Influence of High RAP on Binder Properties in Hot Mix Asphalt of Northeast

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ABSTRACT OF THE THESIS

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The impact of recycled asphalt pavement (RAP) materials on pavement performance is an important topic of study in the asphalt industry due to environmental and cost benefits. A major issue with RAP is that many agencies are still reluctant to allow producers to use more than 10 to 20 percent RAP because of concerns that mixtures with higher RAP contents will be too stiff, less workable and prone to field failures. However, the recent increases in the cost of asphalt binder and the shrinking supplies of quality aggregate has made the use of higher RAP content in hot mix asphalt (HMA) mixtures a priority for the industry. In this study, eighteen plant produced mixtures were obtained from three locations in the Northeast: New York, New Hampshire and Vermont. These mixtures were produced using different RAP contents of 0%, 20%, 30% and 40%.

The eighteen mixtures were carefully extracted using American Association of State Highway and Transportation (AASHTO) T164 method "A" using trichloroethylene

and recovered with AASHTO T170 procedure. The recovered binder was then tested using Direct Shear Rheometer (DSR) and Bending Beam Rheometer (BBR) with AASHTO T315 and T313 procedures respectively. The results obtained from these tests were used to determine the continuous grade of the binders. They were then analyzed and compared to one another. Master curves were created for each recovered binder with RHEA and the data obtained from DSR frequency sweet sequence with a 4mm plate. The data recovered from master curves were used to plot black space and, crossover frequency and R-value graphs to show age hardening of binder.

This paper investigates the influence of high RAP on asphalt binder stiffness and ductility.

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Introduction

Recycled Asphalt Pavement (RAP) has been used since the 1970's in asphalt pavements at percentages ranging from 10-20 percent. The resulting pavements have generally performed as well as pavements made solely with virgin materials. Up to this date, many transportation agencies have been reluctant to allow producers to use more than 10-20 percent RAP. A survey conducted by Federal Highway Administration (FHWA) showed that many state transportation agency specifications allow up to 30 percent RAP in the mixtures even though a majority of these states are still only using 10-20% RAP (1). Some reasons for state transportation agencies being reluctant to use more RAP is due to concerns that the mixtures will be too stiff, less workable, difficult to compact and may lead to premature failures in the field. The recent increases in the cost of asphalt binder the diminishing supply of quality aggregates has made using higher RAP contents in HMA mixtures a priority for the industry as a method to optimize the use of available resources (1).

RAP contains asphalt binder that has been aged. Assuming a good blending of HMA and RAP, it has been a concern that incorporating higher RAP contents into HMA may lead to mixtures that are high in stiffness and accordingly prone to failures in the field (2). In an attempt to mitigate this stiffness increase, state transportation agency specifications have suggested the use of softer binder when RAP contents of 15-20% to be used in a mixture. However, the use of larger RAP contents (>20%) and a softer binder may still result in a mixture that is very stiff. Mixtures that are very stiff may experience low-temperature cracking and may crack prematurely for pavements experiencing higher deflections (1). Further testing of plant-produced mixtures with different RAP contents and different PG grade binders presented herein will address the concerns of state transportation agencies by comparing the binder properties of virgin binder to higher RAP content in mixtures. A significant increase in the stiffness of the RAP mixtures could have detrimental effect on the cracking susceptibility of the mixtures.

Asphalt Background

In a hot-mix asphalt (HMA) design, asphalt binder consists of about 15% of the volume. This small percentage plays a key role in physical characterization of the mix and is a major cost element. This led to a creation of Superpave testing to better understand the physical characteristics and failure mechanisms of asphalt binder (3).

1 Origin and Uses

As defined by The American Society for Testing and Materials (ASTM), asphalt is a black cementitious material, predominantly consisting of bitumen, which can be found in nature or as a by-product of petroleum processing (3). Natural asphalt can be found in Trinidad Lake (TLA) and is a result of evaporation of volatile portions of natural asphalt deposits, leaving behind asphalt fractions. Due to the substantial portion of mineral matter present and the difficult process associate with the mining of the material, natural asphalt is only used as add-in to petroleum derived asphalt (3). Therefore the majority of the United States use asphalt binder distilled from petroleum. Residuum from the distillation process becomes asphalt binder, which has greater gravity and lower sulfur content over natural asphalt (4). Therefore older crude oil source is more desirable.

Nearly 100 million metric tons of asphalt is used annually, a quarter of that being used by the United States. The vast majority of asphalt binder is used in roadway applications, but a big portion is also used by the roofing industry (3). In recent years, the switch has been made from concrete pavement to HMA pavement due to the fact that they are cheaper and easier to replace, repair and construct.

2 Applications

HMA is a flexible pavement that usually consists of multiple layers, generally made of 80% aggregate, 15% asphalt binder and 5% air voids by volume. The asphalt binder holds the mixture together serving as the 'glue' in the mixture. It is generally inexpensive and is a waterproof, visco-elastic adhesive. Although asphalt binder is a small portion of HMA mixture, it has a large influence on performance and overall cost (3). HMA pavement is favored over concrete pavement because it is flexible and the failure mechanisms are not sudden and catastrophic. Asphalt roadways can be constructed quicker and can be done in phases. Additionally, when replacing HMA, the pavement can be milled one day and paved the next day. Whereas, when concrete is laid, it needs to be cured (3). This kind of schedule flexibility does not exist with other pavement types, and that along with lower cost has resulted in its favorability.

3 Testing Process

As the need and use of asphalt continues to increase, it is becoming very important to understand the material and its properties. It is important to understand the failure mechanisms and conditions under which failure occurs (3). In 1993 Strategic Highway Research Program (SHRP) created Superpave grading system to improve understanding of the material and improve its selection. This system correlates the climatic conditions with a performance grade of the asphalt binder, enabling the correct binder to be chosen based on the region where it will be used. Superpave enabled producers to better understand the effects of certain modifiers that can improve the performance of asphalt binder under certain conditions. With the previous testing system that involved a penetration and viscosity test, the effects of certain modifiers went unnoticed due to test temperatures or high viscosity (3,5). As modifiers and RAP used in asphalt production increase, it becomes increasingly necessary to understand the way in which they are altering the asphalt binders and their performance.

As previously mentioned, Superpave testing can be correlated directly with a performance grade, which provides a better understanding of the different failure mechanisms. Another option for analyzing binders is constructing master curves of frequency sweeps to a reference temperature. Master curve shows the correlation of stiffness or phase angle over a range of reduced frequencies (6). It also demonstrates a full range of properties from a glassy modulus to the viscous range.

Rheology Background

Rheology is a material's resistance to deformation which evaluates a material at time-temperature response. Rheology can be used to understand materials that exhibit plastic, elastic and viscous properties based on the test temperature (3). Asphalt properties vary greatly at different temperatures. At high mixing and compaction temperatures, it acts as a Newtonian-viscous fluid. At lower temperatures asphalt is an elastic material with relatively low creep deformation rates. At low temperatures it becomes a brittle elastic solid with very low creep and flow. Below the glass transition temperature (T_g), the asphalt is described as a glassy solid (4,6).

Rheological properties are based on the complex modulus and phase angle of the material as a function of frequencies and temperature. The complex modulus, G*, is the total resistance to deformation under a load. The phase angle, δ, is the distribution of response between in-phase and out of phase component (4,6). In-phase indicates the elastic component and out of phase represents the viscous component where energy is stored and lost respectively. Master curve can be created when the variation of G* and δ is observed as a function of frequency at a constant temperature (6).

Once the major failure mechanisms and the shift to rheology over empirical testing were outlined by SHRP, it was necessary to determine when each failure mechanism was most common and how to test for them in the laboratory setting. The properties and performance of asphalt binders are broken into four temperature ranges (3,6). Most binders are Newtonian fluids and act completely viscous above temperature of 100°C. This is the only temperature stage that will impact the mixing and compaction of asphalt because it is the only stage in asphalt pavement process where the temperatures will be this high. Binder at temperatures of 45° to 100°C is most susceptible to rutting failure. In this temperature range it is assumed that the binder is viscous and G* and δ are measured because they represent resistance to deformation and elasticity or recovery (3,6). At temperatures of 0°C to 45°C pavements usually have fatigue damage due to repeated loading cycle. Similar to rutting, G* and δ are measured to determine the resistance to failure. Both are functions of the frequency of loading. In order to get useful results, this must be simulated in the laboratory to model the rate of truck loading on the pavement. Asphalt pavements at temperatures of 0°C to -50°C, are in the thermal cracking zone due to the shrinkage affected by thermal stresses. The evaluation of this failure is measured by G* and δ, the stiffness and relaxation rate of the material respectively (3, 6). The understanding of failure mechanisms and the temperatures at which they do so, allows for more effective and useful test methods to develop.

Master Curves Background

Asphalt binders need to be evaluated by different means because they behave differently in cold, warm and hot temperatures. With the exception of a few polymer modified asphalts, most asphalts fall under the thermo-rheologically simple material (TSM) category (7).

As previously mentioned, asphalt binders at extremely low temperatures, act as a glassy solid. Binders transition to an elastic solid at slightly warmer temperatures, to viscoelastic material at intermediate temperatures and a viscous liquid at high temperatures. The majority of asphalt binders are covered with the general ranges of temperature. The majority of asphalt binders in the viscous range act linearly, as a Newtonian fluid, meaning that as shear stress increases so does shear rate and vice versa. Asphalt binder can act as shear thickening or dilatant fluids if it contains certain polymers. As such, shear strain increases with the viscosity. Warm asphalts that have not entered the linear range of a Newtonian fluid may act as pseudoplastic or shear thinning fluid. In this range, the viscosity decreases as shear rate increases (8). The relationship of the described asphalt binder at different temperature ranges is shown in Figure 1.

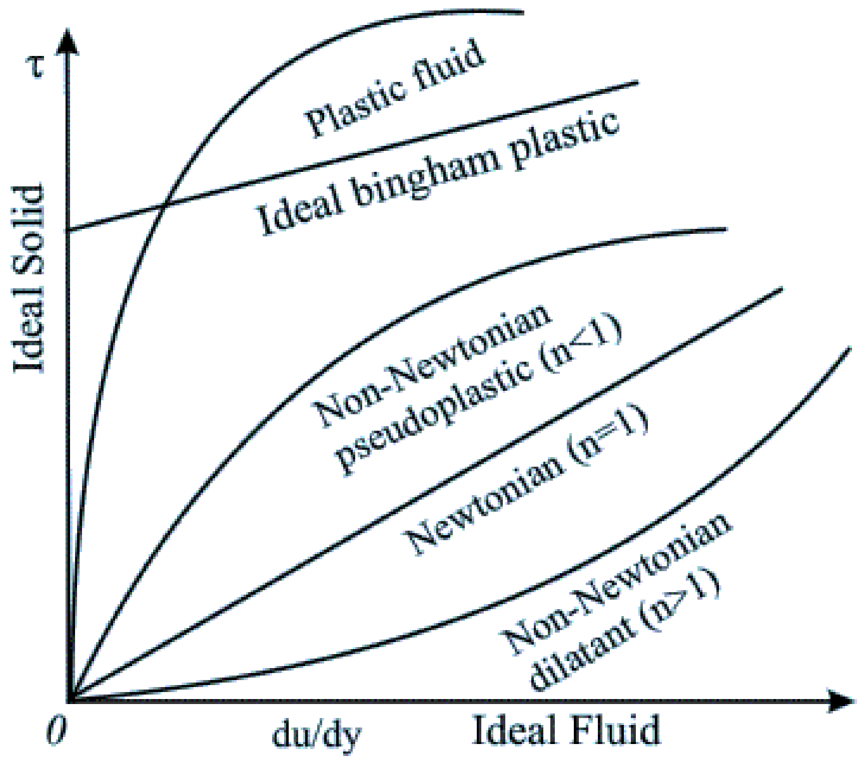

Figure 1 – Shear Stress and Deformation Rate Relationship of Different Fluids

The complex modulus, G*, and phase angle, δ, have been used to grade asphalt binders in the Superpave system with a pass/fail system.

The complex shear modulus is defined as

$$G^* = \tau_{max} / \gamma_{max}$$

Where

τ_{max} = max stress

γ_{max} = max shear strain

The complex shear modulus allows a transition between the elastic and viscous phases. If asphalt acted as elastic, the phase angle would be 0°, and if it was completely viscous, the phase angle would be 90° (8). The complex modulus is shown in Figure 2 below as a vector sum of the storage and loss moduli.

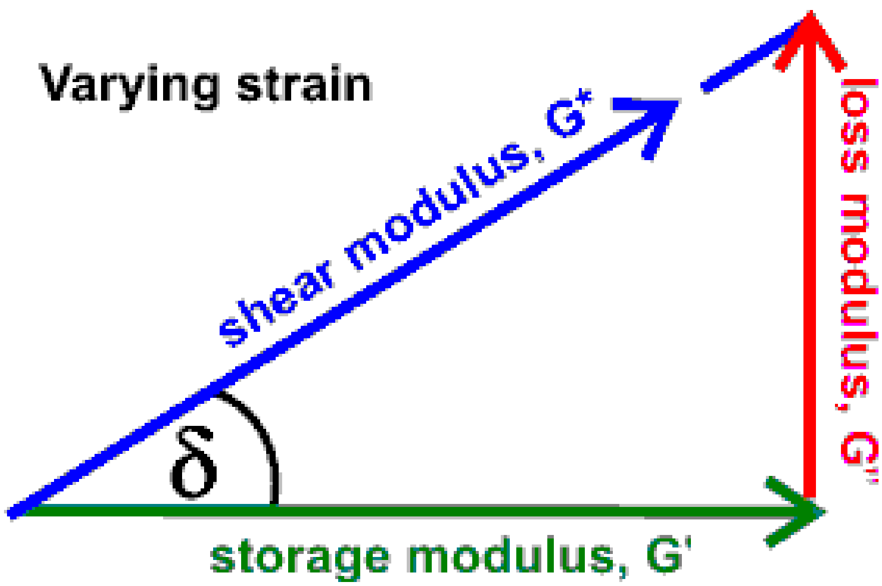

Figure 2 – Correlation of Complex, Storage and Loss Moduli

The storage and loss components of the complex modulus are also known as the elastic (G') and loss (G'') moduli, both of which serve their purposes in the evaluation of other binder properties. Asphalt binder master curves depend on four factors; the complex shear modulus, the frequency, the temperature and the shift factor (8). A master curve can be defined as the variation of G* or δ as a function of frequency at a constant temperature.

In order to construct a master curve, a sample is run through a frequency to extract the raw data required. G* or δ values are extracted through running a sample at a selected range of frequencies for each chosen temperature (8). The results are plotted as such shown in Figure 3, which then the data can be shifted using shift factors to become a continuous master curve.

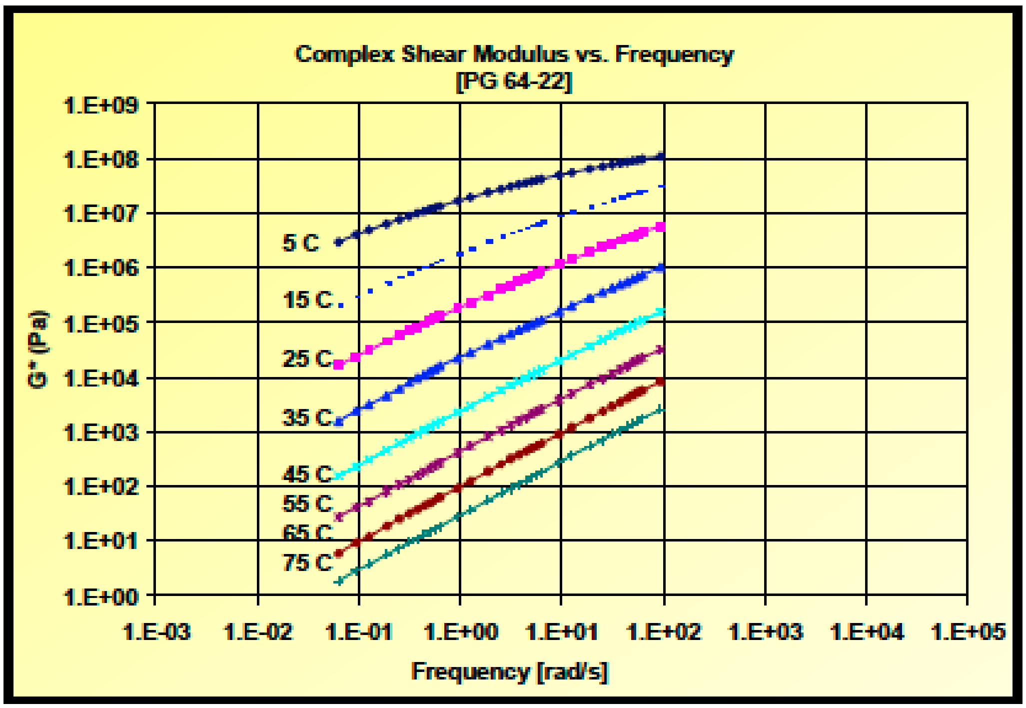

Figure 3 – Typical Frequency Sweep

4 Shift Factors

Different shift factors exist for different temperatures which allow the data to shift into a continuous master curve. Four types of shift factors have been used in shifting asphalt binder, which include the Arrhenius Model, Williams-Landel Ferry Model (WLF), the Sigmoid Model, and the Christensen-Andersen-Marasteanu Model

(CAM). In each case, an arbitrary reference temperature, T_{ref}, is selected at which the shift factor is equal to 1 (9).

