TPF 5(230): Evaluation of Plant Produced RAP Mixtures in the Northeast

Phase II Report

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EXECUTIVE SUMMARY

This report summarizes findings from Phase II of a study that is funded through the Transportation Pooled Fund (TPF) Project 5(230): Evaluation of Plant Produced RAP Mixtures in the Northeast. The objectives of this research project were to: (1) evaluate the performance in terms of low temperature cracking, fatigue cracking, and moisture sensitivity of plant produced RAP mixtures in the laboratory and field; (2) establish guidelines on when it is necessary to bump binder grades with RAP mixtures; and (3) provide further understanding of the blending that occurs between RAP and virgin binder in plant-produced mixtures. Phase I included testing on 18 plant-produced mixtures with RAP contents from 0% to 40% by total weight of mixture, Phase II of the project included testing on 10 plant-produced mixtures with RAP contents of 0% to 40%, Phase III was a controlled laboratory study of 9 mixtures, and there was an additional task that evaluated two sets of mixtures stored in a silo for various time periods. The findings from each phase are summarized in separate reports. In Phase II, extensive material characterization was performed on New Hampshire mixture specimens that were fabricated from raw materials, compacted from plant mix with and without reheating, and field cores. The performance grade and |G*| master curves of tank binders and binder extracted and recovered from the mixtures were determined. Mixture testing included dynamic modulus, uniaxial fatigue, beam fatigue, overlay tester, thermal stress restrained specimen test, indirect tensile strength, and flow number. Testing was also conducted on Virginia mixtures and included dynamic modulus, fatigue, and low temperature testing. Where possible, mixture testing was conducted on plant compacted and reheated specimens for comparison.

The results from Phases I and II generally show that the addition of RAP resulted in an increase in stiffness of the materials. The magnitude of the impact of higher RAP percentages varied with each set of mixtures and the test used to evaluate stiffness. Fatigue performance also varied depending on the test; crack initiation tests (uniaxial and beam fatigue) showed that many of the RAP mixtures performed similarly to the comparison virgin mixtures while the overlay tester (crack propagation) showed clear drops in performance at higher RAP contents. Low temperature testing showed trends similar to those observed with the stiffness measurements with warmer cracking temperatures observed with increases in RAP content. The impact of dropping the virgin binder PG grade to compensate for higher levels of RAP had varied results based on the mixtures evaluated. The extracted binder results generally, but not always, show that the softer virgin binder grade improves both the high and low PG grades, but the magnitude of improvement varies with RAP content and mixture. The mixture testing showed that the impact of using a softer virgin binder grade varies from mix to mix and for different mixture properties. It appears to help improve some properties, has negligible effect on others, and may make others worse. The changes in measured properties appear to also be a function of the specimen preparation method, mix design variables that include the stiffness of the RAP and asphalt content, and production parameters such as mixing/discharge temperatures and silo storage times. In some cases the influence of these factors outweighs the impact of RAP level or PG grade of the virgin binder in the mixtures.

CHAPTER 1 INTRODUCTION

1.1 Background

Production of HMA mixtures with higher percentages of RAP is gaining more attention as a way to save money and more efficiently utilize existing resources. Many state agencies and contractors are very comfortable using RAP percentages up to 20% by total weight of mixture. However, questions about low temperature and fatigue performance and the need to bump binder grades limit the amount of HMA that is produced with greater than 15-20% RAP in many areas of the northeast US. Possible increased moisture susceptibility is also an issue in some regions. In the winter of 2009, the New Hampshire Department of Transportation (NHDOT) and Pike Industries, Inc. (PII) collaborated to perform an evaluation of extracted binder properties for various batch plant produced HMA mixtures containing 0-25% RAP. The results of that study were published in the Transportation Research Record in 2010 and were also presented at the 2009 North Eastern States Materials Engineers' Association (NESMEA) meeting. The general conclusion was that binder bumping was not necessary at the 20% RAP level for the mixtures evaluated.

The purpose of this pooled fund study is to expand on the initial work by PII and NHDOT by including higher RAP percentages, drum and batch plants, and mixture testing. The previous study was limited to testing of recovered binder properties which represent the fully blended condition between the RAP and virgin binder. Testing of plant-produced mixtures allows for evaluation of blending and the impact of higher RAP percentages on material properties and performance with respect to low temperature and fatigue cracking as well as moisture susceptibility of the mixtures containing RAP.

This project will add to the body of knowledge and types of RAP mixtures that have been evaluated in other research projects across the country. Ultimately, the industry needs to understand how RAP interacts with the virgin materials in a mixture so that the proper techniques and procedures can be developed and used to design and construct RAP mixtures that have equal or better performance than virgin mixtures.

1.2 Objectives and Scope of Report

The overall objectives of this research project are to:

1. evaluate the performance in terms of low temperature cracking, fatigue cracking, and moisture sensitivity of plant produced RAP mixtures in the laboratory and field
2. establish guidelines on when it is necessary to bump binder grades with RAP mixtures
3. provide further understanding of the blending that occurs between RAP and virgin binder in plant-produced mixtures

Phase II of the project was conducted on mixtures that were produced in the 2011 construction season with the primary variables being the percentage of RAP in the mixture and the virgin binder PG grade. Table 1.1 below presents a summary of the 19 mixtures that were evaluated as part of Phase II of the project. This report presents the results of the testing conducted on the NH and VA mixtures (10 mixtures total); the NY mixtures are part of the silo storage study additional task and the results of those are included in the Silo Storage Study Additional Task report.

Table 1.1 Phase II mixtures

Plant	**NMAS (mm)**	**Virgin PG Grade**	**RAP Content (%) by total wt. of mix**				
			0	**15**	**25**	**30**	**40**
Pike NH (drum)	12.5	58-28	x	x	x	-	-
		52-34	-	-	x	x	x
Superior VA (drum)	12.5	76-22	x	-	-	-	-
		70-22	-	x	-	-	-
		64-22	-	-	-	x	x
Callanan NY (drum)	12.5	64-28	0, 2.5, 5.0, 7.5 hrs silo storage time	-	0, 2.5, 5.0, 7.5, 10.0 hrs silo storage time	-	-

Testing and Analysis of Asphalt Binders and Mixtures

Binder Testing

Binders from the NH RAP mixtures were extracted and recovered. Testing included PG grading, binder master curve of the fully blended material, and the multiple stress creep and recovery (MSCR). Testing was also done on the virgin binder and the recovered RAP binder. Binder testing was not conducted on the VA mixtures.

Mixture Testing

Plant produced mixtures were sampled and then compacted at the plant to fabricate test specimens. Mix was also be reheated in the laboratory following an established procedure to fabricate additional laboratory test specimens and to allow for the comparison of plant mixed, plant compacted (PMPC) and plant mixed, laboratory compacted (PMLC) properties. The NH mixtures also included laboratory production of specimens from raw materials (laboratory mixed, laboratory compacted LMLC) and field cores (FC). Mixture testing included dynamic modulus, fatigue, low temperature, flow number, and the Hamburg Wheel Tracking Device (HWTD). The fatigue testing included the simplified viscoelastic continuum damage (S-VECD) approach, beam fatigue, and overlay tester. Low temperature testing included the Thermal Stress Restrained Specimen Test (TSRST) and low temperature indirect tensile strength. Mixture testing allowed for the evaluation of the fatigue and low temperature properties and blending of the RAP mixtures.

The report is organized to present a description of the testing performed in Chapter 2, followed by individual chapters for the NH and VA materials. Chapter 5 presents a summary of all of the mixtures tested in Phases I and II.

1.3 Research Team

This phase of the project was conducted by the University of New Hampshire, Rutgers University, and University of Massachusetts at Dartmouth. Testing performed by the FHWA on the NH binders and mixtures is also included. Dr. Jo Sias Daniel at UNH served as the Principal Investigator and oversaw the research, performed data analysis, prepared reports, and presented the findings. UNH has performed dynamic modulus, S-VECD fatigue, and indirect tensile testing on mixtures. Dr. Tom Bennert at Rutgers served as a co-PI and was responsible for the overlay tester and beam fatigue testing, analysis of the data and assisted in report preparation. Dr. Walaa Mogawer at UMass Dartmouth served as a co-PI and was responsible for the TSRST and HWTD testing and analysis of the data and assisted in report preparation.

1.4 Participating States and Technical Committee

The New Hampshire Department of Transportation is the lead agency for this project. Additional states that are participating in this study include: Maryland, New York, New Jersey, Pennsylvania, Rhode Island and Virginia. The Federal Highway Agency has also contributed funds to this project. The technical committee consists of representatives of each participating agency, as shown in Table 1.2.

Table 1.2 Technical committee members

Name	**Agency**
Nelson Gibson	FHWA
Denis Boisvert	NH DOT
Matt Courser	NH DOT
Zoeb Zavery	NYS DOT
Russell Thielke	NYS DOT
Eileen Sheehy	NJ DOT
Stacey Diefenderfer	VA DOT
Bob Voelkel	MD SHA
Timothy L. Ramirez	PA DOT
Mike Byrne	RI DOT

CHAPTER 2 TEST DESCRIPTIONS

The laboratory testing conducted during the study comprised of asphalt mixture and liquid binder testing. The asphalt mixture testing was conducted on test specimens prepared at the asphalt plant (PMPC), on loose mix brought back to the laboratory and reheated prior to sample fabrication (PMLC), on specimens fabricated from raw materials in the laboratory (LMLC) and field cores (FC). The asphalt binder testing was conducted on both tank stored and asphalt binder extracted and recovered using solvent extraction procedures.

2.1 Binder Tests

The asphalt binder testing was conducted on two sets of liquid asphalt binders. The first set asphalt binders were sampled from the storage tank at the asphalt binder plant. The second set of asphalt binders was extracted and recovered from sampled loose mix from the asphalt plant. The asphalt binder from the loose mix was extracted and recovered in accordance with AASHTO T 164 method A using Toluene and after the third wash, an 85/15 blend of Toluene/Ethanol. The captured effluent was then run through the rotary evaporator per AASHTO T319 (excluding the extraction vessel) to recover the binder for characterization.

The performance grades of the binders were determined in accordance with AASHTO M320. All tank sampled asphalt binders were subject to both Rolling Thin Film Oven (RTFO), and Pressure Aging Vessel (PAV) aging. The recovered asphalt binders were only PAV aged. The critical cracking temperature was determined using AASHTO MP 1a for the tank binders and AASHTO 314 for the recovered binders. The Multiple Stress Creep and Recovery (MSCR) testing was performed on the binders in accordance with AASHTO TP 70-11.

The master stiffness curves of the respective extracted/recovered asphalt binder were also determined for these materials. The asphalt binder master curves were constructed by collecting the dynamic complex modulus (G*) and phase angle (δ) over a wide range of temperatures and loading frequencies. The master curve was then generated at a reference temperature of 21.1^{o}C by optimizing the fit of the shifted G* isotherms to a four-parameter logistic function.

2.2 Mixture Tests

2.2.1 *Dynamic Modulus*

The AMPT (Asphalt Mixture Performance Tester) machine was used for the dynamic modulus testing in this study. In order to save time, specimen temperature conditioning was conducted in a support chamber outside the AMPT, and then the specimens were moved to the AMPT chamber. A temperature study was conducted by NC State University during the Phase I work to determine the temperatures at which the supporting temperature chamber and AMPT chamber should be set in order to achieve the target test temperatures for the shortest conditioning time. Table 2.1summarizes the results of the temperature study for the dynamic modulus testing. According to these results, the dynamic modulus test can start 30 minutes after the specimen is set in the AMPT chamber.

