to stiffness, testing by BBR, it was found that for 25 percent RAP, the assumed DOB had no effect. An increase of 0.7 percent was calculated for the change of 70 percent DOB to 100 percent DOB. The results showed that using 35 percent RAP lowered the stiffness of the samples by approximately 27 percent compared to the 25 percent RAP samples. This decrease in stiffness is most likely due to the fact that PG 58-28 is softer than PG 70-28. The control samples yielded stiffness values approximately 15 percent lower and 16 percent higher than the 25 percent and 35 percent samples respectively. Both 35 percent RAP plant mixes from Delaware yielded a higher stiffness than all the laboratory mixed samples which was expected. This is due to the Delaware mixes having more fine materials within the gradation as well as their binder choice for the mixture. A cost analysis was conducted in order to show the benefits of using RAP in asphalt pavements. It was found that approximately $220,000 and $330,000 would be saved by using 25000 tons of 25 percent and 35 percent RAP respectively in roadways. The NCHRP 9-33 Excel sheet was also modified to account for partial DOB of RAP binder.

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