By utilizing any of the mentioned shift factors or by manually shifting the data a user may create a master curve. However, this process is tedious and laborious especially with large sets of data. To ease the construction of master curves, software called RHEA was created by Abatech Inc which manipulates extracted data and creates master curves as well as other useful plots. The analysis in RHEA makes use of shifting procedures defined by Gordon and Shaw shifting methods (9). First, the software uses the WLF parameters to determine an initial estimate of the shift factor. The master curve is then refined by using a pairwise shifting and straight lines representing each data set, and then using a pairwise shifting with a polynomial representing the data being shifted. The order of the polynomial is an empirical function of the number of data points and decades of time / frequency covered by the isotherm pair. This gives shift factors for each successive pair, which is summed from zero at the lowest temperature to obtain a distribution of shifts with temperature above the lowest. The shift at T_{ref} is interpolated and subtracted from every temperature's shift factor, causing T_{ref} to become the origin of the shift factors (9). Frequency sweep results and a constructed master curve are shown in Figure 4.

RHEA software not only produces a master curve graph, but it also gives plenty of other plots that provide additional information as well as validate the results of the master curve. In order for the software to create a master curve, the data points in each isotherm cannot have great errors. The data collected with Malvern Direct Shear Rheometer may have few points that are outside the norm which will restrict RHEA from creating a master curve. However, with RHEA outlying points may be removed to create a master curve (10). Other than the master curves, RHEA can create G* versus δ – Black Space, Dobson Master Curve, Transient Compliance Master Curve Graph, Transient Modulus Stiffness Master Curve Graph, WLF shift factors and Isochrone Graphs (9).

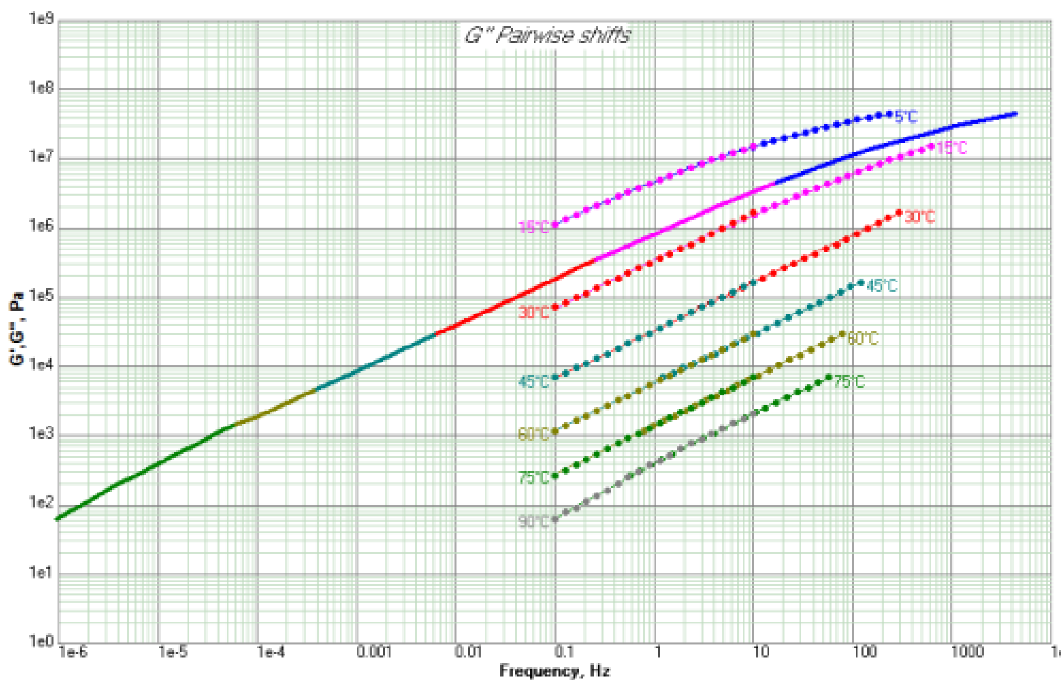

Figure 4 – Pairwise Shifts

5 Black Space in RHEA

Black Space Diagrams are useful in determining or detecting testing errors, which can be created with RHEA. As previously mentioned, RHEA allows for any point to be removed in order for the master curve to be created. These points that are out of norm may be the result of testing errors such as improper trimming of the sample, incorrect torque, or a compliance issue. Since asphalt binders do not exhibit sudden changes in their behavior with respect to time or temperature, any points out of the frequency sweep may be a result of testing error. The black space diagram is a plot of δ versus log $|G^*|$ and this plot is constructed using raw data. The diagram should provide a smooth curve if the material is linear, thermorheologically simple and if there are no testing errors. If these conditions are not met, the diagram will be a series of disjointed lines. At high temperatures, the black space graph should be reaching a horizontal asymptote as it comes near the realm of behaving as a Newtonian Fluid (11).

Rheological Index and Crossover Frequency

Glassy modulus, G_g, is the value that the complex modulus, storage modulus, and relaxation modulus approach at low temperatures and high frequencies and is normally very close to 1 GPa in shear loading. The steady state viscosity represents Newtonian viscosity. In dynamic testing, as the phase angle approaches 90°, it is approximated as the limit of the dynamic viscosity. As the dynamic master curve approaches the 45° line at higher temperatures and low frequencies is frequently referred to as the viscous asymptote (12).

The crossover frequency, ω_0, is defined as the frequency at the given temperature where tanδ is one or phase angle is at 45° and where the storage and loss moduli are equal. For most asphalt binders, the crossover frequency is very close to the point at which the viscous asymptote crosses the glassy modulus, but this is rarely precisely true. The crossover frequency indicates the general consistency of given asphalt at the selected temperature and can be thought of as a hardness parameter (12). In other words, lower crossover frequency means stiffer binder.

Rheological index, R, is a parameter defined as the difference between the glassy modulus and the dynamic complex modulus at the crossover frequency. Rheological index is an indicator of rheologic type and directly proportional to the width of the relaxation spectrum (12). Rheological Index, R, can also determine stiffness of the binder. As R-value becomes larger, it indicates a stiffer binder. The change in R-value is clear as the material ages.

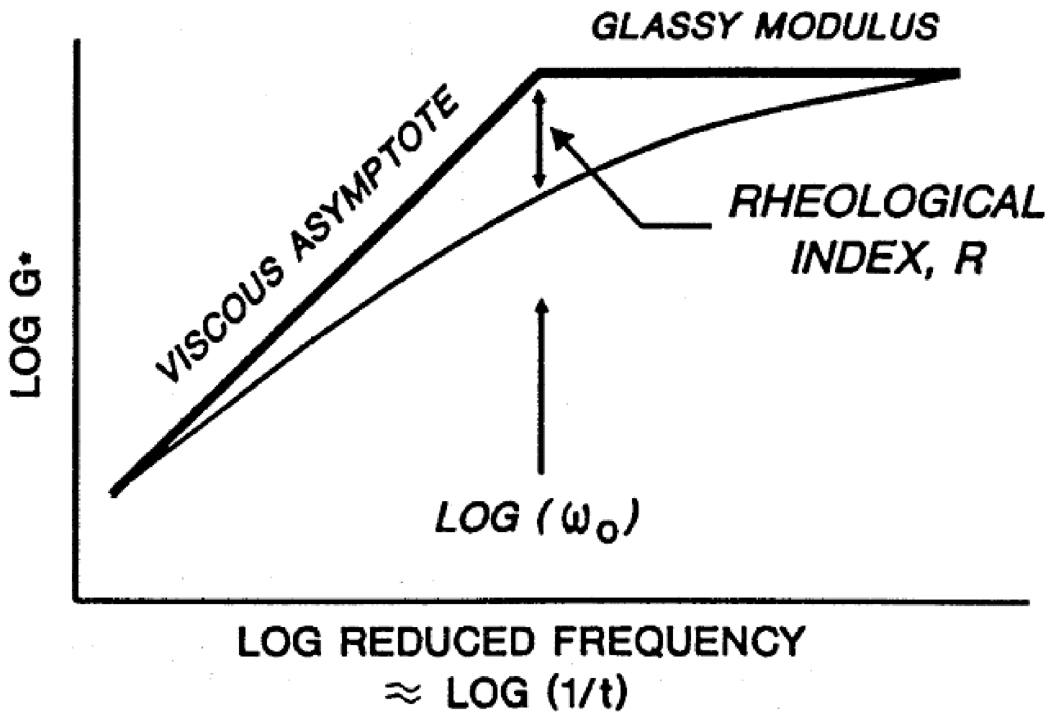

Figure 5 – Characteristic Parameters of the Dynamic Master Curve (12)

A diagram of a typical master curve is shown in Figure 5, graphically illustrating the meaning of these parameters. All of the parameters of this graph are meant to be clearly definable characteristic parameters and truly reflect the mechanical properties of asphalt (12). Also, just by observing Figure 5 graph it is clear that lower frequency indicates a stiffer binder because it would start reaching glassy modulus asymptote earlier. A softer binder would have a more linear master curve and a smaller R-value as opposed to stiffer binder.

Black Space

Thermal stresses are due to material shrinking when it's cooled. Normally there are two types of damage due to thermal cracking, transverse cracking and block cracking. Reports from field surveys suggest that block cracks are typically found in older pavements, whereas transverse cracks may occur as early as the first winter (13). Transverse cracking can be predicted with theories based upon concepts of pavement cooling to a 'limiting stiffness'. On the other hand, block cracking is difficult to predict, although it generally is believed to occur only after significant binder oxidation (14). Therefore, a parameter was developed in black space (G^* vs. δ) to predict transverse cracking.

'Limiting Stiffness' theories used in the Superpave System seem to explain transverse cracking but it's harder to understand block cracking. It is suggested by observations that block cracking is related to low binder ductility after aging (14). Ductility is considered to be an alternate relaxation parameter. Within the PG system, relaxation is defined by the measurement of the phase angle in the DSR. Phase angle and modulus, which can be recorded from DSR testing, relationship is needed to explain block cracking.

According to research conducted at Texas A&M (13), researchers believed that their proposed DSR parameter would relate to ductility at 15°C. The test was performed using the DSR at 44.7°C and 10 rad/s. They also did DSR frequency sweeps for the same binder that was PAV aged 0hours, 20 hours, 40 hours, and 80 hours. The test was done at three temperatures (5°C, 15°C, 25°C) and frequencies from 0.1rad/s to

100 rad/s using a 1%strain. The frequency sweep data was then used to create a master curve at 15°C using RHEA software for each binder (14). Their results were as expected, G* increased at all frequencies and the slope of the master curve became flatter with increased aging.

The DSR parameter G'/(η'/G') is determined at 15°C and 0.005 rad/s, but the testing at 0.005 rad/s would take a very long time, requiring almost 20 minutes to complete one oscillatory cycle. To improve the speed of the test, they chose to conduct testing at a standard frequency of 10rad/s. From their data, the researchers suggested the use of time-temperature superposition to obtain a value of G'/(η'/G') determined at 44.7°C and 10rad/s, is essentially the same as testing at 15°C and 0.005rad/s (14). The initial pick of 10 rad/s was selected because of its frequent use in AASHTO T315 and it is most familiar to asphalt technologists.

The (G'/(η'/G') value can be determined at 15°C and 0.005rad/s by picking out the points from a generated master curve. The G'/(η'/G') value was calculated using G* and δ (phase angle). To convert to a value at 15°C and 0.005rad/s, the calculated value is divided by 2000 (ratio of 10rad/s to 0.005rad/s) (14).

As the G'/(η'/G') value increases with aging of a binder, it indicates the decrease in ductility and a related decrease in expected durability. Black space diagrams are convenient way to look at the rheological behavior of the asphalt binder as aging occurs. In black space, the complex shear modulus (G*) is plotted as a function of the phase angle (δ) (14). Figure 6 shows rheological behavior of binders that were PAV aged for 0, 20, 40 and 80 hours in black space.

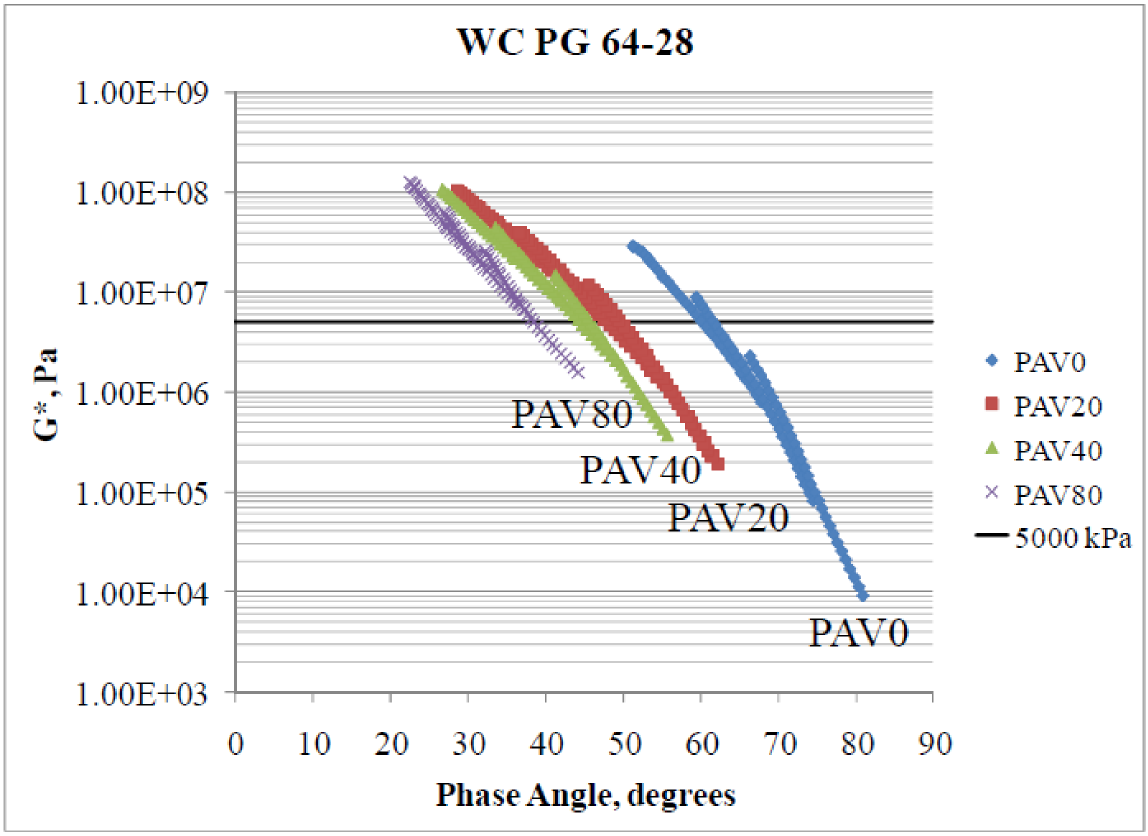

Figure 6 – Black Space Diagram of PAV Aged Binder of 0,20,40 and 80 hours (14)

At G* value of 5000kPa, a stiffer binder will have lower phase angle. Black space curves more to the left on the x-axis as binder ages. This figure indicates that the asphalt binder exhibits more elastic behavior as it ages.

As discussed in SHRP A-369 and Anderson (15), the Rheological Index, R, is the difference between the glassy modulus and the complex shear modulus at the crossover frequency.