Table 2.1 NCSU AMPT temperature study results for dynamic modulus testing

Target Temperature, °C	Environmental Chamber Setting, °C	AMPT Setting, °C	Waiting Time, min.
4.4	2.4	2.9	30
21.1	20.6	20.6	30
37.8	37.8	37.8	30

Dynamic modulus testing was performed in load-controlled mode in axial compression following the protocol given in AASHTO TP 79. Tests were completed for all mixtures at a minimum of three temperatures (typically 4.4°C, 21.1°C, and 37.8°C) and a range of frequencies (typically 25, 10, 5, 1, 0.5, and 0.1 Hz). The LMLC, PMLC, and PMPC specimens were 100 mm in diameter and 150 mm tall with a 70 mm gauge length. Load levels were determined by a trial and error process so that the resulting strain amplitudes were between 50 and 75 microstrains. Testing on the small-scale specimens from the field cores was conducted at lower temperatures due to high creep levels observed using the small cross-sectional area specimens. Testing was conducted at 2.9°C, 18.0°C, and 30.0°C. Some mixtures were also tested at 21.1°C. The results from the NCSU temperature study were not used for the field cores due to the smaller size of the specimens. The environmental chamber and AMPT were both set at the target test temperature and the test began 45 minutes after the specimen was set in the AMPT chamber. The dynamic modulus testing was completed at frequencies of 25, 10, 5, 1, 0.5, and 0.1 Hz. However, at 30°C, the 0.1 Hz frequency was not tested due to the high creep levels observed. Specimens were 38 mm in diameter and 110 mm tall with a 70 mm gauge length. Load levels were determined by a trial and error process, and the resulting strain amplitudes were between 15 and 75 microstrains.

The testing order was from low to high temperatures and from high to low frequencies in order to minimize damage to the specimens. The complex modulus values were obtained from the final six cycles of each loading series, i.e., when the material reached the steady state. Master curves for the FHWA tested materials were constructed at a reference temperature of 21.1°C by optimizing the fit of the shifted G* isotherms to a four-parameter logistic function. Master curves for the UNH tested materials were constructed using RHEA software.

In addition to evaluating master curves, the results of the complex modulus testing were also plotted in Black Space (modulus versus phase angle). The combination of stiffness and phase angle, as evaluated in Black Space, can indicate a material's resistance to cracking. Higher phase angles are indicative of a material's ability to relax under loading instead of fracturing. A material's position further down and to the right in Black Space (lower stiffness, higher phase angle) is an indicator of better cracking performance.

2.2.2 *Fatigue*

2.2.2.1 Simplified Viscoelastic Continuum Damage (S-VECD) Approach

Simplified VECD (S-VECD) model is a mode-of-loading independent, mechanistic model that allows the prediction of fatigue cracking performance under various stress/strain amplitudes at different temperatures from only a few tests. The S-VECD model is composed of two material properties, that is, the damage characteristic curve that defines how fatigue damage evolves in a mixture and the energy-based failure criterion.

The S-VECD test method employs the controlled-crosshead direct tension cyclic test on 100 mm diameter, 130 mm tall cylindrical specimens cut and cored from 150 mm diameter, 178 mm tall gyratory specimens or on 38 mm in diameter, 110 mm tall specimens cored from field cores. Details of the test method can be found in AASHTO TP 107 *Determining the Damage Characteristic Curve of Asphalt Concrete from Direct Tension Cyclic Fatigue Tests*. Since the S-VECD test ends with the complete failure of the specimen, the properties measured from this test reflect the fatigue cracking resistance of asphalt mixture in both crack initiation and propagation stages.

The S-VECD testing was conducted using the AMPT machine. Specimens are preconditioned to the test temperature and cyclic testing can begin 60 minutes after the specimen is set in the AMPT chamber. The waiting time for cyclic testing is longer than in dynamic modulus testing because it takes more time to set up the specimen in the AMPT chamber for cyclic testing (end plates need to be screwed to the AMPT). Testing temperatures are based on the PG grade of the virgin binder and are determined according to Equation 2.1 below.

$$Test\ Temp = \frac{High\ PG - Low\ PG}{2} - 3 \qquad (2.1)$$

Vertical deformations were measured using loose-core, CD-type LVDTs with a gauge length of 70 mm. Targets were glued to the specimen face, and the LVDTs were mounted to the targets to measure the deformation in the middle part of the specimen. For consistency in the measurements, a gluing device was used to maintain consistent spacing between the LVDT targets. Figure 2.1 shows a test specimen with the LVDTs mounted on their sides. DEVCON® steel putty was used to glue the steel end plates and targets for the LVDTs that were used for testing the specimens.

Figure 2.1 LVDT mounting and spacing for SVECD Fatigue

Cyclic testing was conducted in crosshead-controlled mode, in which the machine actuator's displacement was programmed to reach a constant peak level at each loading cycle. The actual on-specimen strain levels were significantly lower than the programmed ones due to machine compliance. Fingerprint dynamic modulus tests were conducted by determining the dynamic modulus ratio (DMR) to check the variability of the test specimens before running the direct tension cyclic tests. A DMR in the range of 0.9 to 1.1 guarantees that the linear viscoelastic properties obtained from the dynamic modulus tests can be used properly in the S-VECD analysis.

All cyclic tests were performed at a minimum of three different amplitudes to cover a range of numbers of cycles to failure (N_f). Once the fatigue tests are conducted, the damage characteristic curves are developed by calculating the secant pseudo stiffness (S) and the damage parameter (S) at each cycle of loading. These values are cross-plotted to form the damage characteristic curve. An example of characteristic curves from fatigue tests conducted at different strain amplitudes is shown in Figure 2.2. For all the mixtures, the exponential form shown in Equation (2.1) was used to fit the C versus S characteristic curves.

$$C\left(S\right)=e^{aS^{b}} \qquad (2.1)$$

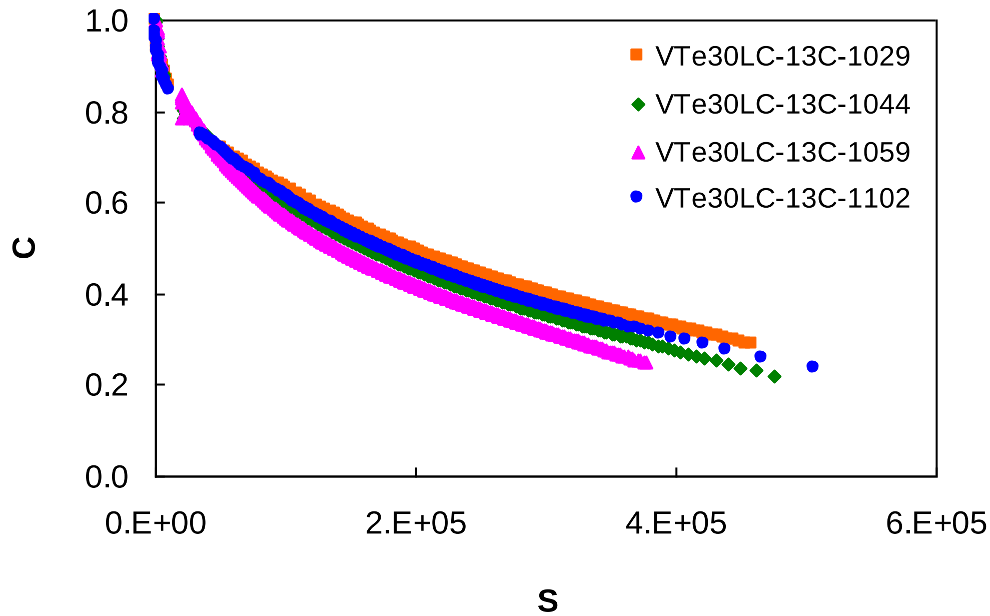

Figure 2.2 Example SVECD Fatigue Results

The S-VECD fatigue failure criterion, called the G^R method, involves the released pseudo strain energy. This released pseudo strain energy concept focuses on the dissipated energy that is related to energy release due to damage evolution only and is fully compatible and predictable using the S-VECD model. G^R method development details are discussed in detail in the Phase I report. The G^R characterizes the overall rate of damage accumulation during fatigue testing. A characteristic relationship, which is found to exist in both recycled asphalt pavement (RAP) and non-RAP mixtures, can be derived between the rate of change of the averaged released pseudo strain energy during fatigue testing (G^R) and the final fatigue life (N_f). The equation to calculate G^R is shown below and Figure 2.3 shows an example of this relationship.

$$G^R = \frac{\int_0^{N_f} W_C^R}{N_f^2} \tag{2.3}$$

The analysis of SVECD fatigue is conducted using the alpha-Fatigue software by Instrotek. Using the G^R relationship and the S-VECD model, the fatigue life of asphalt concrete under different modes of loading and at different temperatures and strain amplitudes can be predicted from dynamic modulus tests and cyclic direct tension tests at three to four strain amplitudes.

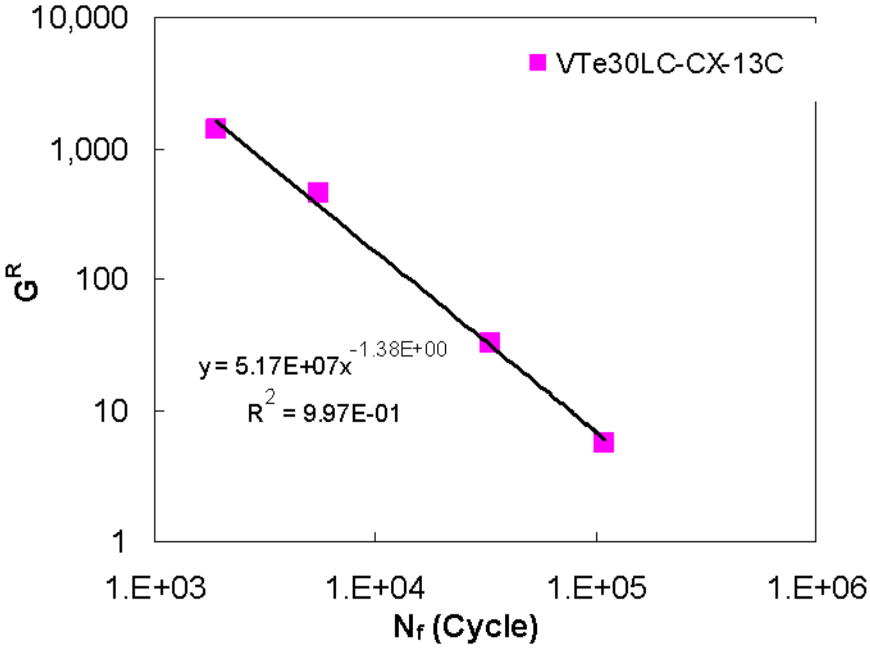

Figure 2.3 Relationship between G^R and N_f

2.2.2.2 Beam Fatigue

Flexural fatigue testing was conducted using the Flexural Beam Fatigue test procedure outlined in AASHTO T321, *Determining the Fatigue Life of Compacted Hot-Mix Asphalt (HMA) Subjected to Repeated Flexural Bending* (Figure 2.4). The applied tensile strain levels used for the fatigue evaluation were; 300, 500, 600, 700 and 900 micro-strains. However, the number strain levels tested was reduced when the amount of loose mix available for testing was limited. AASHTO T321 is a test procedure to evaluate the crack initiation properties of the asphalt mixture. Therefore, "fatigue life" during this test is defined as the time at which crack initiation has begun.

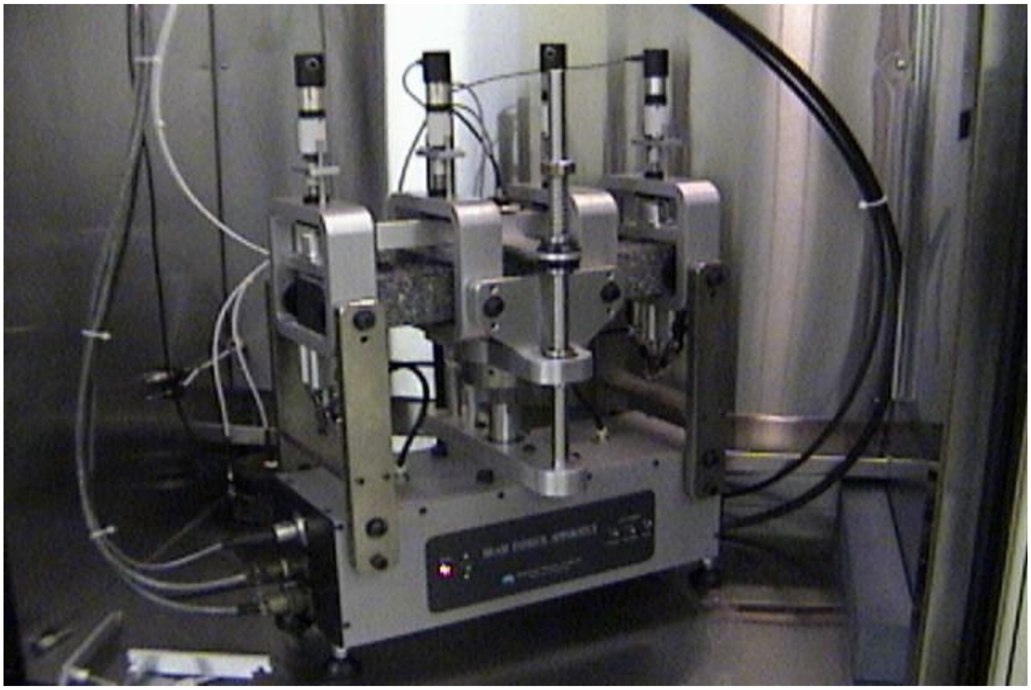

Figure 2.4 Flexural beam fatigue test apparatus

Specimens used for the flexural beam fatigue test were compacted using a vibratory compactor designed to compact brick samples of 400 mm in length, 150 mm in width, and 100 mm in height. After the specimen compaction was complete, the specimens were trimmed to within the recommended dimensions and tolerances specified under AASHTO T321. The test conditions utilized were those recommended by AASHTO T321 and were as follows:

- Test temperature = 15°C;
- Sinusoidal waveform;
- Strain-controlled mode of loading; and
- Loading frequency = 10 Hz

Due to limitations in material quantities, typically only one replicate per strain level was conducted.

2.2.2.3 Overlay Tester

The Overlay Tester evaluates the asphalt mixture's ability to resist or retard crack propagation. Specimen preparation and test parameters used in this study followed that of TxDOT Tex-248-F testing specifications. These include:

- 25°C (77°F) test temperature;
- Opening width of 0.025 inches;
- Cycle time of 10 seconds (5 seconds loading, 5 seconds unloading); and
- Specimen failure defined as 93% reduction in initial load

Five replicate specimens were tested for each mixture. The low and high values were discarded and the remaining three were used to calculate the average value and standard deviation. Figure 2.5 shows a photo of the overlay tester used in this study.

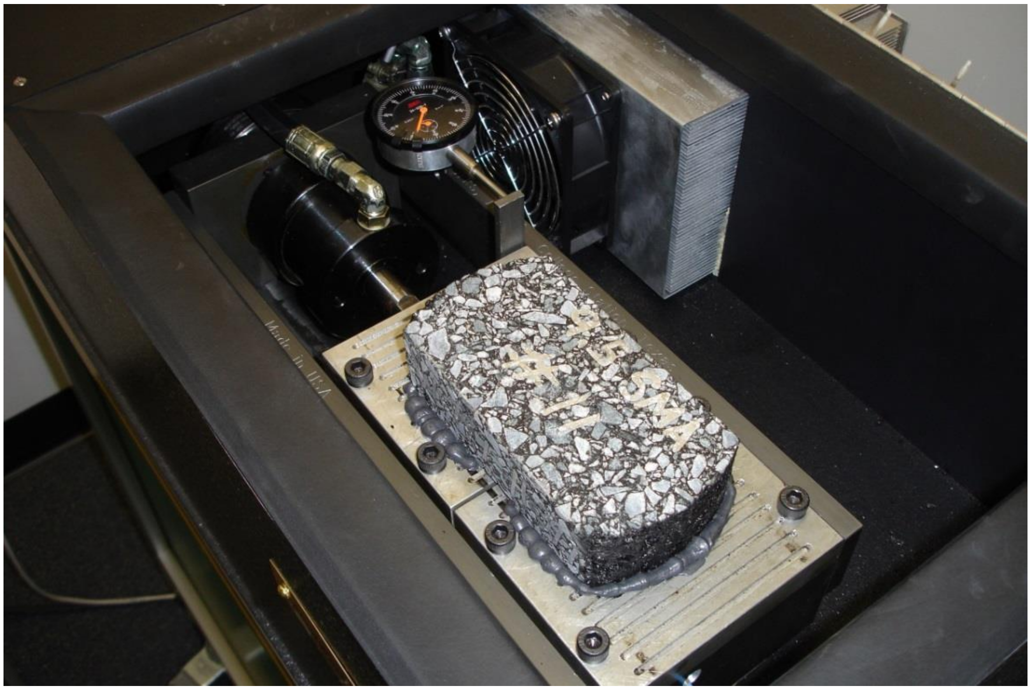

Figure 2.5 Overlay tester with a mounted test specimen

2.2.3 *Low Temperature*

2.2.3.1 Thermal Stress Restrained Specimen Test

In order to assess the low temperature cracking, the VA mixtures were tested in the Thermal Stress Restrained Specimen Test (TSRST) device in accordance with AASHTO TP10-93. In the TSRST test, the asphalt specimen is cooled at a constant rate (-10ºC/hour) while its original length is held constant by the TSRST device. As the specimen gets colder it is restrained from contracting, resulting in the accumulation of thermal stresses. Eventually the thermal stresses exceed the tensile strength of the specimen resulting in specimen fracture (crack). The temperature at which this fracture occurs is recorded and noted as the low cracking temperature of the mixture.

A minimum of three replicate gyratory specimens 185 mm (7.3 in) tall by 150 mm (5.9 in) in diameter were fabricated for each mixture. TSRST specimens were then cored and cut to a final height of 160 mm tall (6.3 in) by 54 mm (2.1 in) in diameter. The air voids of the final cut specimens were 6±1%.

2.2.3.2 Low Temperature Indirect Tensile Strength

Low temperature strength tests at -10°C were conducted following AASHTO standard method of test for "Determining the Creep Compliance and Strength of Hot-Mix Asphalt (HMA) Using the Indirect Tensile Test Device" (AASHTO, T322-03). Specimens were tested using a closed-loop servo-hydraulic system manufactured by Instron Inc. shown in Figure 2.6.

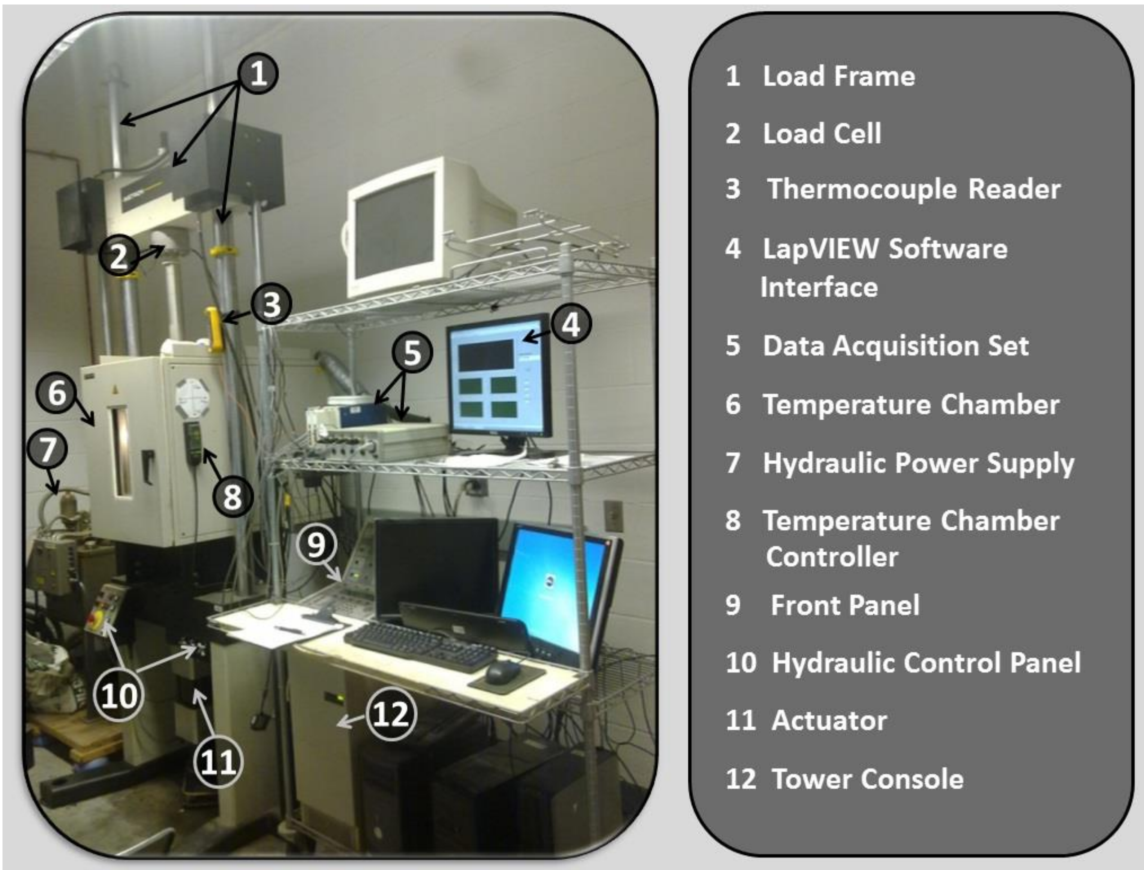

Figure 2.6 A closed-loop servo-hydraulic system manufactured by Instron Inc.

2.2.4 *Flow Number*

Flow Number testing was conducted using the AMPT for this project. The testing was done by FHWA as part of the work completed by the mobile lab. Flow number testing was conducted according to AASHTO TP 79 at multiple deviator and confining stresses. The test temperature for all NH mixtures, based on the climactic location, was 44.7°C. Testing was performed on both mix design and production specimens for the NH materials. The test conditions for each specimen type are shown in Table 2.2.