It was hypothesized that the R-value should relate to the DSR parameter at the same temperature, because it's a measure of shear rate dependency. R was calculated for each of the master curves with the following equation that was developed during SHRP (14):

$$R = \frac{(log2) * log\frac{G^*(\omega)}{G_g}}{\log(1 - \frac{\delta(\omega)}{90})}$$

Where:

$G^*(\omega)$ = complex shear modulus at frequency ω (rad/s), Pa

G_g = glassy modulus, Pa (assumed to be 1E+09 Pa)

$\delta(\omega)$ = phase angle at frequency ω (rad/s), degrees (valid between 10° and 70°)

As the phase angle decreases towards 0°, the denominator decreases and the value of the R increase, and the same is true vice versa. In other words, at a given G*, the lower the phase angle the higher the DSR parameter and the lower the ductility (14). R can be determined using the equation above at nearly any phase angle. It is proposed that (G'/(η'/G') parameter can be expressed simply as a function of G* and δ (removing the frequency term), as $G^*(\cos\delta)^2/\sin\delta$. When expressed in this manner the limiting value in Figure 7 of 9E-04 MPA/sec at 0.005rad/s becomes $G^*(\cos\delta)^2/\sin\delta \leq 180$kPa (14).

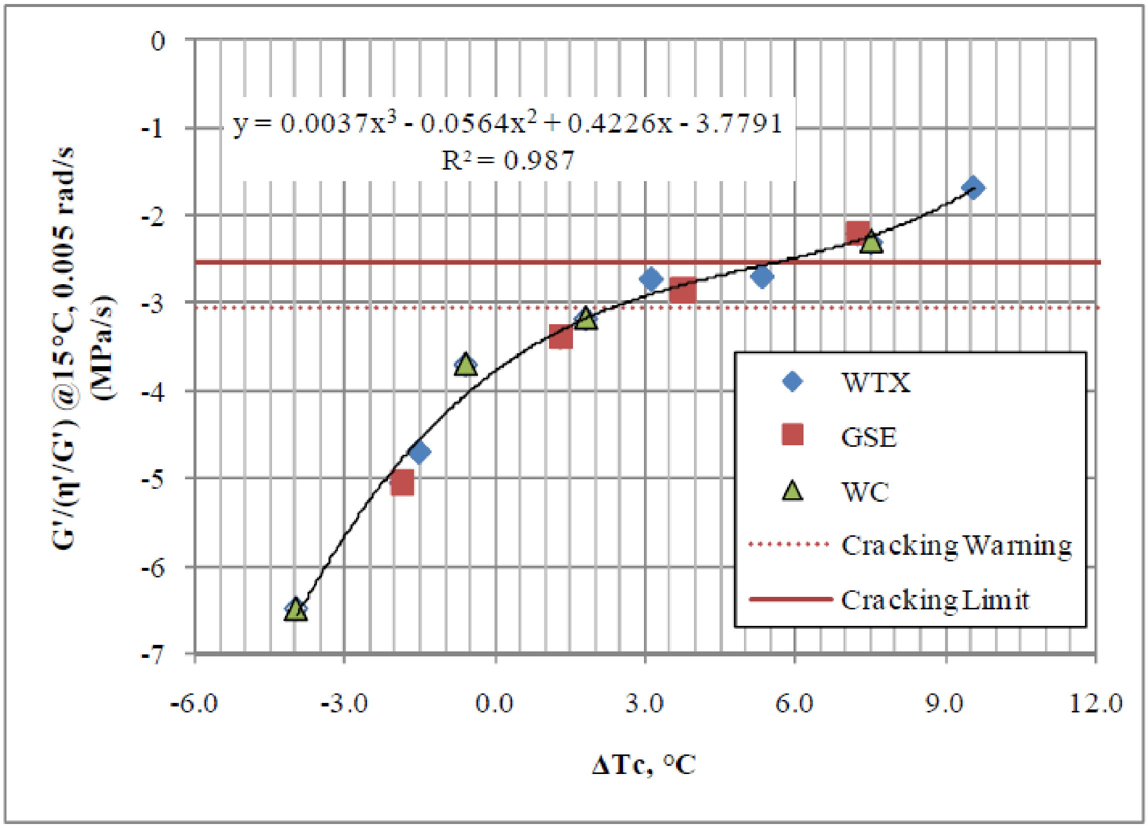

Figure 7 – Relationship Between Log (G'/(η'/G') and ΔT_c (14)

When this parameter is expressed as $G^*(\cos\delta)^2/\sin\delta$, it becomes very similar to the other Superpave parameters ($G^*/\sin\delta$ and $G^*\times\sin\delta$).

A great advantage of using parameters such as G^* and δ is that they can be plotted in a black space diagram. Black space diagrams clearly illustrate the effects of aging and help with the understanding of specification parameters.

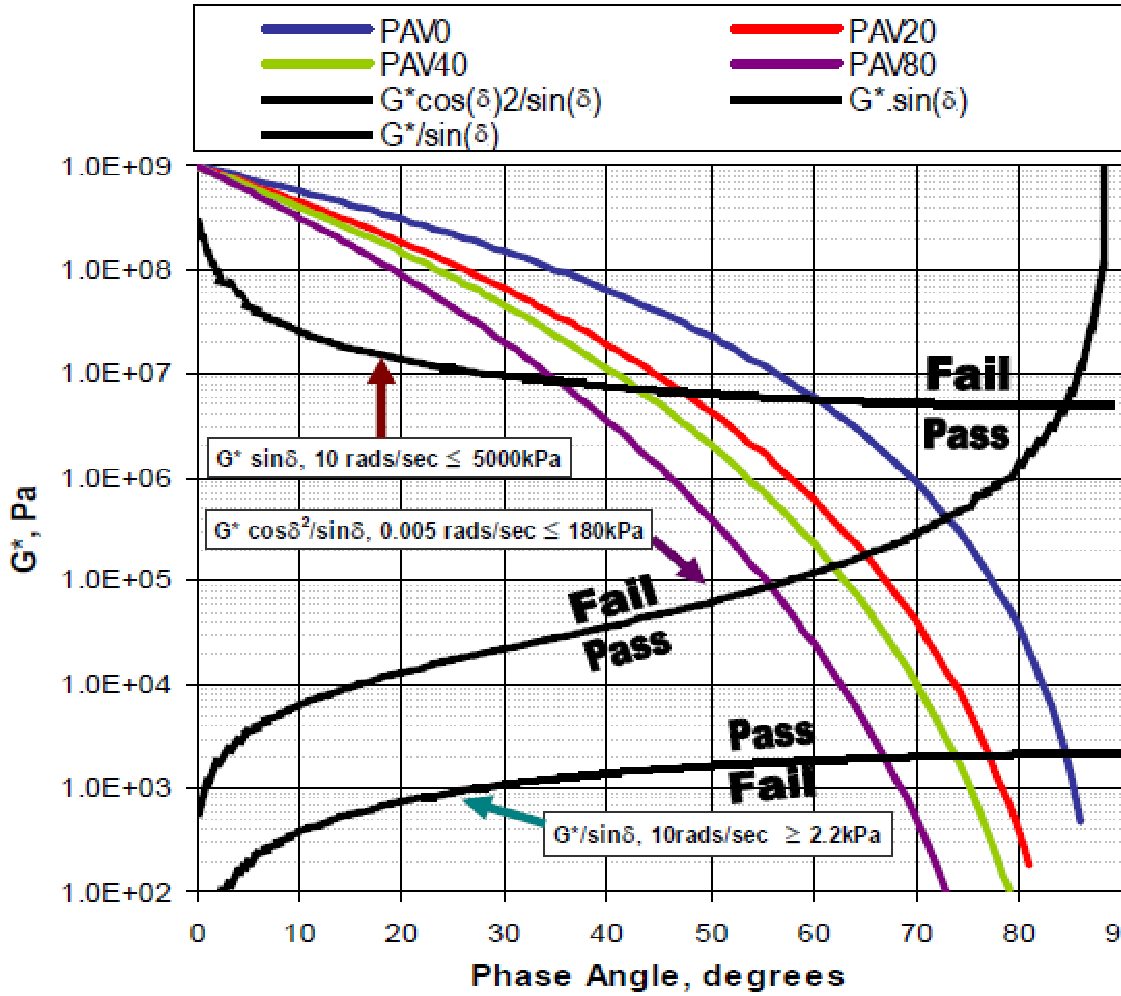

Figure 8 – Black space – Master Curve for Different Aging Conditions Compared to Different Specification Parameters (14)

Figure 8 shows the G*(cosδ)²/sinδ function compared to the other two Superpave parameters but is more sensitive to the phase angle in the range in which measurements would be typically made (14). This parameter is currently not a standard and is not yet recognized by National Cooperative Highway Research Program (NCHRP) and may only be of interest. In black space, the curves move from the lower right to the upper left as material ages. The (G'/(η'/G') parameter is another representation of G* and δ, and could be viewed in black space (14).

Recycled Asphalt Pavement Background

Over 90% of U.S. highways and roads are constructed with HMA. As these highways and roads age, they must be maintained and rehabilitated. Reuse of HMA will provide another source of aggregate, economic savings, environmental benefits, conserved energy, lowers transportation costs required to obtain quality virgin aggregate, and preserves resources. Additionally, using RAP reduces the amount of virgin asphalt binder required in the production of HMA, decreases the amount of construction debris placed into landfills and does not deplete nonrenewable natural recourses such as virgin aggregate and asphalt binder (1). It is important to recycle asphalt for the reason being that the materials compromise for about 70% of the cost to produce HMA shown in Figure 9.

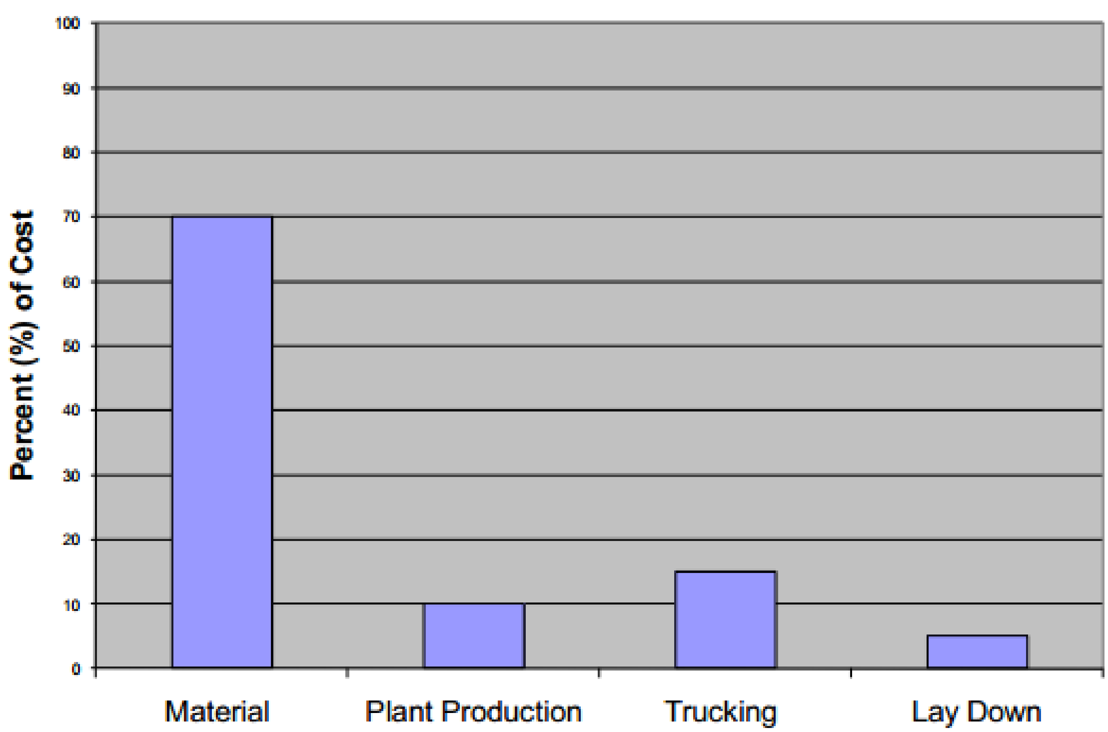

Figure 9 – Graph. Estimated Asphalt Production Cost Categories (1)

Recycling asphalt pavement became popular in the 1970s due to high cost of crude oil during the Arab oil embargo. Demonstration Project 39 was partially funded by the FHWA to construct paving projects using RAP and to document the effective use of recourses (1).

Since 2000 The New Jersey Department of Transportation has tracked the approximate quantities of RAP used. It found a significant increase in the amount of RAP used since 2002 as shown in Figure 10.

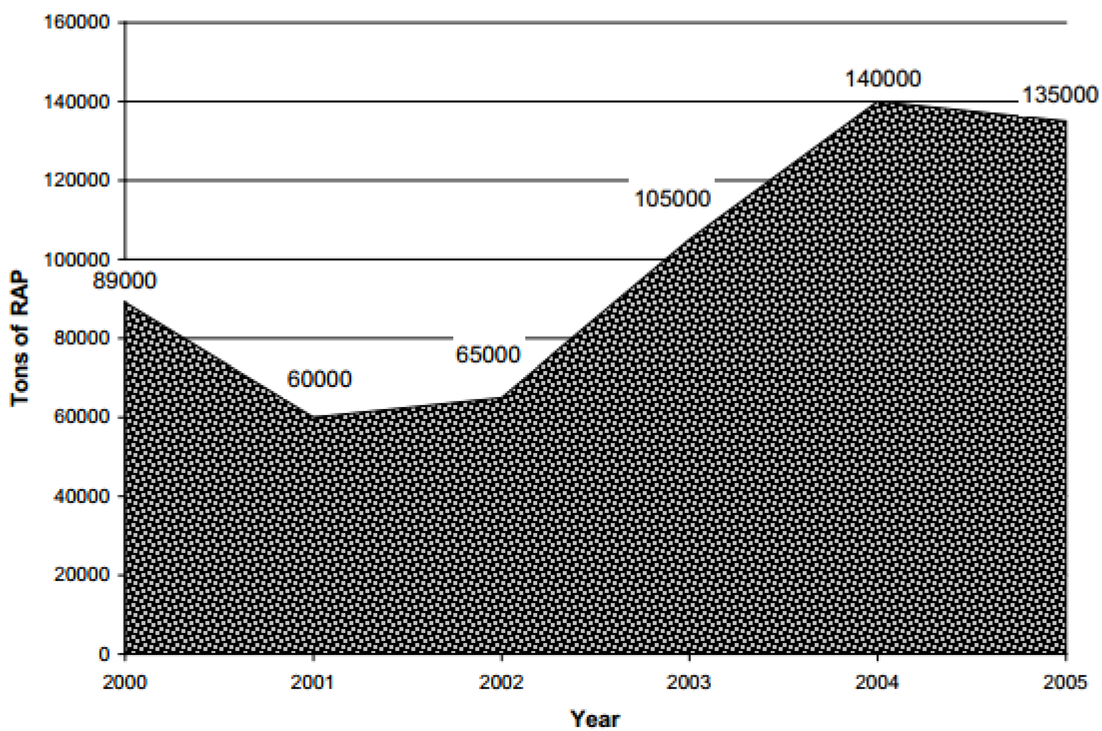

Figure 10 – Approximate Tons of RAP Used in Recycled Asphalt in New Jersey per Year (1)

According to NAPA survey, 68.3 million tons of RAP were used in new asphalt pavement mixes in the United States during 2012, which was nearly 22% increase from 2009. Also, that year was the first time the amount of RAP used by producers exceeded the amount collected (16).

Detailed Work Plan

A thorough Literature Review on relevant published books, technical reports, journal articles and newsletters regarding binder testing, recycled asphalt pavement, RHEA software, master curves and black space diagrams has been conducted. Based on the Literature Review, the following work plan was developed.

Plant produced mixtures were obtained from plants in three states: New York, New Hampshire, and Vermont. For these mixtures, the percentages of RAP in the mixtures were 0%, 20%, 30% and 40%. The PG binder utilized were a PG 52-34, PG 58-28, PG 64-22 and PG 64-28. The exact RAP percentage and PG binder combinations are shown in Table 1.