Table 2.2 Flow Number Testing Conditions

Test Condition	**Mix Design**	**Production**
600 kPa Deviator Stress, 69 kPa Confining Stress		x
690 kPa Deviator Stress, 69 kPa Confining Stress	x	x
800 kPa Deviator Stress, 69 kPa Confining Stress		x
690 kPa Deviator Stress, Unconfined	x	

2.2.5 *Hamburg Wheel Track Testing*

Testing was conducted using the Hamburg Wheel-Track Device (HWTD) by researchers at the University of Massachusetts at Dartmouth. Specimens were prepared with an air void content of 7±0.5% in the superpave gyratory compactor and then trimmed to the required test specimen dimensions. The testing was performed in accordance with AASHTO T324 in a water bath at 50^{o}C. The tests were run until the number of passes reached 20,000 or an average displacement of 20 mm was reached. The stripping inflection point was determined for each mixture.

CHAPTER 3 NEW HAMPSHIRE MIXTURES

The laboratory testing conducted on the NH materials comprised of asphalt mixture and liquid binder testing. The asphalt mixture testing was conducted on field cores, test specimens prepared at the asphalt plant (PMPC), loose mix brought back to the laboratory and reheated prior to sample fabrication (PMLC), and specimens fabricated from raw materials (LMLC). The asphalt binder testing was conducted on both tank and asphalt binder extracted and recovered from the mixtures. The FHWA Mobile Laboratory was onsite during construction; they fabricated and tested the LMLC specimens and a set of PMPC specimens. The binder testing was conducted by FHWA. NHDOT personnel fabricated a set of PMPC specimens and sampled loose mix and field cores for testing conducted at UNH. Field performance of these mixtures to date is also included.

3.1 Mixture Information

The mixtures were produced at an H&B plant with 250-300 tons per hour capacity owned by Pike Industries and located in Northfield, New Hampshire (NH). The mixtures produced had a nominal maximum aggregate size of 12.5 mm with an optimum asphalt content of 5.8%. Six different mixtures were produced using two different virgin binder grades and different RAP contents. The RAP used in the mixtures has a continuous PG grade of 82.3-19.7. Table 3.1shows the mixture design volumetric information and the production volumetric information for each mixture. During production, the asphalt content for all mixtures was higher than the optimum, with the largest difference of 0.4% in the 30% and 40% RAP 52-34 mixtures.

The mixture design gradations are shown in Figure 3.1 and the gradations determined by ignition oven during production are shown in Figure 3.2. The gradations are very similar for all six mixtures, with the largest differences in the #4, #8, and #16 sieves; the differences between the mixtures are greater during production. Figure 3.3 shows a comparison of the mix design and production gradations, points that fall above the line of equality indicate that the production gradation was finer than the mix design gradation. As expected, the smaller sieve sizes show a larger percent passing in production versus mix design. The 30% and 40% RAP 52-34 mixtures had the finest gradations during production, and the 25% RAP mixtures were the coarsest.

Table 3.1 Mixture Volumetric Data

Mix		Mixing/Discharge Temp (ºC)	Pb	Gmm	Va	VMA	VFA	F/Pbe	% Gmm @ Nini	Gsa	Gse	Gsb
Mixture Design	Virgin 58-28	146-152	5.90	2.494	4.4	16.8	74.0	0.9	89.3	2.756	2.739	2.697
	15% RAP 58-28	146-152	5.80	2.479	4.3	16.9	74.2	0.8	89.2	na	2.715	2.687
	25% RAP 58-28	146-152	5.80	2.479	4.1	16.7	75.3	0.8	89.2	na	2.715	2.687
	25% RAP 52-34	138-144	5.80	2.467	3.5	16.5	79.0	0.8	90.1	na	2.703	2.687
	30% RAP 52-34	138-144	5.80	2.469	3.6	16.4	78.1	0.8	90.4	na	2.706	2.682
	40% RAP 52-34	138-144	5.80	2.471	4.2	17.0	75.2	0.8	89.5	na	2.708	2.687
Production	Virgin 58-28	152	5.96	2.472	3.5	16.9	79.5	0.71	90.2	2.735	2.714	2.701
	15% RAP 58-28	143	6.11	2.471	2.5	15.6	84.2	0.77	91.1	2.716	2.719	2.680
	25% RAP 58-28	146	5.98	2.463	2.2	15.2	85.9	0.73	91.4	2.709	2.703	2.672
	25% RAP 52-34	145	5.91	2.454	2.5	15.8	84.1	0.54	91.1	2.709	2.692	2.673
	30% RAP 52-34	146	6.23	2.466	3.7	16.4	77.7	0.78	90.3	2.701	2.723	2.664
	40% RAP 52-34	145	6.19	2.447	3.4	16.7	79.7	0.68	90.7	2.701	2.696	2.664

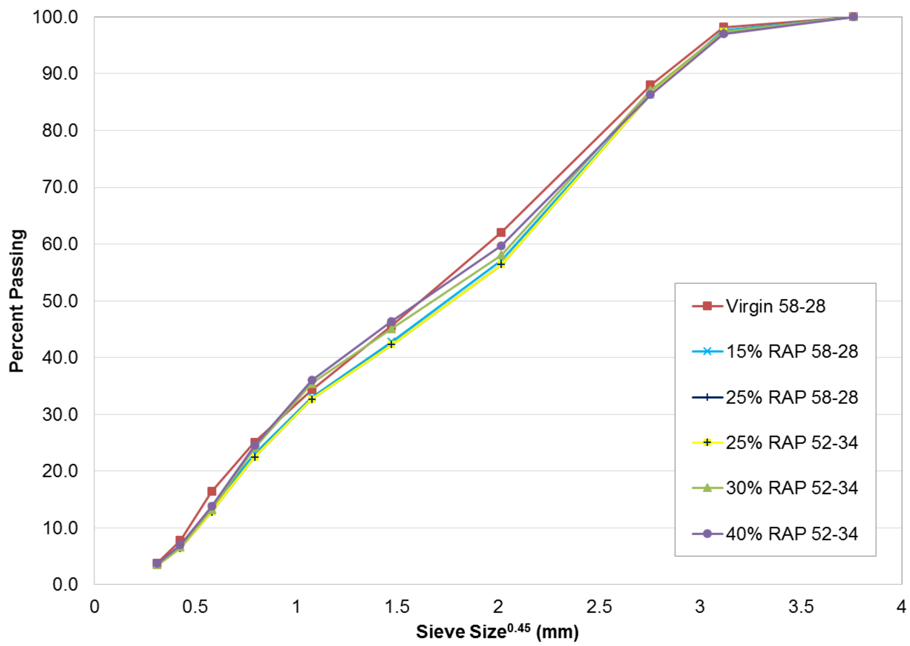

Figure 3.1 Mix Design Gradations

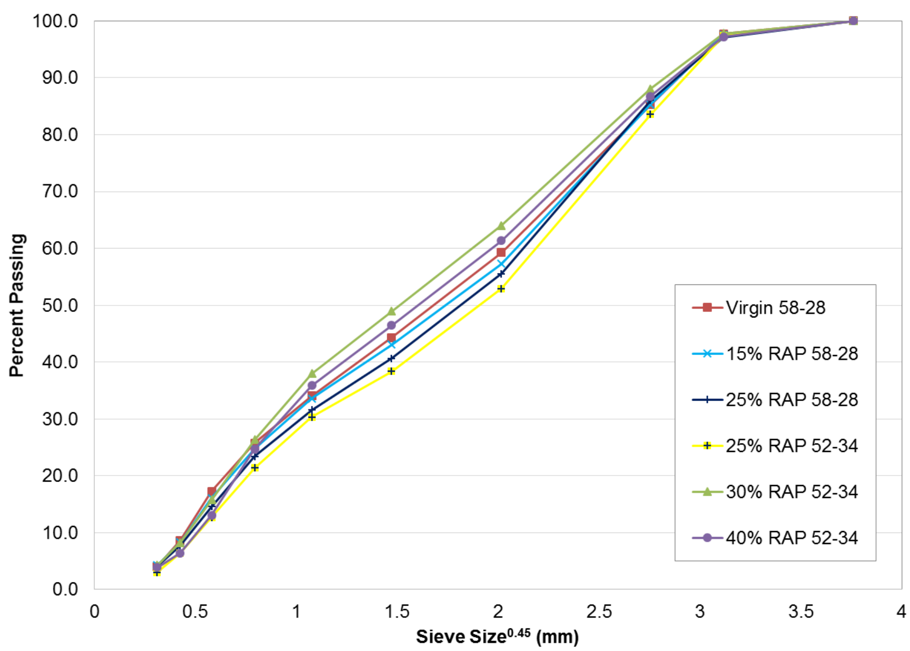

Figure 3.2 Production Gradations

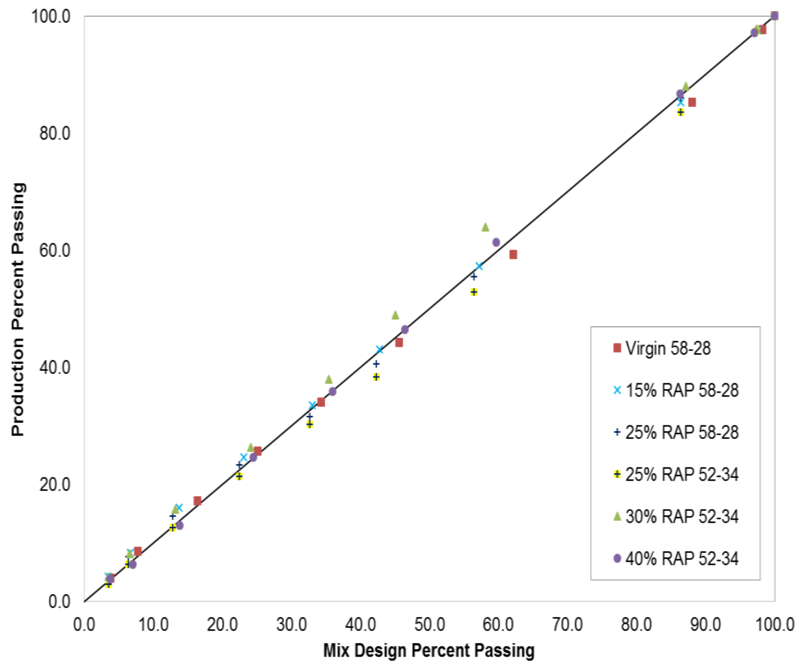

Figure 3.3 Comparison of Production and Mix Design Gradations

3.2 Specimen Fabrication

3.2.1 *Laboratory Mixed Laboratory Compacted (LMLC)*

Specimens for four mixtures (virgin, 25% RAP PG 58-28, 25% RAP PG 52-34, 40% RAP PG 52-34) were fabricated using raw materials (aggregate, RAP, and binder). The materials were batched using the mixture design proportions, mixed at the recommended temperatures, and short term oven aged at 135^{o}C for 4 hours before being compacted using a Superpave gyratory compactor. Specimens 150 mm in diameter and approximately 170 mm tall were compacted to a target air void content of 7 ± 0.5% so that the final cut and cored test specimens (100 mm in diameter, 150 mm tall) had an air void content of 6 ± 0.5%. These laboratory mixed, laboratory compacted (LMLC) specimens were fabricated and tested onsite by the FHWA mobile laboratory.

3.2.2 *Plant Mixed Plant Compacted (PMPC)*

Loose mix was sampled at the plant and then compacted immediately without reheating to produce the plant mixed, plant compacted (PMPC) specimens. Specimens 150 mm in diameter and approximately 170 mm tall were compacted to a target air void content of 7 ± 0.5% using a Superpave gyratory compactor. PMPC specimens were fabricated by both the FHWA mobile laboratory and NHDOT personnel. The FHWA specimens were cut and cored to 100 mm diameter, 150 mm tall specimens with an air void content of 6 ± 0.5%

and then tested by the mobile laboratory very soon after fabrication. The specimens fabricated by NHDOT were transferred to the UNH laboratory and stored for future cutting, coring, and testing.

3.2.3 *Plant Mixed Laboratory Compacted (PMLC)*

Loose mix was sampled at the plant and stored in sealed metal 5-gallon buckets. To prepare specimens, the loose mix was reheated to 10^{o}C below the discharge temperature, divided into the appropriate weights and then heated to compaction temperature. Mixtures were not reheated for more than four hours and were not cooled and reheated. Specimens 150 mm in diameter and approximately 180 mm tall were compacted to a target air void content of 7 ± 0.5% in the UNH laboratory using a Superpave gyratory compactor. The specimens were then cut and cored to the final test specimen dimensions and tested in the UNH laboratory. All tested specimens had an air void content of 6 ± 0.5%.

3.2.4 *Field Cores*

Test strip locations along I-93 between Lincoln and Woodstock, New Hampshire were constructed in June 2011. Ten field cores were extracted for each of the six mixtures and transported to the UNH laboratory for future specimen fabrication and testing. Field cores measured 150 mm in diameter and ranged from approximately 30-85 mm in thickness. Small geometry specimens 38 mm in diameter and 110 mm tall were obtained from the field cores. To produce these small specimens, field cores were secured in a fabricated jig and cored along the diameter, slightly offset from the center. This method allowed for each field core to yield two specimens of 38 mm diameter. Figure 3.4 shows a field core sample and the two test specimens that were obtained. A comparison of a standard size specimen and a small-scale specimen is shown in Figure 3.5. The air void content of the tested specimens ranged from 4.2% to 6.7%.

Figure 3.4 Two small specimens produced from one field core

Figure 3.5 Comparison of standard size (left) vs. small geometry specimens (right)

3.3 Binder Testing

3.3.1 *PG Grading*

The continuous PG grades and critical cracking temperatures were measured by FHWA on both the virgin and extracted and recovered binders. Figure 3.6 and Figure 3.7 show the measured continuous high and low temperature grades determined from AASHTO M320, respectively. The addition of RAP stiffens the continuous high temperature grades, but there is not a consistent trend with RAP content for these mixtures. The low temperature grades for the PG 58-28 mixtures show little impact from the addition of RAP; the PG 52-34 mixtures show slightly warmer low temperature grades with RAP, but no trend with increasing RAP content. Figure 3.8 shows the critical cracking temperature determined by MP1-a for the virgin binders and M314 for the extracted and recovered binders. The recovered binder from PG 58-28 mixtures actually show slightly colder cracking temperatures than the virgin binder, while the recovered binders from the PG 52-34 mixtures show cracking temperatures that are warmer than the virgin binder, but colder temperatures with increasing RAP content. It is possible that the extraction and recovery process impacted these results.

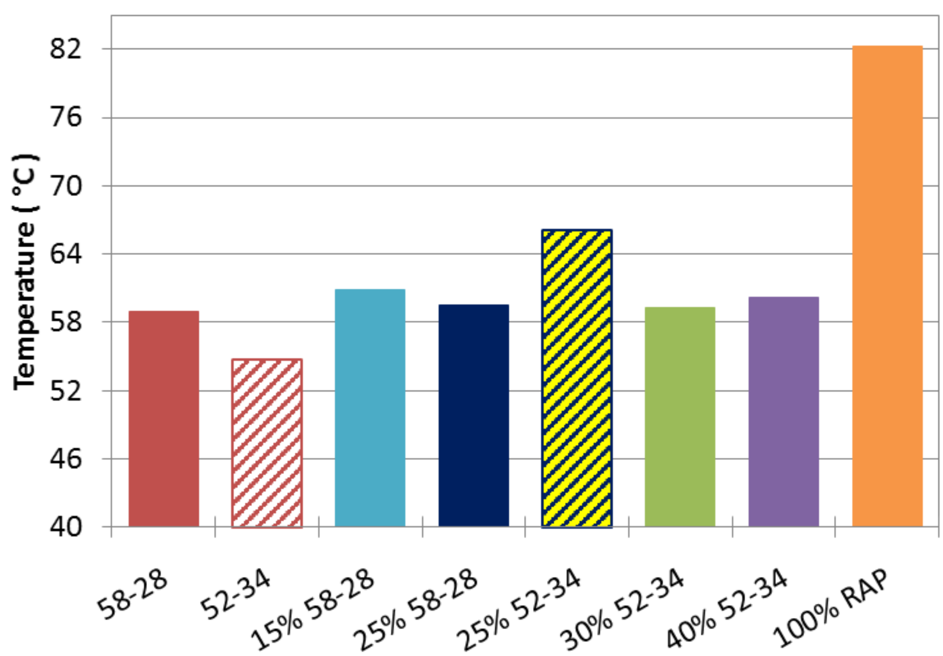

Figure 3.6 Continuous High Temperature Grade for Virgin and Extracted and Recovered Binders

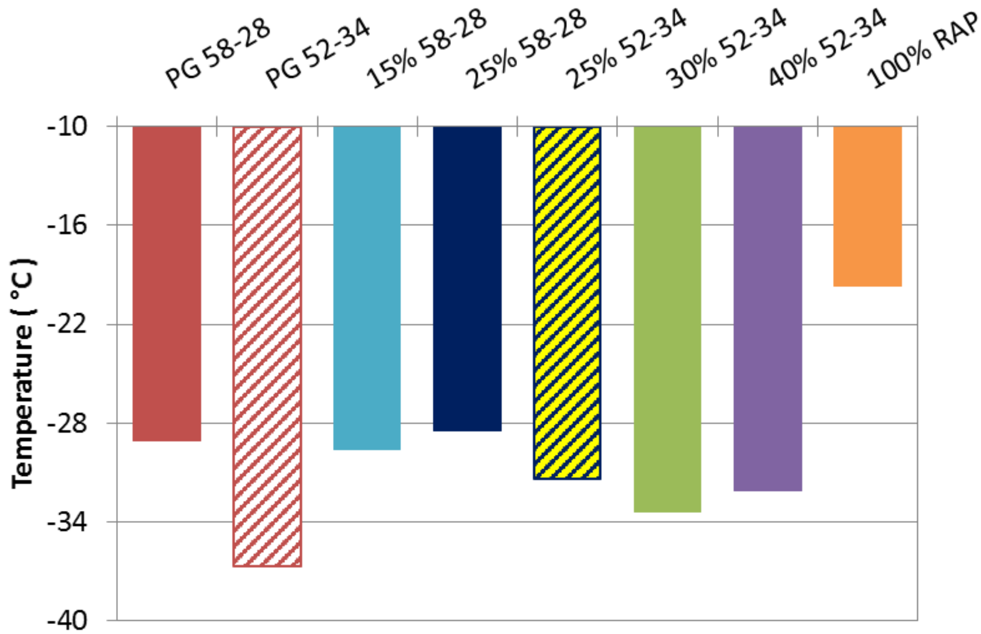

Figure 3.7 Continuous Low Temperature Grade for Virgin and Extracted and Recovered Binders

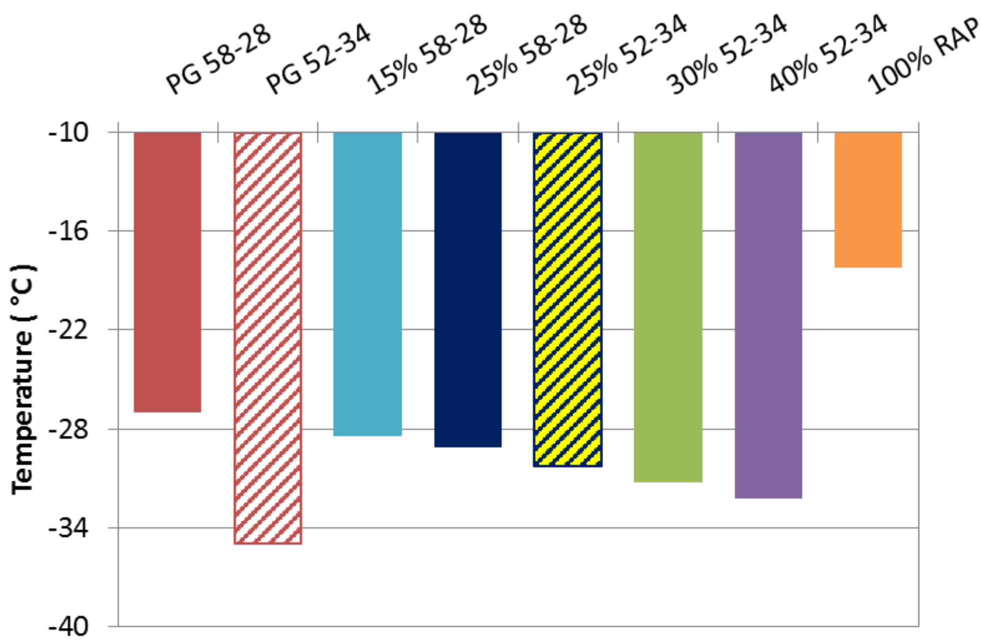

Figure 3.8 Critical Cracking Temperature for Virgin and Extracted and Recovered Binders

3.3.2 *Asphalt Binder Master Curves*

The complex shear modulus was measured on both virgin and extracted and recovered binders by FHWA. The virgin binders were RTFO aged and the recovered binders are assumed to be at RTFO aging condition having gone through production. The shear modulus master curves are shown in Figure 3.9. The extracted and recovered RAP binder has the highest stiffness, as expected. The PG 58-28 virgin binder is stiffer than the PG 58-34 binder over most of the frequency range, although the two binders have similar stiffness at low frequencies. The extracted and recovered binders from the PG 52-34 base binder mixture show increasing stiffness with RAP content, except at low frequencies where the 25% RAP mixture shows a stiffer response. The extracted and recovered binders from the PG 58-28 base binder mixtures are stiffer than the PG 52-34 base binder materials at high frequencies, but have similar response at low frequencies.

The Black Space master curves for the binders are shown in Figure 3.10. The location of the PG 52-34 binder is unexpected; it would be expected that the softest binder have the largest phase angles. Instead, the PG 52-34 results are showing the lowest phase angles. This may indicate a performance issue with this binder as it may not have adequate relaxation capacity, especially at low temperatures. The extracted and recovered binders from the mixtures with both virgin binders show that as the amount of RAP increases, the black space curve shifts away from the virgin binder and towards the RAP curve.