Binder Material	Callahan NY 58-28	Callahan NY 64-22	Pike NH 64-28	Pike VT 52-34	Pike VT 64-28
RAP Content		Virgin	Virgin	Virgin	Virgin
		20%	20%	20%	20%
	30%	30%	30%	30%	30%
	40%	40%	40%	40%	40%

Table 1 – Exact RAP Percentage and PG Binder Combination of the Mixtures

These mixtures were then sent to Rutgers University Center of Advanced Infrastructure and Transportation (CAIT) Laboratory for testing. The project was executed in multiple steps.

1. Verification/Calibration of extraction and recovery process
2. Extraction and recovery of all 18 plant produced mixtures

3. PG grading of the mixtures (direct shear rheometer (DSR) and bending beam rheometer testing (BBR))
4. Frequency sweep testing using 4mm plate with Malvern DSR
5. Calculations of DSR and BBR data to obtain continuous grade for each binder
6. Construction of master curves with RHEA from DSR 4mm plate results
7. Creating black space and, crossover frequency and R-value graphs with data obtained from RHEA
8. Evaluation of results

6 Extraction and Recovery

The first step to testing North East Pool Fund Study (NEPFS) mixtures is to extract and recover (ER) the binders, carefully separating binder from aggregate. This is a two phase process. First, the asphalt binders need to be extracted from HMA in accordance of AASHTO T164 method "A" procedure using trichloroethylene. Second, the asphalt binders need to be carefully recovered in accordance of AASHTO T170 procedure using the rotary evaporator (17).

Preliminary steps were taken to ensure that the extraction and recovery process was completed with minimal errors. Initially the first few extractions and recoveries were done using asphalt binder with known continuous grades. Then the recovered binder was PG graded and compared with original continuous grades. These results were almost identical, but this part of testing was done only using asphalt binder and not mixtures with aggregate in it. In addition to this initial testing, in 2013 CAIT of Rutgers University participated in a sensitivity study, where CAIT and 10 other laboratories extracted and recovered a binder and performed a PG grade on that binder. The result of this study is shown in below in Table 2.

Lab #	Method	Solvent	PG Continuous Grade		
			High	Inter.	Low
1	D 5404 - M	Toluene	66.2	21.4	-26.4
2	D 5404	Toluene	66.4	20	-26.3
3	D 1856	TCE	66	19.7	-26.9
4	D 5405	Toluene	66.7	22	-23.2
5	D 1856	TCE	67.5	20.7	-26.3
6	D 1856	TCE-R	67.7	21	-26
7	D 5404	TCE	67.4	20.4	-26.4
CAIT	**D 5404**	**TCE**	**66.2**	**20.8**	**-26.3**
9	D 5404	Toluene / 15% Ethanol	66.9	20.4	-26
10	D 5404	TCE-R	61	18.7	-27.3
11	D 5404	Toluene	64.3	25	-26.6
		Average =	66.03	20.92	-26.15
		Std Dev =	1.91	1.61	1.05
		Max =	67.70	25.00	-23.20
		Min =	61.00	18.70	-27.30
		Range =	6.70	6.30	4.10

Table 2 –Sensitivity Study Results of Extracted and Recovered Binder

Our laboratory performed very well in this study. For high, intermediate and low temperatures we were within ± 0.2°C. The percentage error for high, intermediate and low temperatures with respect to average of all the labs were 0.25%, 0.57% and 0.57% respectively. This study confirms the preliminary testing that our procedure has minimal errors and our results are nearly flawless for this step of the project.

For a better perspective of the results refer to Figure 11 through Figure 13. These figures show how the results from each laboratory compare to the average and one another. The number 8 red bar in the graphs represent Rutgers laboratory while the other 10 bars are the other well established laboratories. The black arrow points at the line representing average temperature. It is clear that Rutgers laboratory extraction and recovery falls right in the average of all the laboratories that participated in this study.

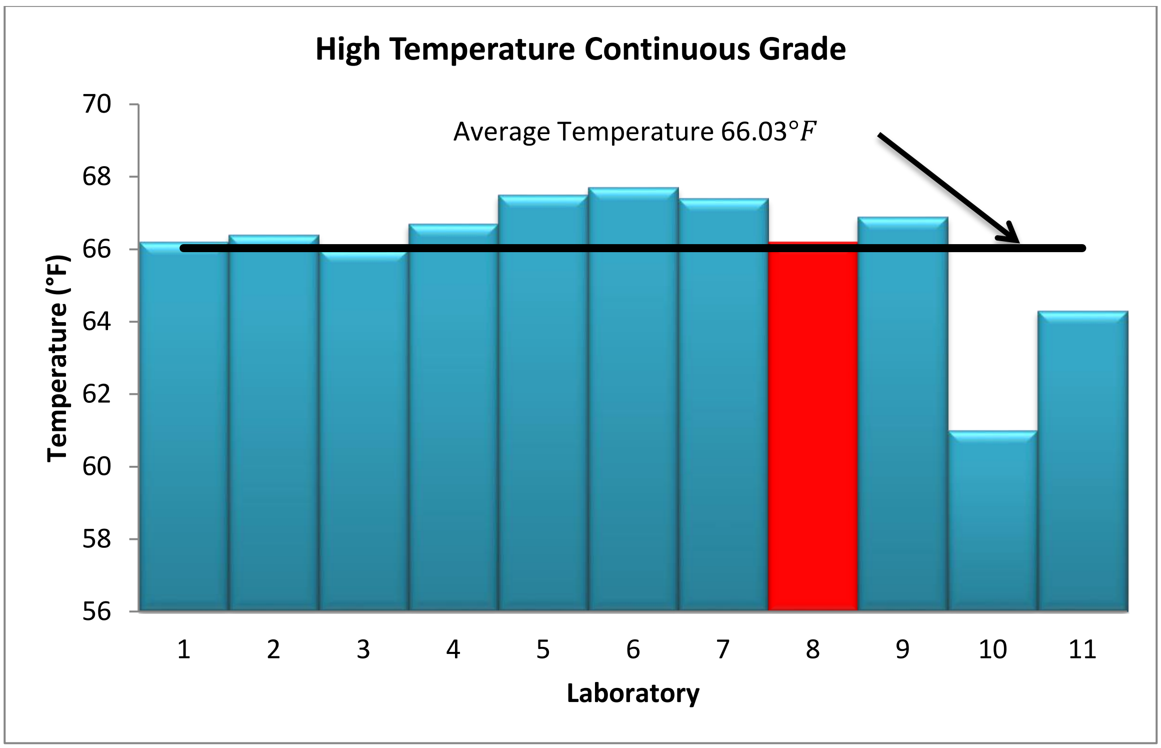

Figure 11 – Comparison of High Temperature Continuous Grade of Extracted Binder between Different Laboratories

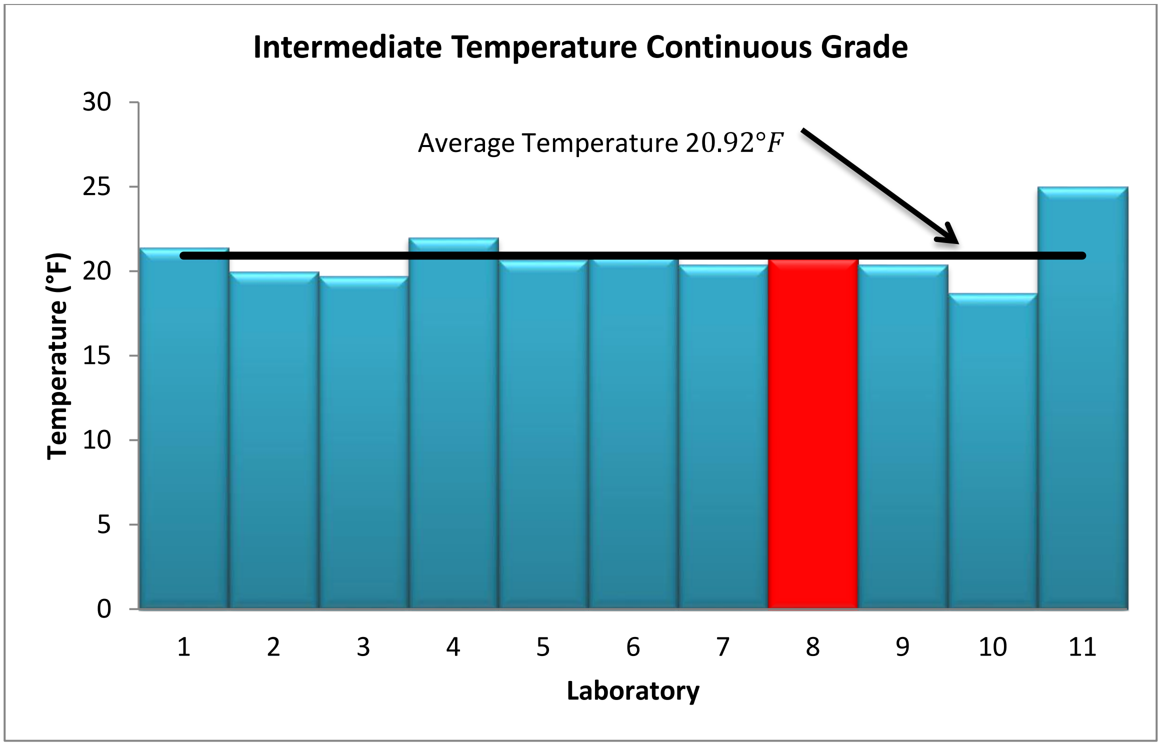

Figure 12 – Comparison of Intermediate Temperature Continuous Grade of Extracted Binder between Different Laboratories

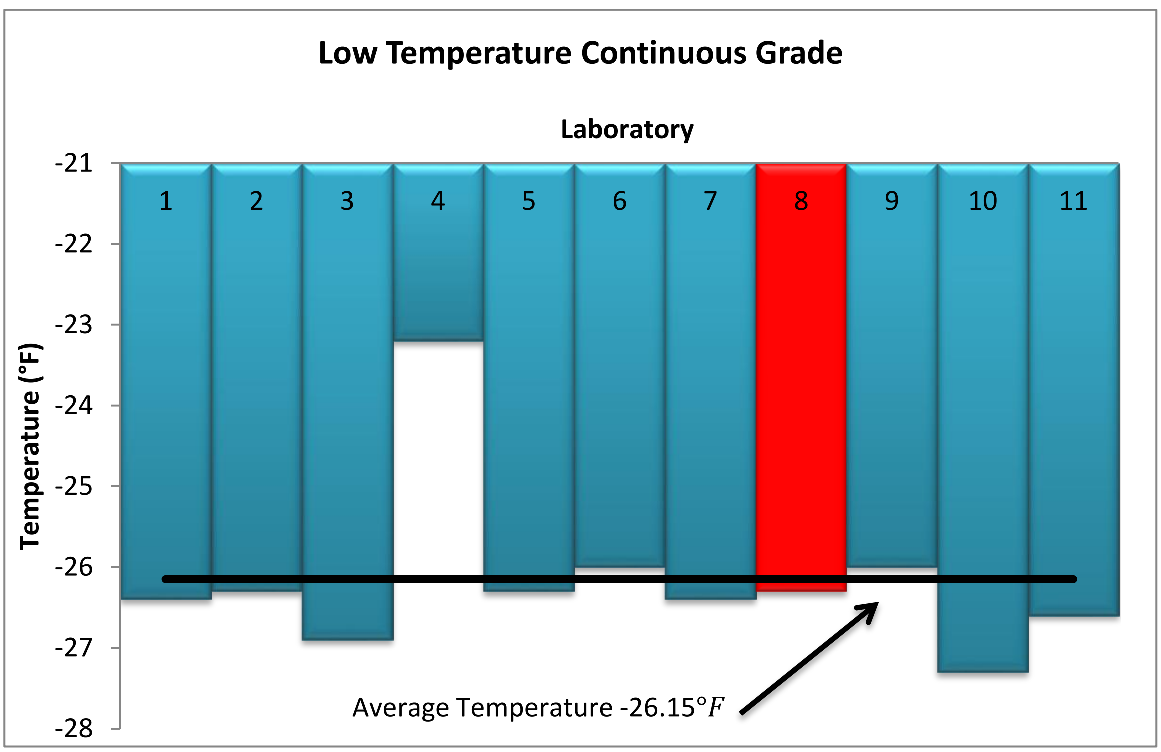

Figure 13 – Comparison of Low Temperature Continuous Grade of Extracted Binder between Different Laboratories

6.1 Extraction

As previously mentioned the extraction process is in accordance to AASHTO T164 procedure and is the first phase of the process (17). The test sample is heated in an oven of 110 ± 5°C, and then the sample is broken down and placed into extraction bowl shown in Figure 14. The bowl containing test sample is then placed into extraction apparatus (centrifuge). The sample is covered with trichloroethylene and allowed for sufficient soaking time for solvent to disintegrate material, but not exceeding 1 hour. A dried filter, also shown in Figure 14 is placed around the rim of a bowl and cover on the bowl is tightly clamped. A beaker is set up to collect the extract, centrifuge is slowly started and the speed is gradually increased until solvent ceases to flow from the drain. Centrifuge is then stopped and additional 200 mL of solvent is added to sample and the procedure is repeated. This step is repeated a minimum of three times and until extract becomes a straw color. The extract is completely removed of aggregates and collected in a suitable beaker. In this first phase, extract is a mixture of binder and trichloroethylene (17). All of the aggregate is removed from the mixture.

Figure 14 – Extraction Bowl and Filters

In phase two, continuous flow centrifuge shown in Figure 15, will remove any fine particles that has passed through the filter in the first extraction bowl. The extract is transferred

Figure 15 – Continuous Flow Centrifuge

to a feed container equipped with a feed control valve. The centrifuge is started, when the operational speed is obtained, the control valve is opened and allowed the extract to flow at a rate of 100 – 150mL/min. After all of the extract has passed the centrifuge and is collected in a suitable container, the feed mechanism is fed with solvent until the extract is colorless. The extract is now ready for step two of this process. Any fine particles that were presented in the extract before phase two is now removed and collected in a cylinder (17). This mixture of asphalt binder and trichloroethylene is now free of fine particles and ready for the next step of the process to separate asphalt binder from trichloroethylene.

6.2 Recovery

Step two of the process is in accordance to AASHTOT170 Recovery of Asphalt from Solution Using the Rotary Evaporator procedure (17). The Rotary Evaporator is shown in Figure 16. This process is intended to recover asphalt from a solvent using the rotary evaporator to ensure that changes in the asphalt properties during the recovery process are minimized.

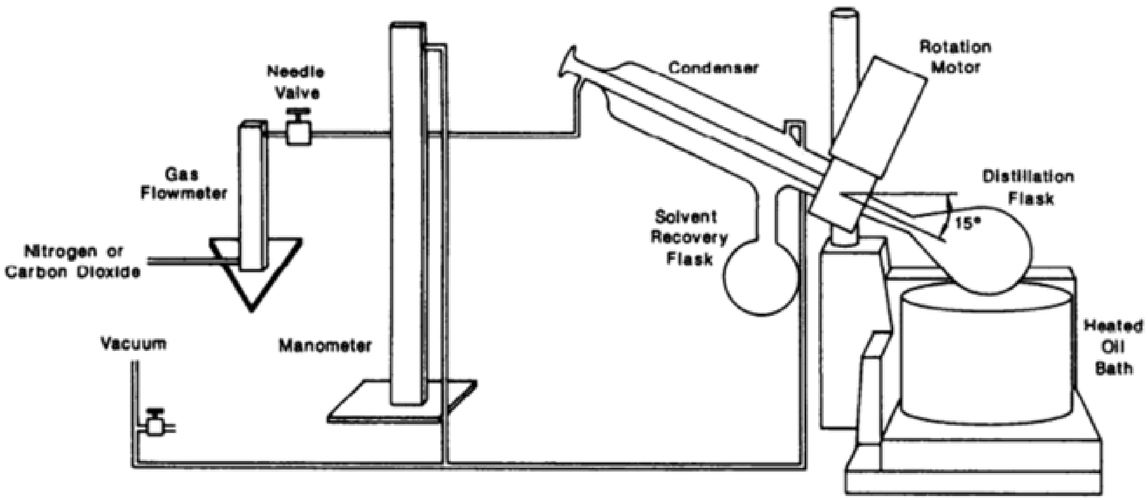

Figure 16 – Rotary Evaporator and Recovery System

Oil bath is heated to a temperature of 140 ± 3°C and cold water is circulated through the condenser. Then a vacuum of 5.3 ± 0.7 kPa [40 ± 5 mm of Hg] below atmospheric pressure is applied and approximately 600 mL of asphalt solution is drew from the sample container into the distillation flask by way of sample line. After, carbon dioxide flow of approximately 500mL/min through the system and rotation of the distillation flask of 40 RPM is started (17). Then the flask is lowered into the oil bath and initial immersion depth of the flask is determined by the need to achieve a controlled solvent evaporation rate.