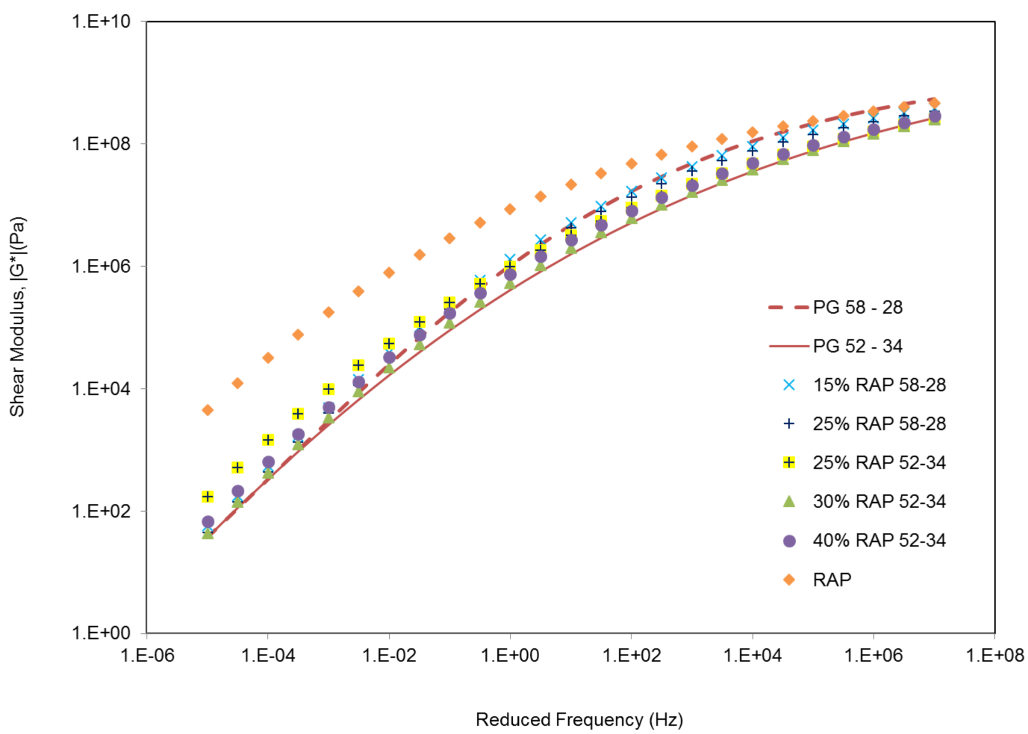

Figure 3.9 Shear Modulus Master Curves at 21°C for Virgin and Extracted and Recovered Binders

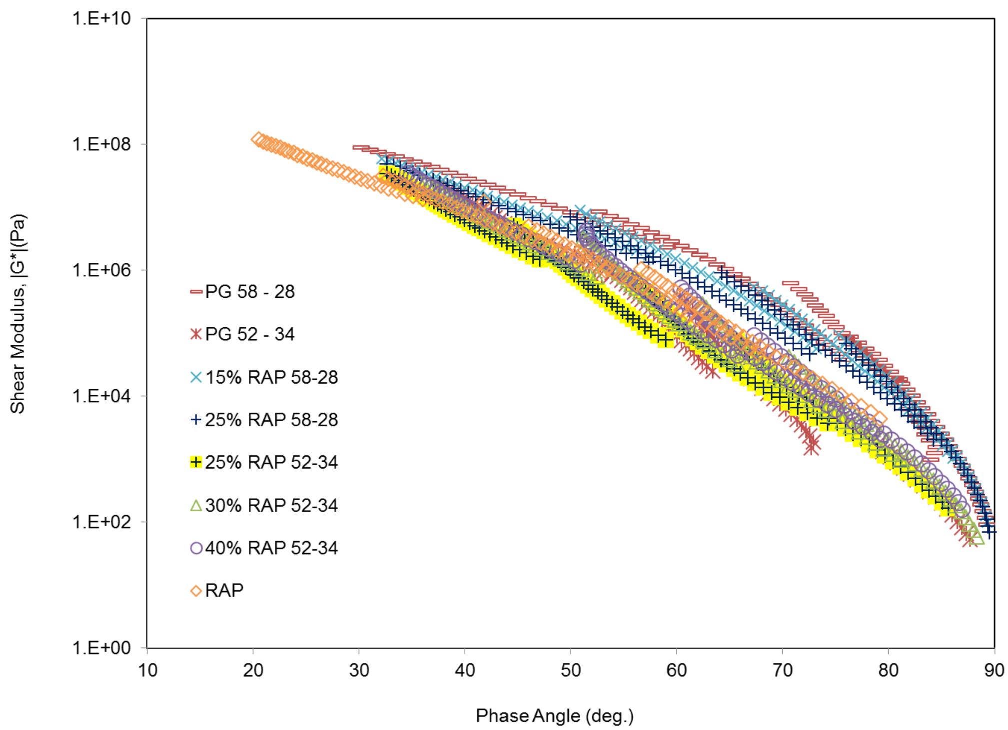

Figure 3.10 Black Space Curves for Virgin and Extracted and Recovered Binders

3.3.3 *Multiple Stress Creep and Recovery (MSCR)*

The MSCR test was conducted on all of the virgin and extracted and recovered binders to evaluate the rutting susceptibility of the materials. The temperatures at which each binder met the criteria for Standard (Jnr = 4.0 1/kPa), Heavy (Jnr = 2.0 1/kPa), and Very Heavy (Jnr = 1.0 1/kPa) traffic at a loading level of 3200 Pa are shown in Table 3.2 below. All indicate that they should perform satisfactorily under standard traffic. The PG 58-28 base binder materials increase stiffness with an increase in RAP content, however the PG 52-34 base binder materials show a decrease in stiffness with an increase in RAP content.

Table 3.2 Multiple Stress Creep and Recovery Passing Temperatures

	PG 58-28	PG 52-34	15% RAP 58-28	25% RAP 58-28	25% RAP 52-34	30% RAP 52-34	40% RAP 52-34	100% RAP
Standard Traffic "S" Grade Temp (^oC)	58.0	54.8	59.5	59.9	65.2	61.5	60.5	82.0
Heavy Traffic "H" Grade Temp (^oC)	53.2	51.5	54.5	54.9	60.3	54.5	55.5	76.7
Very Heavy Traffic "V" Grade Temp (^oC)	48.8	47.0	50.0	50.5	56.0	50.2	50.0	72.0

3.4 Mixture Testing

3.4.1 *Dynamic Modulus*

3.4.1.1 Lab Mixed, Lab Compacted Specimens (LMLC)

The dynamic modulus of LMLC specimens was measured on four of the six mixtures by the FHWA mobile laboratory. These were fabricated and measured to determine the differences in the mixtures that would be identified during the mix design process. Four replicate specimens were fabricated and tested for each mixture. The average dynamic modulus master curves for the four mixtures are shown in Figure 3.11 below. The virgin and the 25% RAP PG 58-28 mixture have similar curves, with the 25% RAP mixture showing slightly stiffer response over the mid to high frequency range. The two mixtures with the PG 52-34 base binder show softer response than the PG 58-28 base binder mixtures, with a slight increase in stiffness at the higher RAP content.

Figure 3.12 shows the average Black Space curves for the LMLC specimens. The phase angles for the virgin and the 25% RAP PG 58-28 curves follow the expected trend that the addition of RAP decreases the maximum phase angle. The 25% RAP PG 52-34 mixture has a smaller phase angle than the 25% RAP PG 58-28 mixture, which is not expected with the softer binder. Also, the PG 52-34 base binders show an increase in phase angle with the increase in RAP. In summary, the PG grade of the base binder shows a larger impact on the dynamic modulus and phase angle than the RAP percentage for the specimens that were mixed and produced in the lab. The phase angles for the PG 52-34 mixtures do not follow expected trends with RAP content or in relation to the PG 58-28 mixtures.

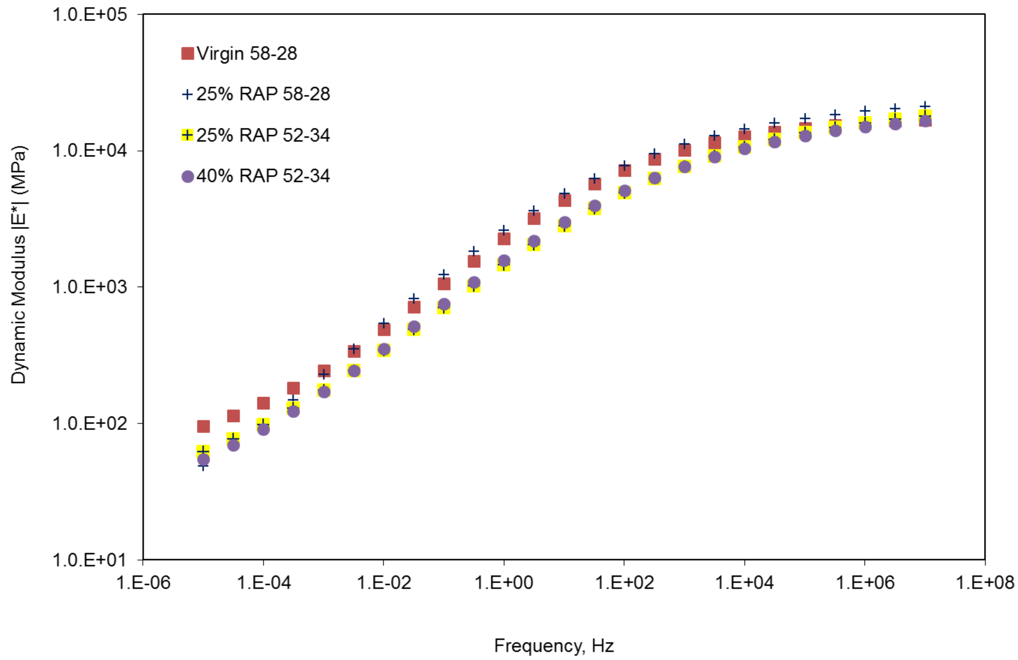

Figure 3.11 Average Master Curves at 21°C for LMLC Specimens

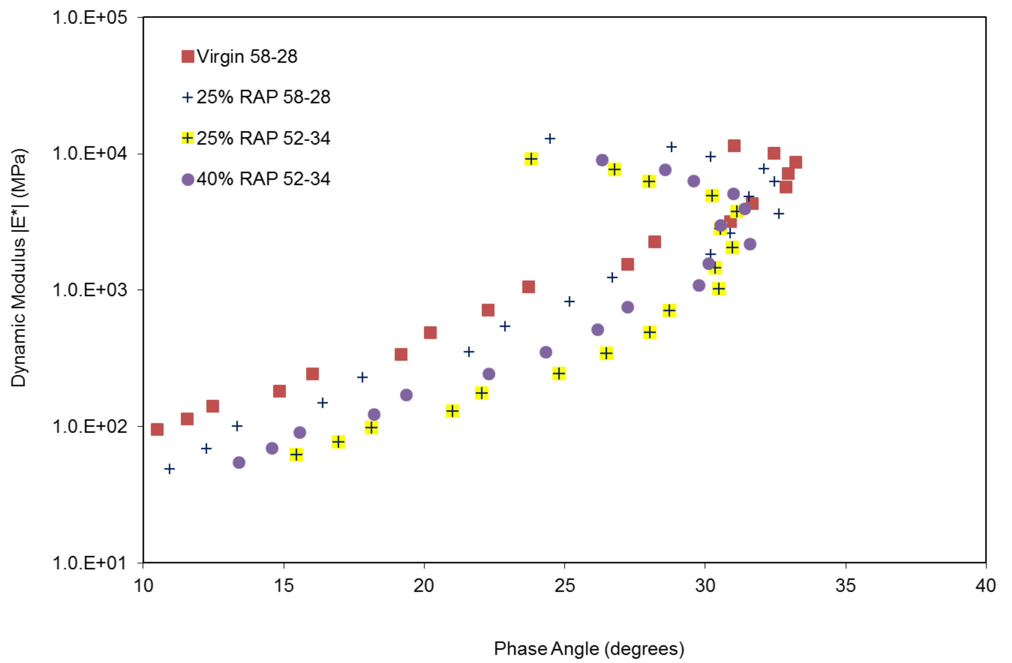

Figure 3.12 Average Black Space Curves for LMLC Specimens

3.4.1.2 Plant Mixed, Plant Compacted Specimens (PMPC)

FHWA Testing

The FHWA mobile lab compacted specimens at the plant during each day of production (shoulder, passing, and travel lane) for each of the six mixtures. Four replicate specimens were produced and tested for each mixture during each day of production. The average dynamic modulus curves for the six mixtures over all three production days are shown in Figure 3.13. Each curve represents the average of twelve specimens. The PG 58-28 base binder mixtures have similar responses with minimal impact of RAP on the average stiffness of the mixtures. The PG 52-34 base binder mixtures all show softer response than the virgin PG 58-28 mixture and show slight increases in stiffness with increasing RAP content. The PG 58-28 base binder mixtures do not have statistically significant differences in dynamic modulus from one another over most of the master curve range; there are differences at the lower asymptote (high temperature, slow frequency). The PG 52-34 base binder mixtures are also all statistically similar. All the dynamic modulus values for PG 58-28 base binder mixtures are statistically different than all of the PG 52-34 base binder mixtures. The statistical analysis of the phase angle values is similar, with the exception that most mixtures showed statistically similar phase angle values at the 21^{o}C testing temperature and 5-25 Hz frequency range. In summary, the base binder grade shows a larger, statistically significant, impact on the dynamic modulus than the RAP content.

The average Black Space curves for the six mixtures are shown in Figure 3.14. The three mixtures with the PG 58-28 binder are very similar in Black Space, with a slight decrease in the phase angle with RAP. The mixtures with PG 52-34 binder have lower phase angles than the PG 58-28 mixtures and also show an increase in phase angle with increasing RAP content. This is similar to the trends observed with the LMLC specimens, and is not expected behavior for a softer binder.

The average dynamic modulus master curves for each day of production are shown in Figure 3.15 through Figure 3.20. Each curve represents an average of four replicate specimens. In general, the PMPC master curves for each production day are very similar for all six mixtures, indicating consistent production at the asphalt plant. The LMLC master curve is also shown for the mixtures that included this testing for comparison; the differences in the specimen types are discussed in Section 3.4.1.5 below.

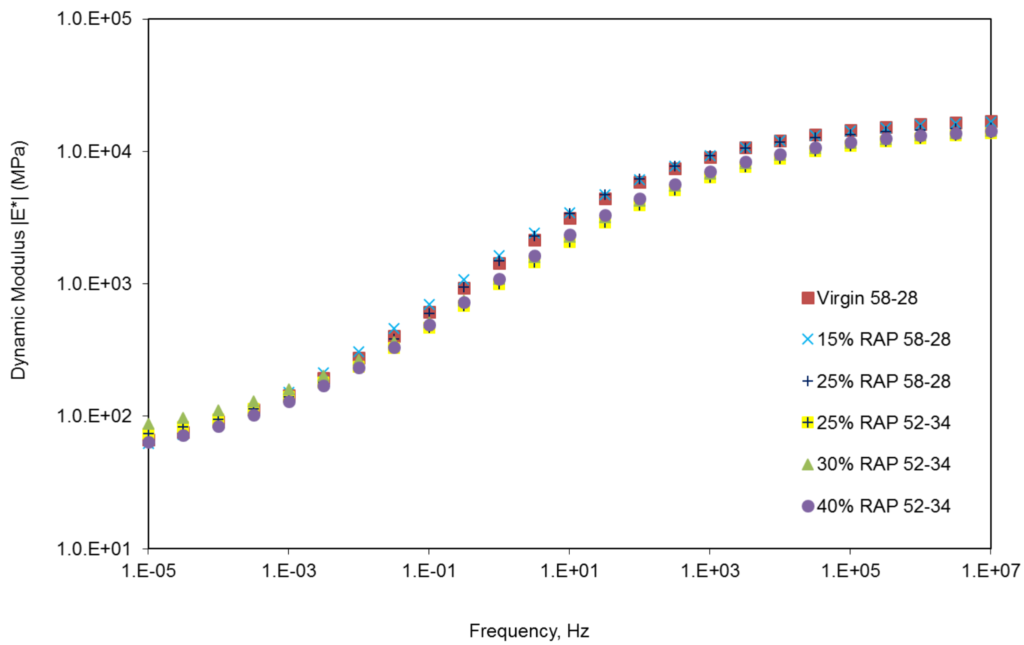

Figure 3.13 Average FHWA PMPC Dynamic Modulus Master Curves at 21°C for All Production Days

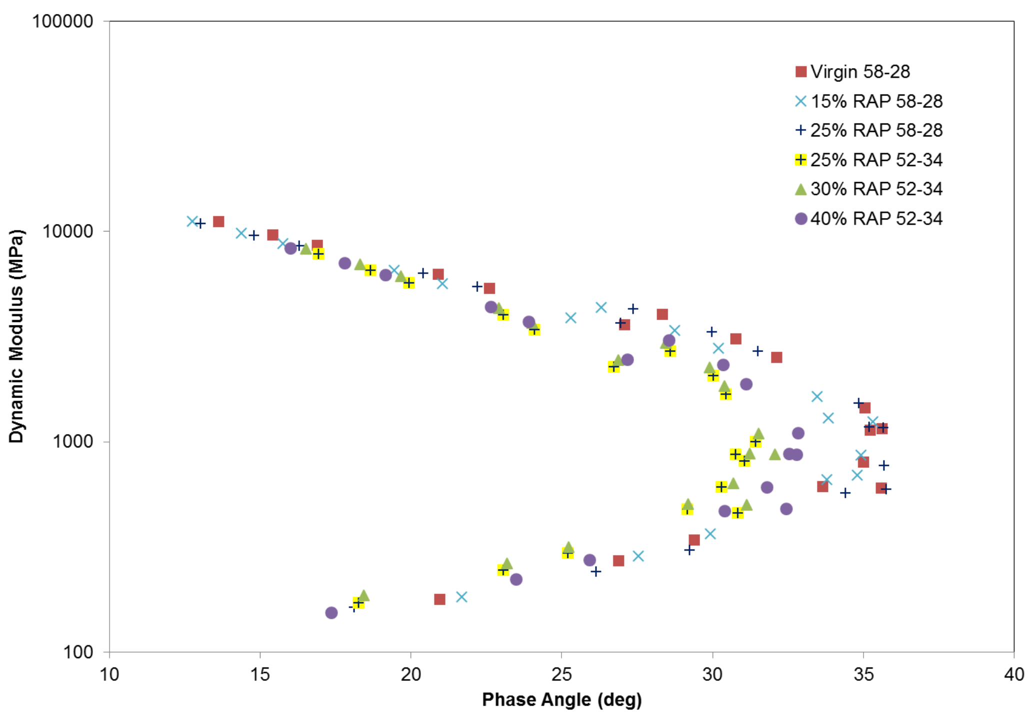

Figure 3.14 Average Black Space Curves for FHWA PMPC Specimens

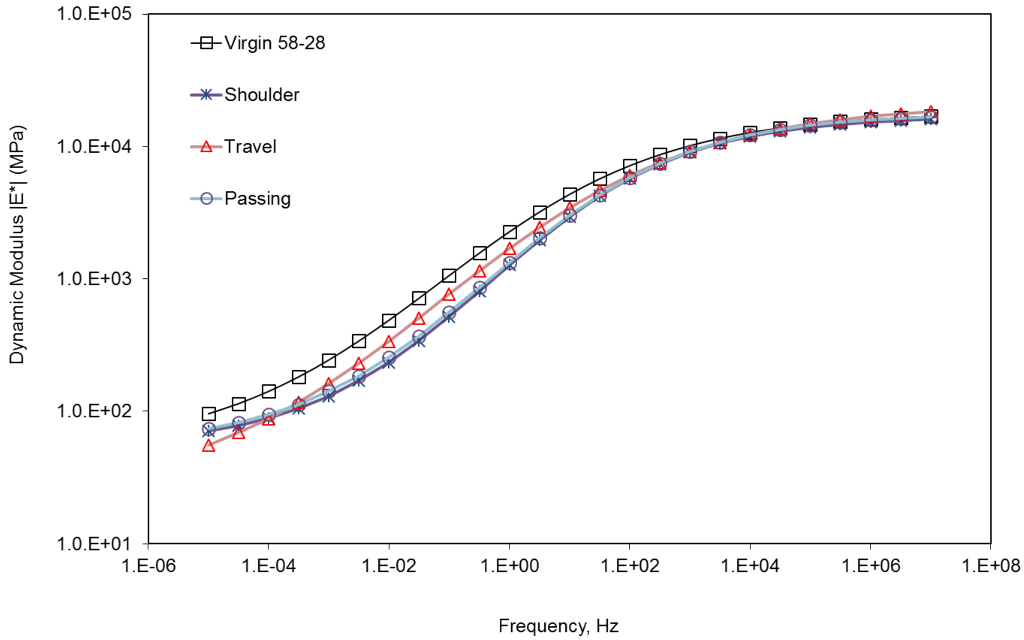

Figure 3.15 Virgin PG 58-28 Average Dynamic Modulus Curves at 21°C for LMLC and all PMPC Production Days

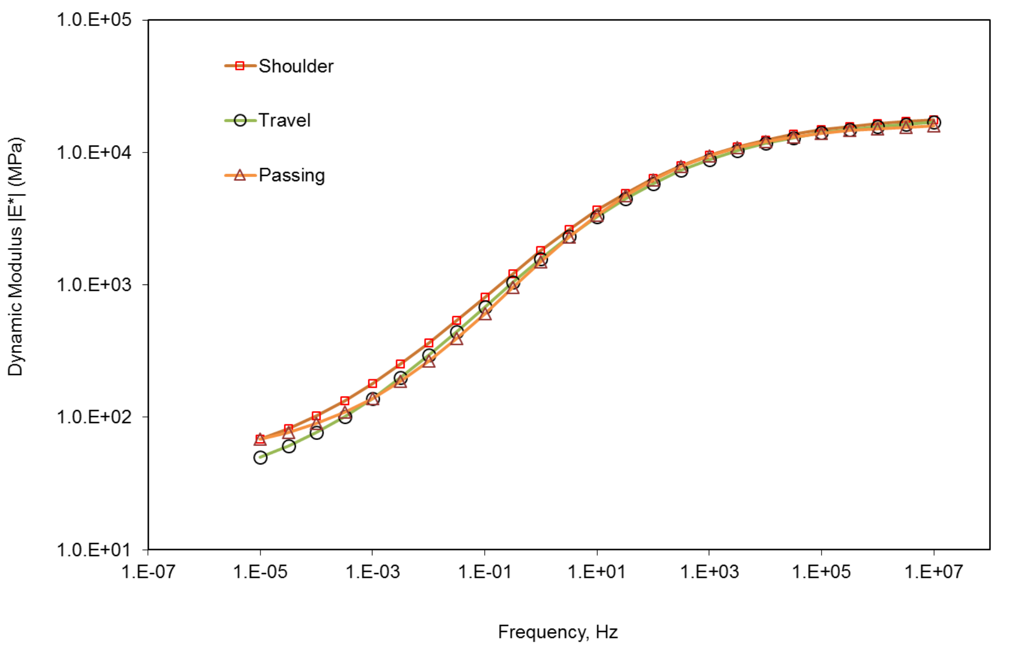

Figure 3.16 15% RAP PG 58-28 Average Dynamic Modulus Curves at 21°C for all PMPC Production Days