When the amount of asphalt solution within the distillation flask appears low enough so that more solution may be added, carbon dioxide is discontinued and more asphalt solution is added into the distillation flask. When the bulk of the solvent has been distilled from the asphalt and no obvious condensation is occurring on the condenser, a vacuum of 80.0 ± 0.7 kPa [600 ±5 mm of Hg] below the atmospheric pressure is slowly applied. Carbon dioxide flow is increased to approximately 600 mL/min and the spin of the distillation flask to about 45 RPM. When foaming subsides maximum vacuum is applied. This condition is maintained for 15 ± 1 min. At the end of the 15 min period, the distillation flask is removed from the apparatus and the flask is wiped clean of oil. The flask is inverted and placed into an oven at 165 ± 1°C [329 ± 2°F] for 10 to 15 min and let the asphalt to be poured into a proper size container (17). Asphalt binder has been recovered and PG grade will be performed to determine the continuous grade of the binders.

7 Binder Testing (PG Grade)

The next step to testing NEPFS mixtures is binder testing which includes Pressure Aging Vessel (PAV), Dynamic Shear Rheometer (DSR) and Bending Beam Rheometer (BBR). Extracted and recovered binder from step one was tested and binder properties were found and continuous grades were determined. Rolling Thin Film Oven (RTFO) test was not performed due to the assumption that the NEPFS plant produced mixtures were aged during the production and in step one of this work plan.

7.1 Pressure Aging Vessel

This process is in accordance to AASHTO R21. The PAV apparatus accelerates aging (oxidation) of asphalt binders by means of pressurized air and elevated temperature. This is intended to simulate the changes in rheology which occur in asphalt binders during in-service oxidative aging of approximately 10 years but may not accurately simulate the relative rates of aging. The apparatus is shown in Figure 17 along with PAV pans.

Figure 17 – Pressure Aging Vessel and Pans

Pressure Aging Vessel is turned on and let to preheat. Binders that are to be aged are heated up and poured into PAV pans. For each pan 50 ± 0.5 g of binder is added. Filled pans are placed in the pan holder which is then placed inside the PAV. When the desired temperature inside the PAV is reached, the air pressure is applied of 2.10±0.1 MPa and the test is started. The temperature and air pressure inside the pressure vessel is maintained for 20h±10min (17).

At the end of the 20-hr conditioning period, PAV will slowly reduce the internal pressure thus avoiding excessive bubbling and foaming of the asphalt binder. During depressurizing process, the vacuum oven is preheated to 170 ± 5°C. When the PAV is depressurized, the pans are taken out and placed in an over set to 168 ± 5°C for 15 ± 1 min. The pens are then taken out of an oven and scraped into a single container. When all the pans are scraped, the container is transferred to the vacuum degassing oven. The degas oven is started. The oven will maintain a temperature of 170°C for 15 min and then a vacuum of 15 ± 2.5 kPa absolute is applied for 30 min.

If any bubbles remain on the surface of the container after the degassing is done, they are removed by flashing the surface with a torch or hot knife (17). This aged binder is ready for further testing.

7.2 Dynamic Shear Rheometer

Dynamic Shear Rheometer test method is in accordance to AASHTO T315. This test method covers the determination of the dynamic shear modulus and phase angle of asphalt binders when tested in dynamic (oscillatory) shear using parallel plate geometry. It is intended for determining the linear viscoelastic properties of asphalt binders as required for specification testing and is not intended as a comprehensive procedure for the full characterization of the viscoelastic properties of asphalt binders. DSR is used to measure the complex shear modulus (G*) and phase angle (δ) of asphalt binders (17). The apparatus for this test is show in Figure 18 below.

Figure 18 – Malvern Dynamic Shear Rheometer

Since we assume that the extracted and recovered binder is already aged, the binder and PAV material will be tested using Malvern DSR. The binder is heated in the oven of 163°C and then poured in to corresponding silicone moldings. 25mm moldings were used for extracted and recovered material and 8mm moldings for PAV material. The samples are allowed to cool to room temperature for no more than 4 hours. While the samples are cooling, the DSR is prepared by starting a sequence made for RTFO (extracted and recovered) or PAV material. It will be preheated to a temperature corresponding to the high grade of the binder. The hardened samples are then loosened from the molding and gently pressed against the top surface of the pellet of the preheated test plate forcing the asphalt binder to adhere to the plate. Immediately after the specimen has been placed on top of the plate, the gap is minimized to a trimming height of 1.05mm and 2.1mm for 25mm and 8mm moldings respectively. Excess binder is trimmed by moving a heated trimming tool around the edges of the plates so that the asphalt binder is flush with the outer diameter of the plates. When the trimming is complete, that gap is decreased to 1mm and 2mm for RTFO and PAV material respectively. The decreasing of a gap is required to create a bulge (17). After the gap is set, it is preceded with the sequence. The Malvern DSR determines the high and intermediate temperatures by testing recovered and PAV material respectively.

7.3 Bending Beam Rheometer

Bending Beam Rheometer is a standard test method is in accordance to AASHTO T313. BBR is used for the determination of the flexural-creep stiffness or compliance an m-value of asphalt binders. It is applicable to material having flexural-creep stiffness values in the range of 20 MPa to 1 GPa and is mostly used with aged material. The test apparatus may be operated within the temperature range of -36 °C to 0°C. Test results are not valid for test specimens that deflect more than 4 mm or less than 0.08 mm when tested in accordance with this test method.

First is the preparation of metal molds. To prepare the metal molds, very thin layer of grease is spread on the interior faces of the three long metal mold sections. Plastic strips are then placed on the metal molds and inspected for any air bubbles that may be trapped underneath the plastic strip. The molds are then assembled using rubber O-rings to hold the pieced of the mold together. Inside faces of the two metal end pieces are covered with a thin film of glycerol and talc mixture to prevent the asphalt binder from sticking to the metal end pieces. Asphalt binder that is aged in accordance to AASHTO T240 or aged through plant production is placed in an oven of 168 ± 5°C. When the binder is sufficiently fluid it is poured into the metal molds and let cool for 45 to 60 min to room temperature. After cooling to room temperature, exposed faces of the cooled specimens are trimmed with a hot knife or a heated spatula (17). Just prior to demolding, the metal mold is cooled in a cold chamber for long enough to stiffen the test specimen so that it can be readily demolded without distortion.

When the asphalt beam is demolded it is placed in BBR. The beam is conditioned for 1 h ± 5 min. After conditioning, the test specimen is placed on the test supports, a 35 ± 10 mN contact load is manually applied for no longer than 10 sec and the test is started. BBR test is required to obtain a low temperature of the PG grade.

7.4 RHEA / Dynamic Shear Rheometer

A two-step process is used for the last step of testing. First the data was collected with DSR WRI Test Sequence with LVER Determination by Strain Sweep with Temperature Choices. Then the data is extracted from rSpace (DSR program) into an excel spreadsheet, altered and saved with a file extension that later was recognized by RHEA.

The RTFO binder is heated in the oven of 163°C and then poured in to corresponding 8 mm molding and let cool to room temperature. The DSR gap is zeroed at 0°C and then preheated to 45°C. When the temperature has been reached, the sample is loaded on a 4 mm plate and a rough trim conducted at a gap of 2.5 mm. Then another trim is conducted again at 2.1 mm. The gap is changed again to 2.0 mm and the WRI Test Sequence is run. The parameters of this sequence are 0.1 rad/sec to 100 rad/sec frequencies for temperatures of -30°C, -15°C, 0°C and 20°C. For higher temperatures of 40°C and 60°C, the frequency range is reduced to 0 rad/sec to 50 rad/sec (10). These parameters are shown in Table 3.

Temperatures	Frequencies	Reference Temperature
-30°C, -15°C, 0°C, 20°C	0.1 rad/s to 100 rad/s	25°C
40°C, 60°C	0.1 rad/s to 50 rad/s	

Table 3 – Parameters Used in DSR Testing for Master Curves

When the sequence is finished running, the file is saved and opened in rSpace. From this file, the temperature, frequency and shear modulus is extracted into excel spreadsheet where that data is altered and saved as a file that can be read by RHEA. Then master curves are created in RHEA from previously saved file. Any points that are out of the norm can be removed to make a smooth master curve. Once the master curve is created, phase angle and G* is extracted from RHEA at 15°C and 0.005rad/sec will be used to plot in black space graph. In addition to phase angle and shear modulus, the crossover frequency as well as the R-value are also recorded at 15°C and 0.005rad/sec.

Statistical Analysis of Data

Binder from each plant produced mixture was extracted in accordance with Method A of AASHTO T164 "Quantitative Extraction of Asphalt Binder from Hot Mix Asphalt" and then recovered in accordance with AASHTO T170 "Standard Practice for Recovery of Asphalt from Solution Using the Rotary Evaporator" (17). The effect of the production parameter on the rheological properties of the binders was examined by PG grading, constructing a master curve, plotting G* and phase angle in black space and creating crossover frequency and R-value graphs for each recovered binder. The master curve provides a relationship between binder stiffness (G*) and reduced frequency over a range of temperatures and frequencies. Accordingly, the master curve makes it possible to predict viscoelastic properties over a wide frequency range, beyond the range that actual measurements were carried out and also to predict viscoelastic properties at any temperature (18, 19). The master curves of recovered binder from the RAP mixtures were compared to the master curves of the virgin recovered binder to evaluate the effect of RAP contents on the viscoelastic properties of binders. Values of G* and δ were recorded at 44.7°C and 0.005rad/s from master curve and plotted in black space. In addition to black space diagrams, crossover frequency and R-value graphs were also generated.

8 Rutgers Methodology

In order to obtain an idea of the "aging" characteristics of the asphalt binder, it is important to look at the form or shape of the G* master curve. Exemplified in Figure 19 and Figure 20 are the G* master curves for a PG64-22 asphalt binder which had been exposed to various levels of laboratory aging; RTFO, 20, 40, and 60 hours in the PAV (20). As the level of aging increases, the shape of the master curves can be seen becoming flatter and the magnitude of the shear modulus stiffer, as shown in Figure 19 and Figure 20.

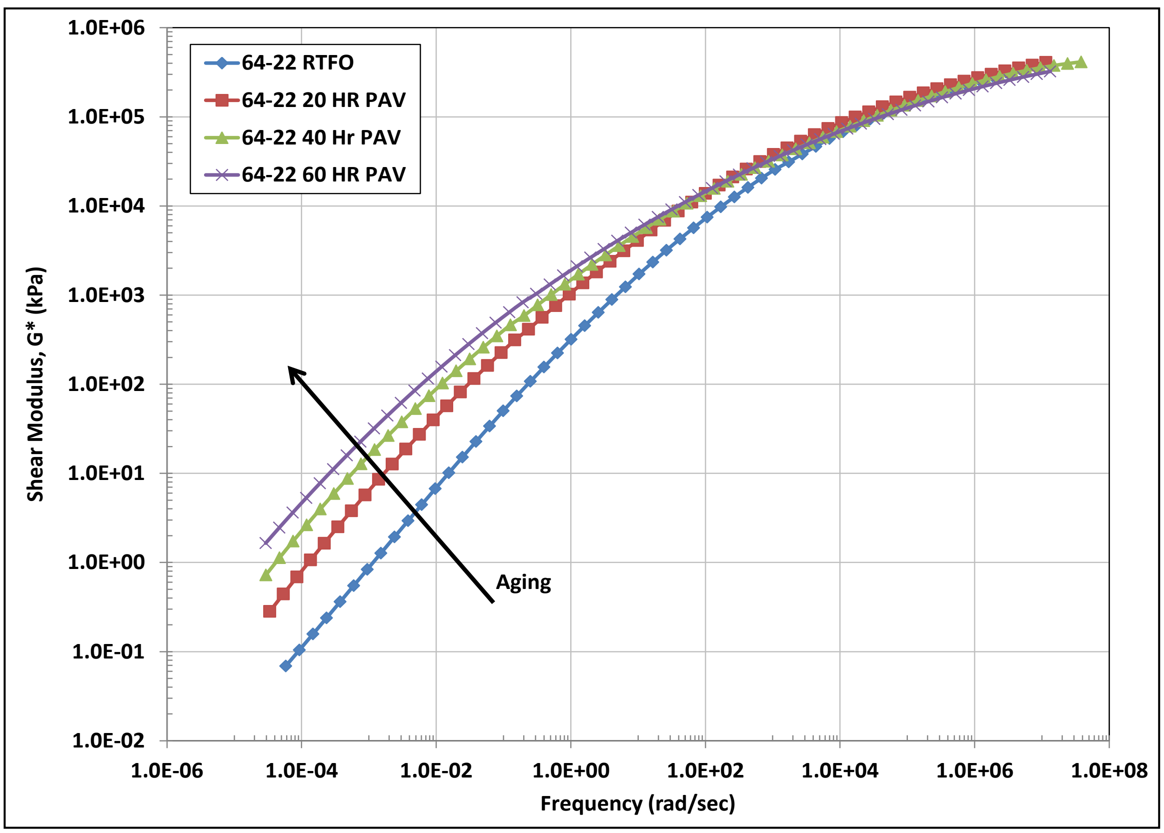

Figure 19 – Master Curves for PG64-22 Asphalt Binder (20)

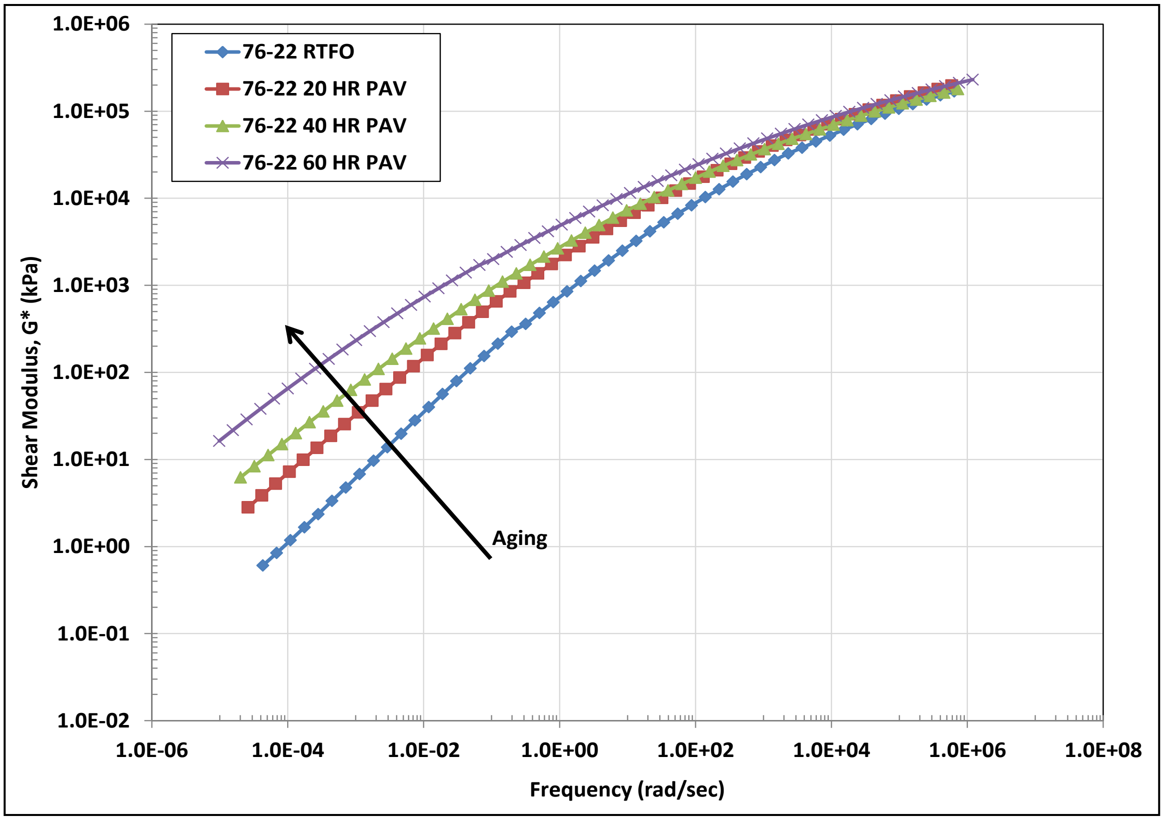

Figure 20 – Master Curves for PG76-22 Asphalt Binder (20)

Figure 5 exemplifies two parameters, Rheological Index (R) and Crossover Frequency (ω_o), which are shape parameters within the model used to describe the inflection and general slope of the G* master curve. This phenomenon had been originally noted by Christensen and Anderson, who developed the Christen-Anderson Model which describes shape parameters to define the master curves. With this in mind, an asphalt binder that undergoes different levels of aging should show a change in shape parameters. Figure 21 takes into account the Rheological Index and Crossover Frequency changes reflected by the G* data in Figure 19 and Figure 20. The shape parameters move from the upper left quadrant of the R – ω_o

Space to the lower right quadrant (20). One should be able to determine whether or not an asphalt binder has undergone a degree of aging, although a specific magnitude would not be able to be determined.

Taking into account the work by Glover et al, Anderson et al, and Rowe, the master curve analysis can be used to evaluate the non-load associated cracking potential. Rowe proposed, based on the original work of Glover et al, to use master curve analysis to evaluate the parameter, $G^*(\cos\delta)^2/\sin\delta$, at a temperature of of 15°C and loading frequency of 0.005 rad/sec (14).

Expressed in these terms, Figure 22 proposes a limiting value of 9E-04 MPa at 0.005 rad/sec becomes $G^*(\cos \delta)^2/(\sin \delta) < 180$ kPa. Subsequently, Black Space (G^* vs. phase angle) can be used to express the master curve information. Using the same principles initially proposed by Glover et al, Rowe's Black Space provides a means of assessing an asphalt binder and pre-screening it to determine if it is susceptible to cracking (20).

Figure 22 exemplifies that when plotted in black space, the asphalt binders move from the right (Passing) side of the proposed criteria to the left side (Failing) side of the proposed criteria by using the same PG64-22 and PG76-22 asphalt binder samples from earlier. As one would assume that asphalt binders would be more susceptible to cracking as the degree of aging increases, the migration of test results is shown to be intuitive.

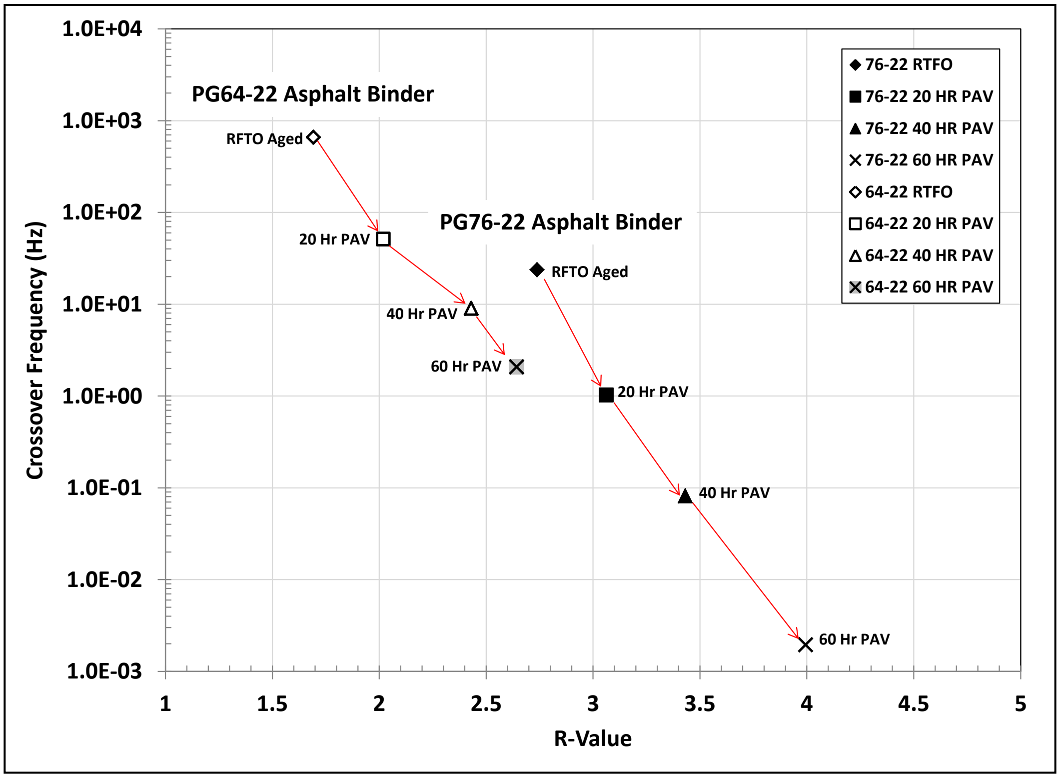

Figure 21 – Christensen-Anderson Model Shape Parameter Changes Due to Different Levels of Aging (20)

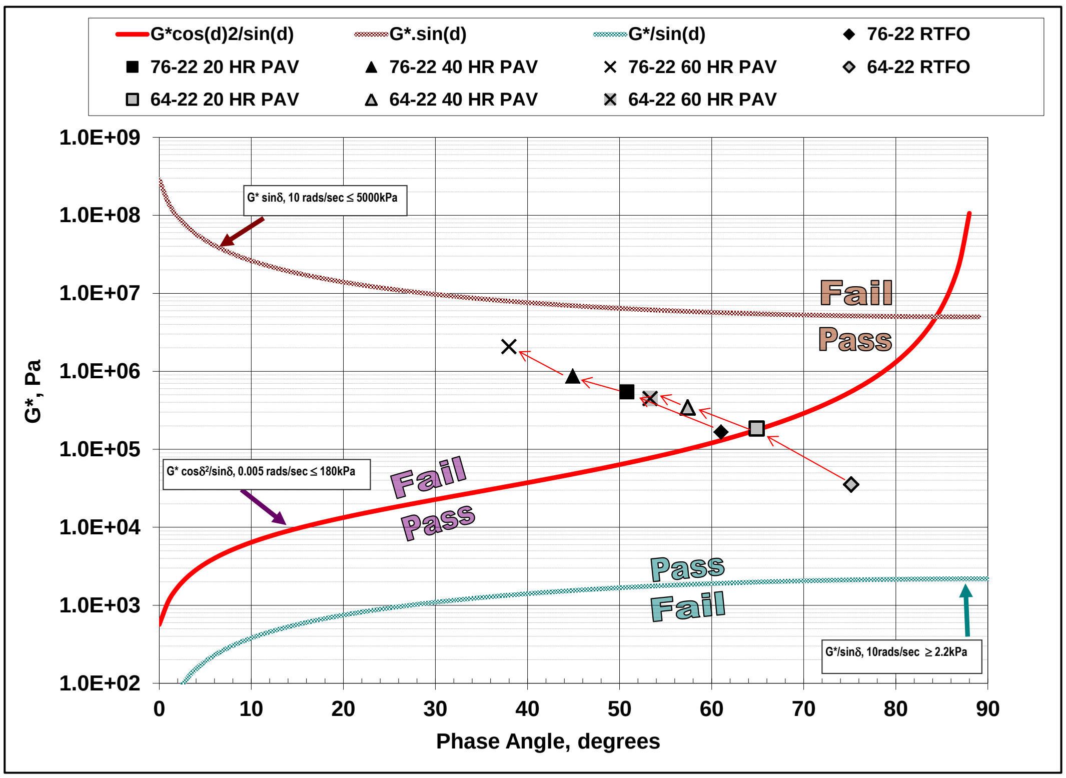

Figure 22 – Rowe's Black Space Analysis for Non-Load Associated Cracking Potential (20)

9 Performance Grade of Extracted Binders

All tank sampled and recovered binders were graded in accordance with AASHTO M320 "Standard Specification for Performance Graded Asphalt Binder". The results of the binder grading are shown in Table 4 and Table 5. The recovered binders were graded to determine the effect of plant type, use of RAP, use of a softer binder, and production parameters on the grade of the fully blended binder (RAP and Virgin). This was done by comparing the grade of the recovered binder from RAP mixtures to the grade of the recovered binder from mixtures with no RAP.

		Continuous PG Grade (°C)		
Mixture	Type	High	Low	PG Grade
Pike NH 64-28	Extracted 0% RAP	71.8	-28.4	70-28
	Extracted 20% RAP	76.7	-24.1	76-22
	Extracted 30% RAP	78.1	-26.5	76-22
	Extracted 40% RAP	79.8	-23.7	76-22
Callahan NY 64-22	Extracted 0% RAP	75.5	-22.2	70-22
	Extracted 20% RAP	78.3	-21.8	76-16
	Extracted 30% RAP	78.4	-19.9	76-16
	Extracted 40% RAP	80.9	-17.6	76-16
Callahan NY 52-28	Extracted 30% RAP	72.1	-26.5	70-22
	Extracted 40% RAP	81.7	-22.0	76-22

Table 4 – Binder Continuous Grading Results (New Hampshire and New York)

Based on the examination of Table 4 and Table 5, the following observations were made. The New Hampshire (drum plant) mixtures had a steadily increase in high temperature grade. Both, the high and low temperature grade of the binder, were increased by a single grade when RAP was added to the mixture. The New York (drum plant) mixtures (PG64-22) had a steadily increase in high and low temperature grade with the increase of RAP content. Similarly, New York 64-22 also had a single grade increase in mixtures with added RAP. There were only two New York mixtures (PG 52-28) that included 30% and 40% RAP content. A mixture with 40% RAP content had moderate increase in the continuous grade and a single grade increase in the high temperature.

The Vermont mixtures (batch plant) steadily increased in the high grade and low grade except for the 40% RAP content in a low grade when PG 64-28 was used. At the 30% and 40% content of RAP, the high temperature grade increased by a single and double grade respectively, while the low temperature grade increased a full grade for all binder with added RAP.

When a softer binder (PG 52-34) was used, the continuous grade steadily increased in both high and low temperature grade. The low temperature grade of binders with 30% and 40% RAP content decreased a full grade in each while the high temperature increased by a full grade only for the 30% RAP content.

		Continuous PG Grade (°C)		
Mixture	Type	High	Low	PG Grade
Pike VT 64-28	Extracted 0% RAP	67.4	-28.1	64-28
	Extracted 20% RAP	69.6	-27.0	64-22
	Extracted 30% RAP	74.7	-23.0	70-22
	Extracted 40% RAP	78.0	-24.9	76-22
Pike VT 52-34	Extracted 0% RAP	65.4	-28.3	64-28
	Extracted 20% RAP	68.3	-28.1	64-28
	Extracted 30% RAP	71.4	-26.3	70-22
	Extracted 40% RAP	68.6	-21.0	64-16

Table 5 – Binder Continuous Grading Results (Vermont)

Along with differences in plant type, there were also differences in storage time among the three different plants. The mixtures produced by both New York and New Hampshire drum plants were siloed at temperatures exceeding 300°F for over 2 hours. Meanwhile, the mixtures produced at the batch plant in Vermont had zero silo storage time prior to sampling. As noted above, all three plants witnessed changes in both high and low temperature PG grade. It would appear that stiffening witnessed in the asphalt binder grading may not be affected by the length and temperature at which the material is stored, as well as the method of mixing (drum or batch plant).

Given the concern that the use of more than 20% RAP in the asphalt mixture might be too stiff, binders with 30% and 40% RAP were compared to 20% RAP. All mixes from New Hampshire and New York with added RAP had no change in high grade temperature, with the exception of the softer New York binder that had a single grade jump from 30%RAP to 40%RAP. Vermont (PG64-28) mixtures of 30%RAP and 40%RAP had a single and double increase in high temperature respectively when compared to 20%RAP.

Figure 23 and Figure 24 shows the summary of the results from PG grading of the extracted and recovered binders. As expected, RAP stiffens the binder; however, the magnitude at which it affects each set differs. In this study, for every 10% RAP added high temperature and low temperature increases range from 1-3°C and 1-2°C. The average increase in the high temperature is 1.8°C and low temperature is 1.2°C for every 10% RAP added.

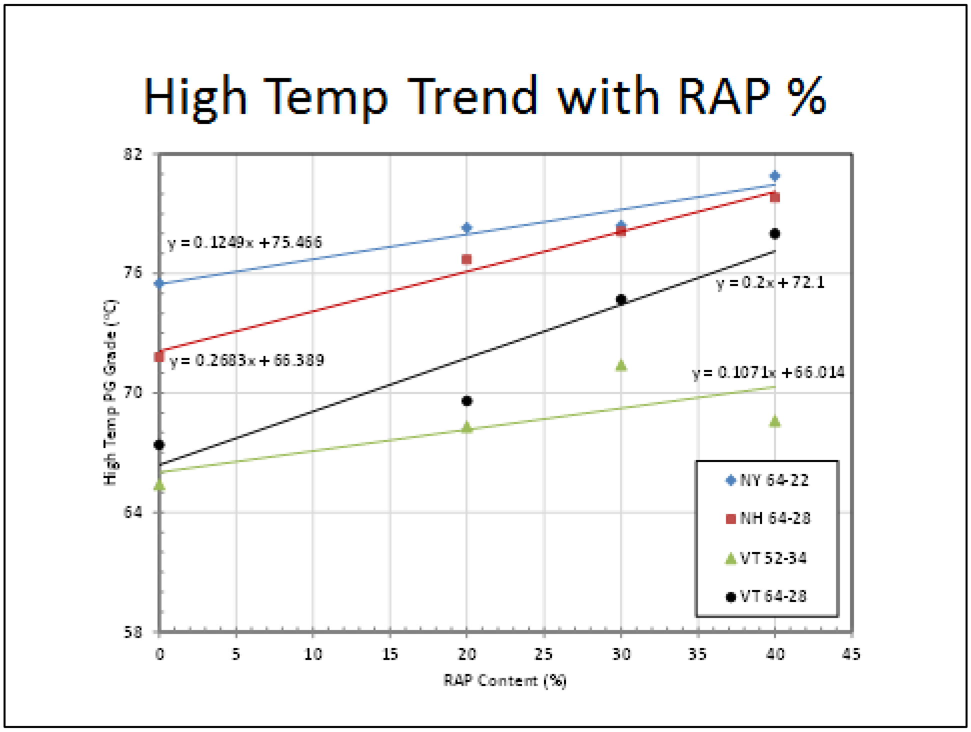

Figure 23 – Extracted and Recovered High Temperature PG Grade as a Function of RAP Content

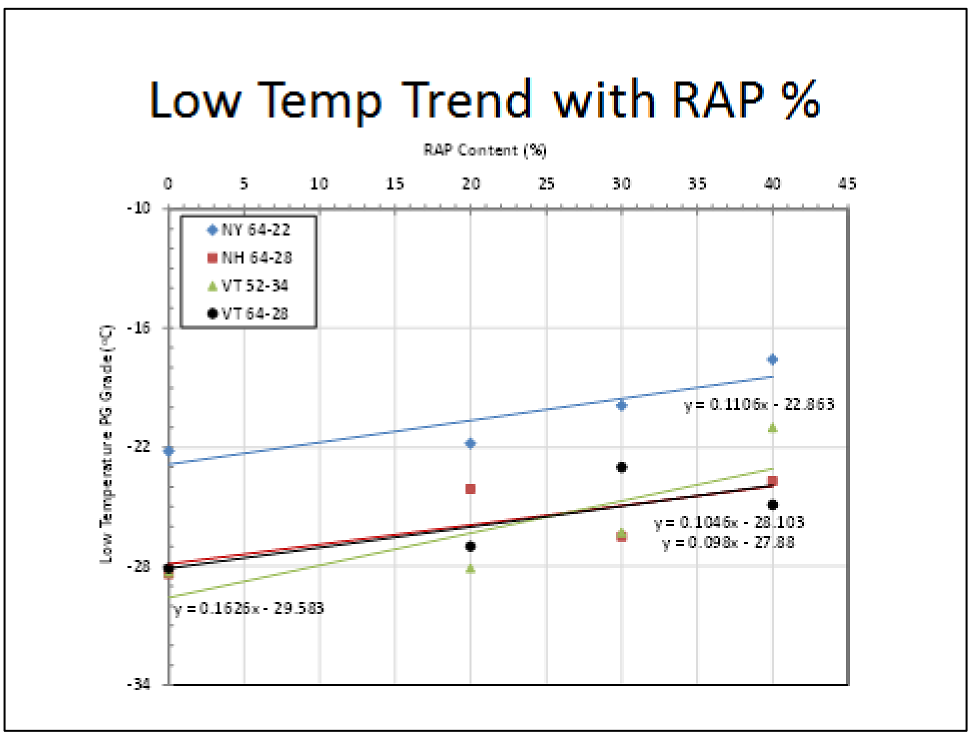

Figure 24 – Extracted and Recovered Low temperature PG Grade as a Function of RAP Content

10 Recovered Binder Master Curves

To completely characterize the stiffness characteristics of the recovered binders, master curves were constructed of the recovered binders. Master curves required Dynamic Shear Rheometer (DSR) and RHEA Program analysis. The DSR testing was conducted in accordance with AASHTO T315 "Determining the Rheological Properties of Asphalt Binder Using Dynamic Shear Rheometer" (17). The complex shear modulus (G*) was measured using the DSR at the frequencies and temperatures listed in Table 3.

The data generated from the testing parameters listed in Table 3 were used to construct a master curve for each recovered binder. The master curve provided the relationship between G* and reduced frequency ω_r at the defining temperature T_d (21). Data was shifted so that the resulting master curve would fit the shape of the Christensen-Anderson model (21) using RHEA. All the master curves were shifted to the reference temperature of 25°C in order to compare the master curves of the different mixtures. Examining Figure 25 through Figure 28 individually, it was observed that as the amount of RAP increased the recovered binder would become stiffer. For all of mixtures tested, this trend held true.

The black arrow in the each figure indicates the shift of master curves and increase of the stiffness. All sets of binders had a steady shift towards the upper left indicating stiffening of binder. Binder becomes stiffer as more RAP is added to the mixture.

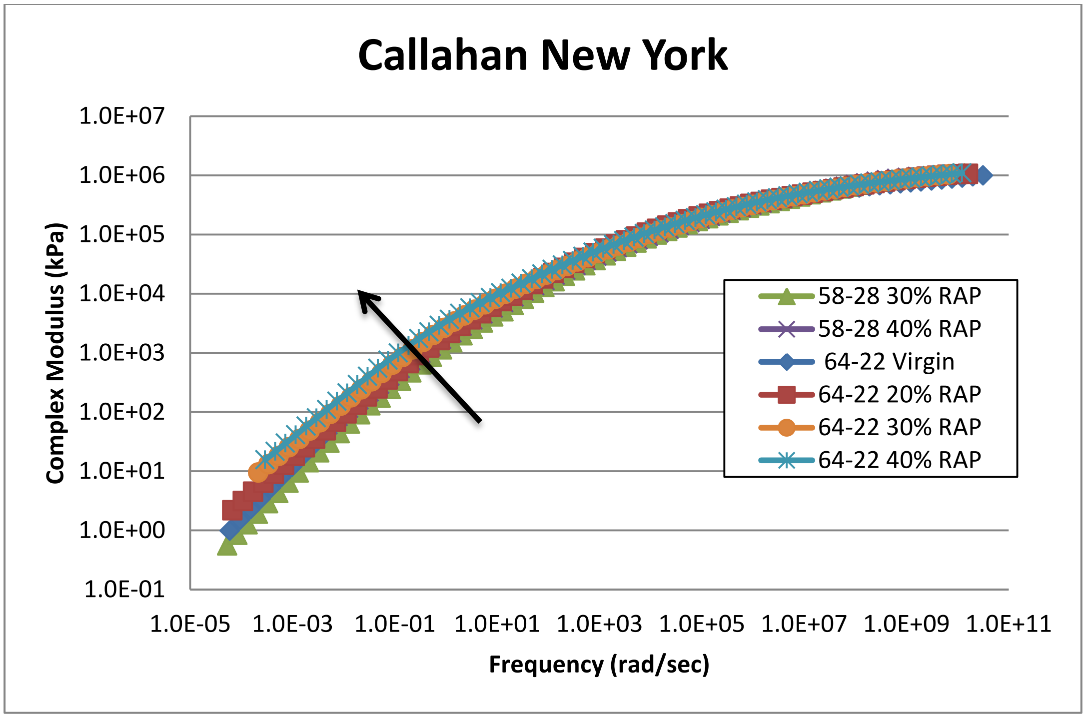

Figure 25 – Comparison of New York Mixtures' Master Curves (58-28 and 64-22)

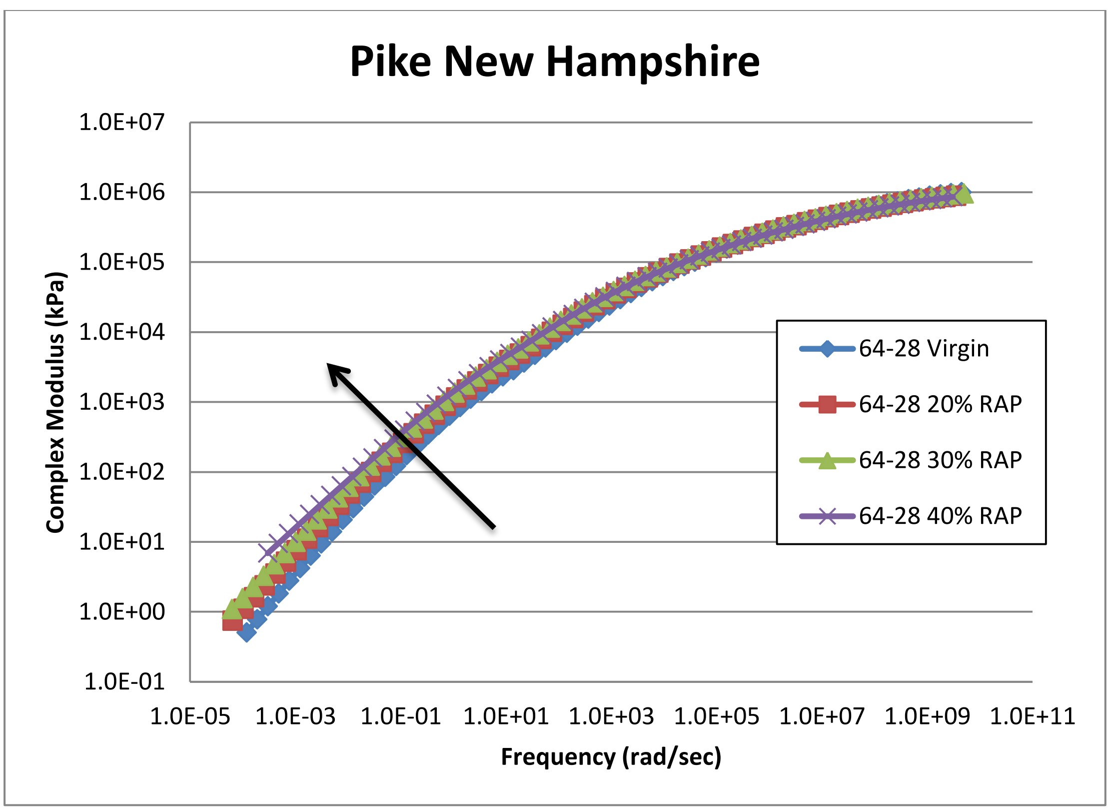

Figure 26 – Comparison of New Hampshire 64-28 Mixtures' Master Curves

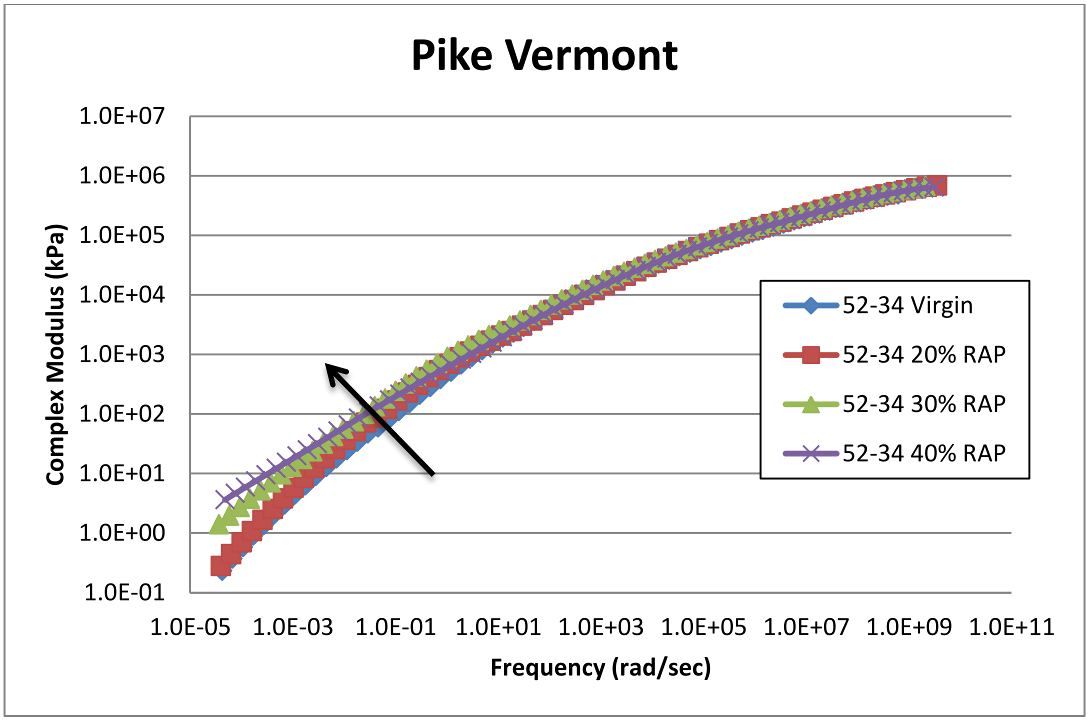

Figure 27 – Comparison of Vermont 52-34 Mixtures' Master Curves

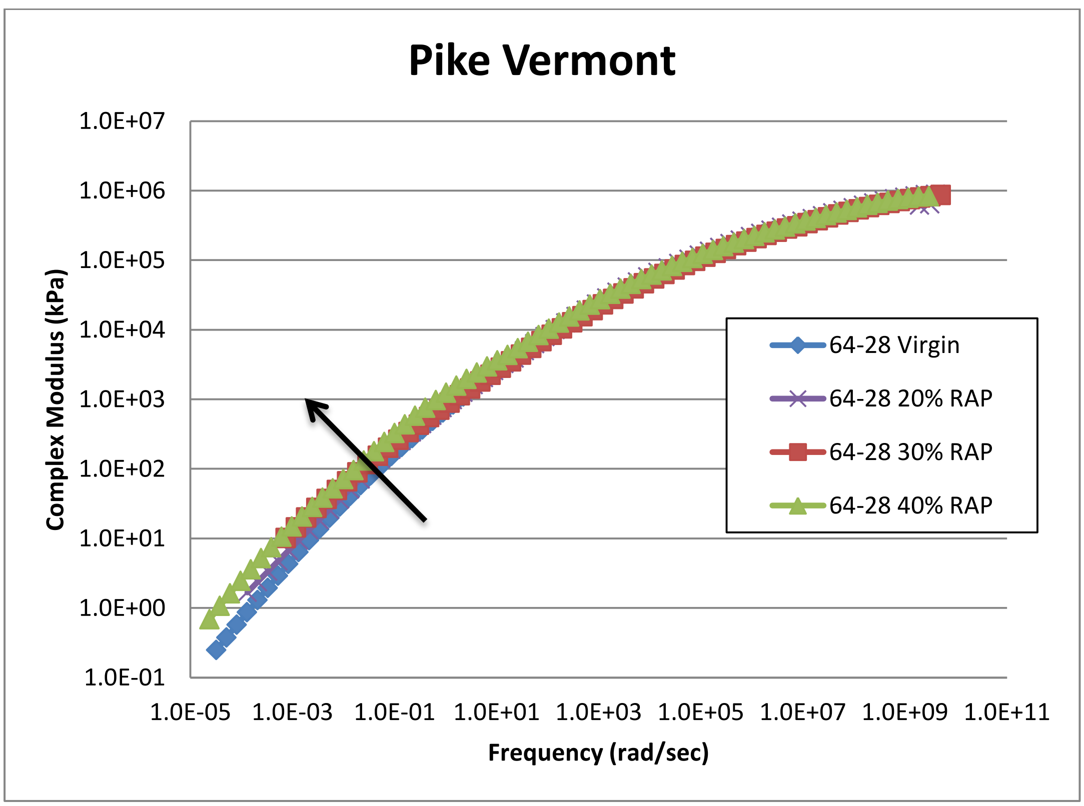

Figure 28 – Comparison of Vermont 64-28 Mixtures' Master Curves

11 Black Space Analysis

After the master curves were generated, the G* and phase angle values were determined at 15°C and 0.005rad/s using RHEA software. As the G* values increased with aging of a binder, it indicated the decrease in ductility and a related decrease in expected durability (14).

As the asphalt binder ages, the G* and phase angle on the black space diagram move to the left on the x-axis and up on the y-axis indicating a decrease in phase angle and an increase in G*. Figure 29 through Figure 31 shows how the G* and phase angle values shift in black when RAP is added in the mixture. The stiffening of the binder is indicated with the black arrow in the graphs.

All binders fall within the passing range of the two typical Superpave parameters, even binders with as high as 40%RAP in the mixtures. But the suggested parameter of interest, $G^*(\cos\delta)^2/\sin\delta$, indicates that all of the binders except for virgin binders fall in the fail zone of this parameter and most likely will fail due to thermal cracking.

According to Superpave, mixtures with up to 40%RAP will not be too stiff and may be used by the agencies if the only concern is stiffness. If the $G^*(\cos\delta)^2/\sin\delta$ parameter was adopted by the Superpave, binders with RAP in them would be too stiff for use.

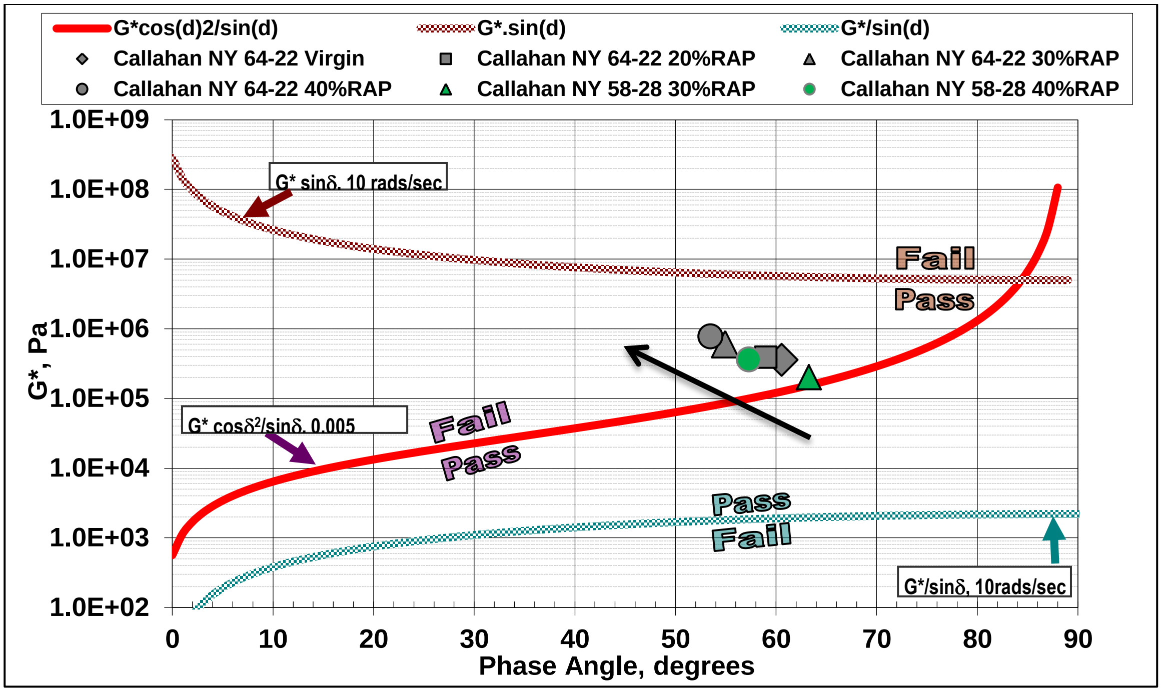

Figure 29 – Black Space of New York Binders (64-22 and 58-28)

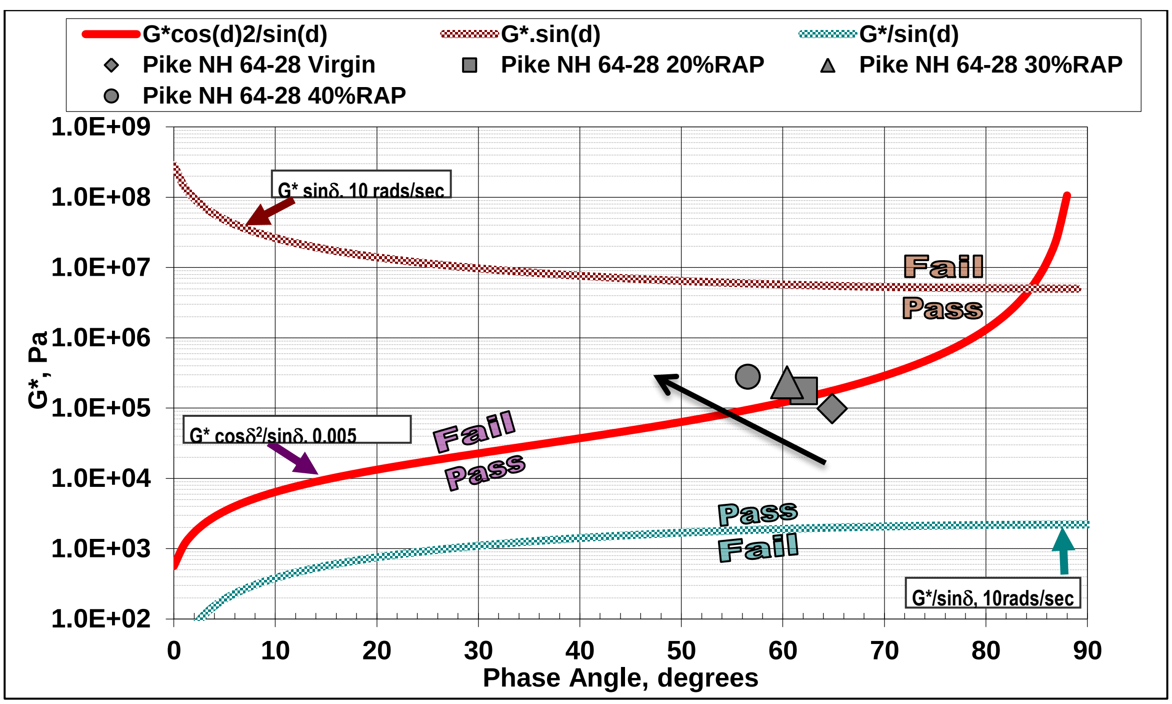

Figure 30 – Black Space of New Hampshire 64-28 binders

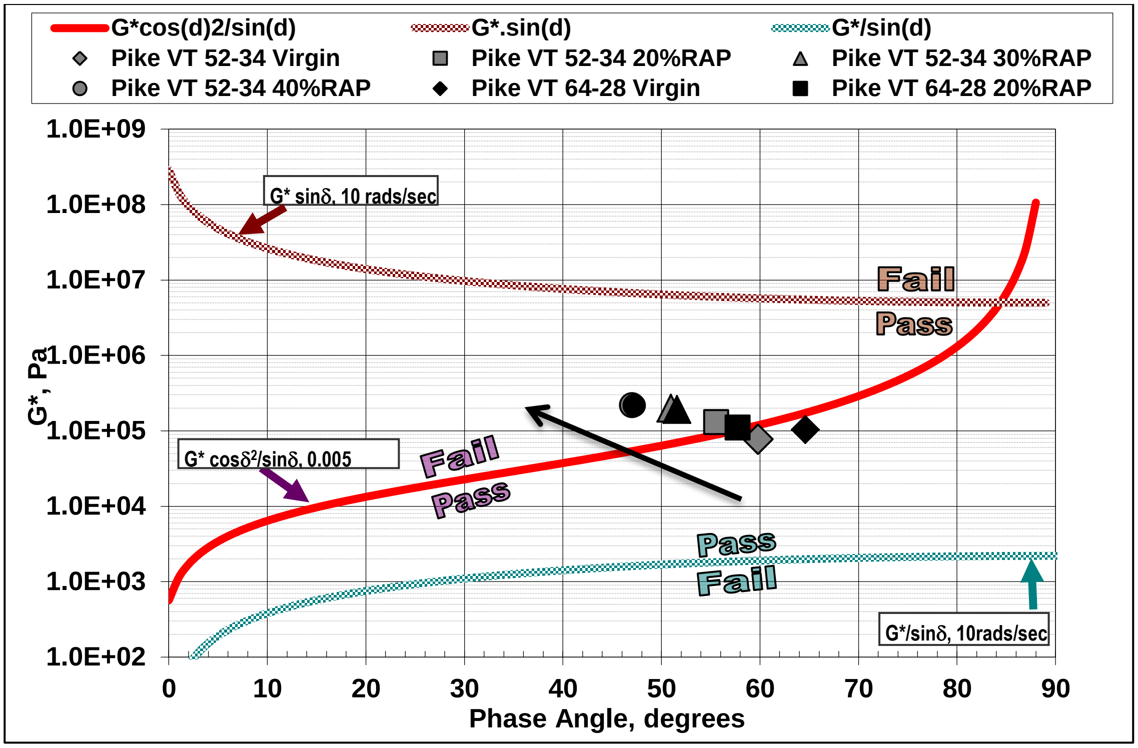

Figure 31 – Black Space of Vermont Binders (52-34 and 64-28)

12 Crossover Frequency and Rheological Index

Rheological index, R-value, and crossover frequency help understand the aging of asphalt binder. As binder becomes stiffer, R-value becomes larger and crossover frequency becomes lower (12). These values of Northeast mixtures are graphed in Figure 32 through Figure 34. In each figure, a black arrow denotes hardening of binder as more RAP is added in the mixtures.

The graphs conclude that binders with higher contents of RAP in the mixtures have higher oxidation aging.

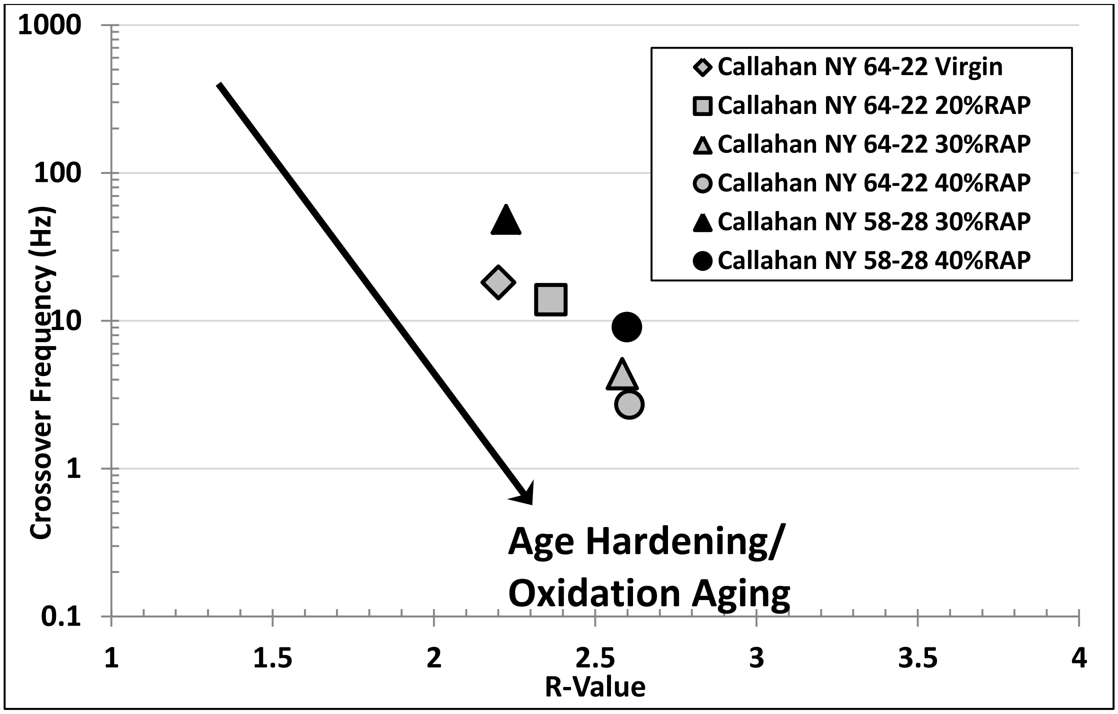

Figure 32 –Crossover Frequency and R-Value of New York Binders (64-22 and 58-28)

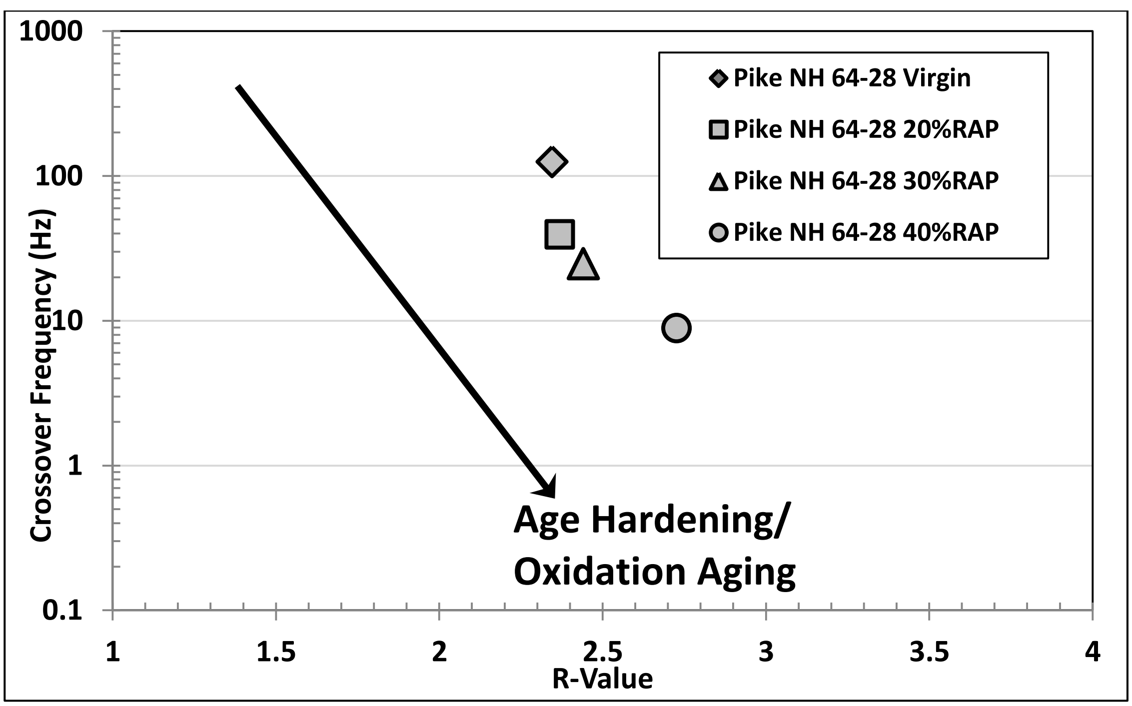

Figure 33 – Crossover Frequency and R-Value of New Hampshire 64-28 Binders

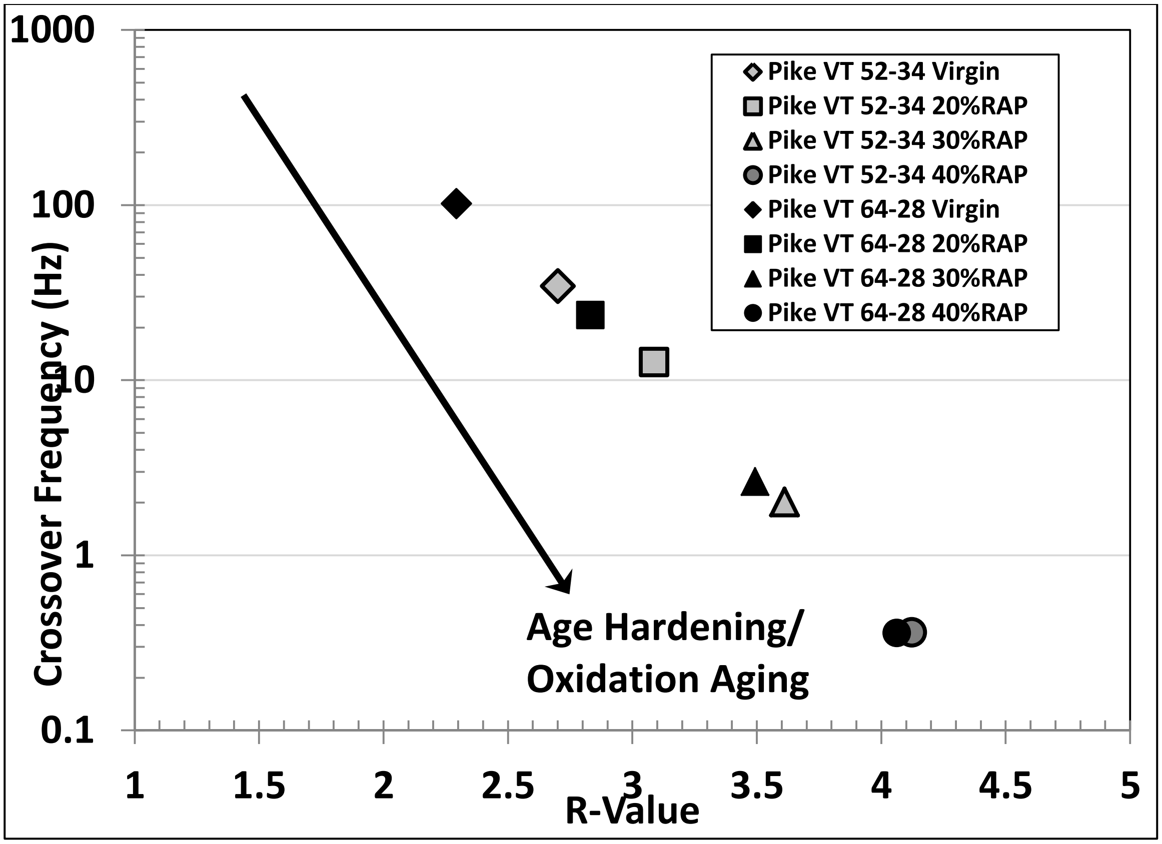

Figure 34 – Crossover Frequency and R-Value of Vermont Binders (52-34 and 64-28)

Conclusion

In this study, plant produced mixtures were obtained from high RAP projects located in New York, New Hampshire and Vermont. Based on the testing and the data analysis, the following conclusions were made.

The test results collected in this study showed that both plant production and silo storage times will not have an impact on the mixture performance. Therefore, to properly document research findings, it is important to also document how the mixtures were produced prior to testing. In general, discharge temperatures and silo storage times were found to not influence mixture stiffness.

The tables showing continuous grading for each binder show a gradual increase in stiffness. Addition of RAP also increased most of the binder mixture by a single grade. While using a softer binder may decrease the stiffness of the binder mixture, it is not conclusive in this study.

The master curve graphs of recovered binders showed that as the amount of RAP increased the recovered binder becomes stiffer. The use of softer binder in the mixtures is also inconclusive from the master curves in our study. Further research may be conducted to better understand how softer binder affects high RAP binder properties.

The crossover frequency and R-value graphs show higher oxidation aging in mixtures with higher RAP content. Therefore, using more RAP may lead mixtures that are too stiff to work with. Black space diagrams show the same sequence where binder becomes stiffer with additional RAP. All binders pass the Superpave parameters in black space, but $G^*(\cos\delta)^2/\sin\delta$, which is the suggested parameter of interest, shows that most binders fail this parameter. The fail zone of this parameter suggests that pavement life will be shortened because of stiffened binder due to added high percentages of RAP. It is suggested that this failure will be due to transverse cracking.

The suggested parameter of interest in black space is related to ductility and may predict a premature failure of asphalt pavement due to cracking. This parameter may set the limit of how much RAP could be used in asphalt binder mixtures.

Further testing would be required in order to make definitive conclusions regarding the impact of using softer binder, discharge temperatures and storage times on the stiffness of high RAP mixtures.

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