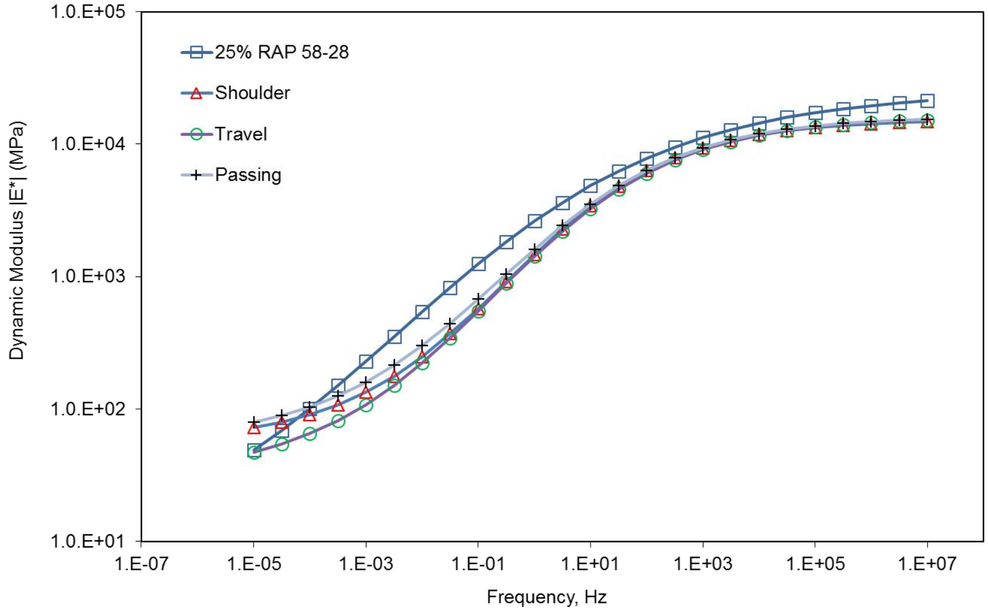

Figure 3.17 25% RAP PG 58-28 Average Dynamic Modulus Curves at 21°C for LMLC and all PMPC Production Days

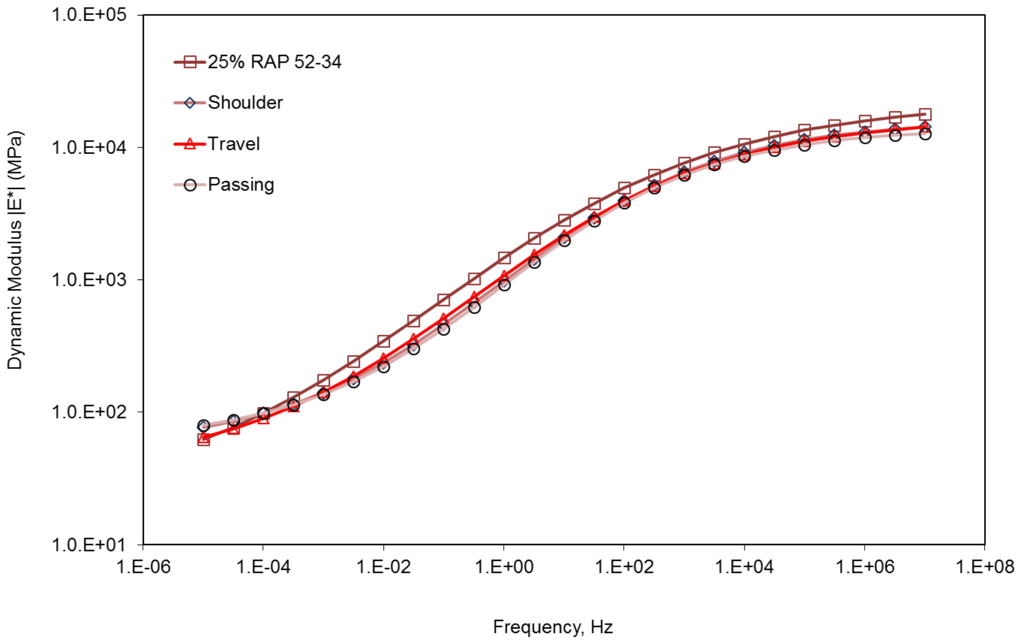

Figure 3.18 25% RAP PG 52-34 Average Dynamic Modulus Curves at 21°C for LMLC and all PMPC Production Days

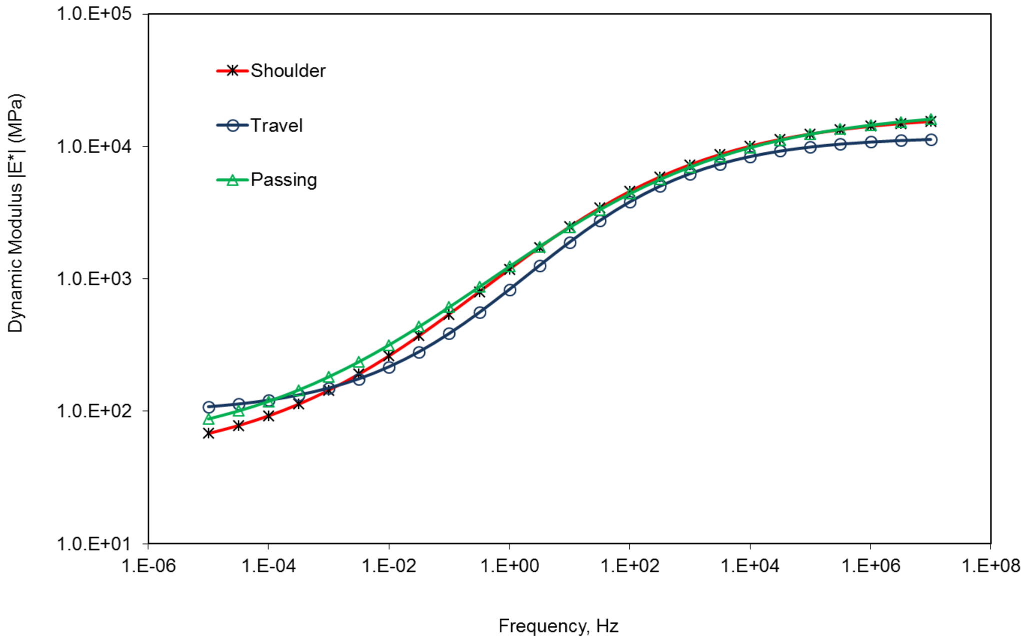

Figure 3.19 30% RAP PG 52-34 Average Dynamic Modulus Curves at 21°C for all PMPC Production Days

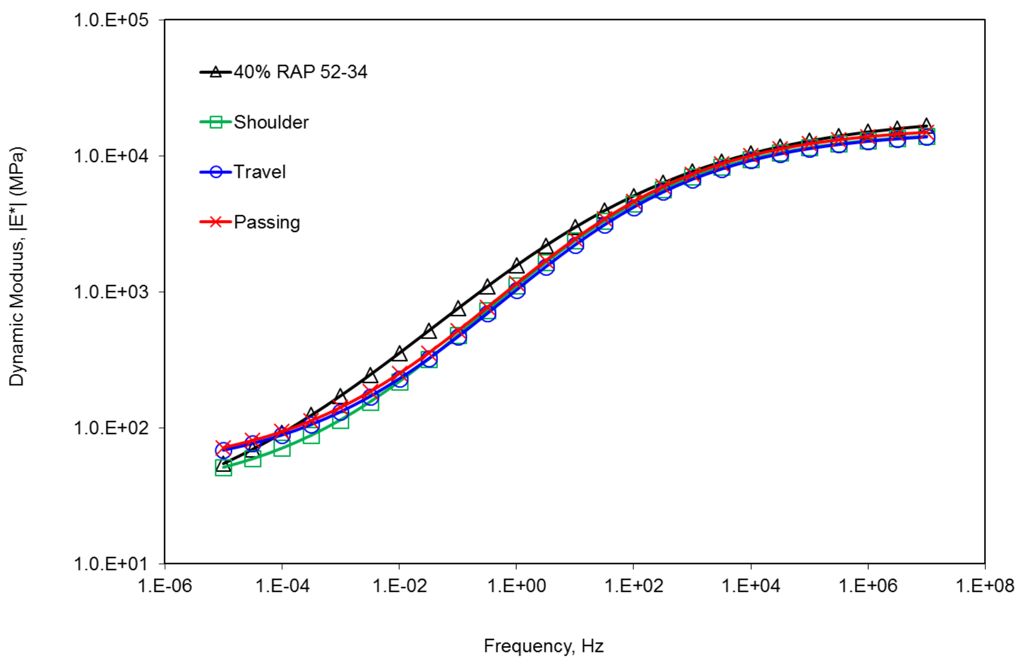

Figure 3.20 40% RAP PG 52-34 Average Dynamic Modulus Curves at 21°C for LMLC and all PMPC Production Days

UNH Testing

The NHDOT compacted specimens at the plant during for each of the six mixtures. Three replicate specimens were produced and tested for each mixture. The average dynamic modulus curves for the six mixtures are shown in Figure 3.21. The PG 58-28 base binder mixtures show an increase in average stiffness as the RAP content increases. The PG 52-34 base binder mixtures all show softer response than the PG 58-28 mixtures and show slight increases in stiffness with increasing RAP content. The dynamic modulus for the virgin PG 58-28 and 25% RAP 58-28 mixtures are statistically different at the mid to high frequency range, but all other PG 58-28 base binder mixtures are statistically similar. The PG 52-34 base binder mixtures are all statistically similar. There are statistically significant differences in dynamic modulus between the 25% RAP 58-28 mixture and PG 52-34 base binder mixtures with 25% RAP and 30% RAP at the mid to high frequencies. The 15% RAP 58-28 mixture is statistically different than the PG 52-34 base binder mixtures at the low frequencies. The phase angles for all mixtures are statistically similar.

The average Black Space curves for the six mixtures are shown in Figure 3.22. The three mixtures with the PG 58-28 binder are very similar in Black Space. The mixtures with PG 52-34 binder have lower phase angles than the PG 58-28 mixtures and also show an increase in phase angle with increasing RAP content. This is similar to the trends observed with the LMLC and FHWA PMPC specimens, and is not expected behavior for a softer binder.

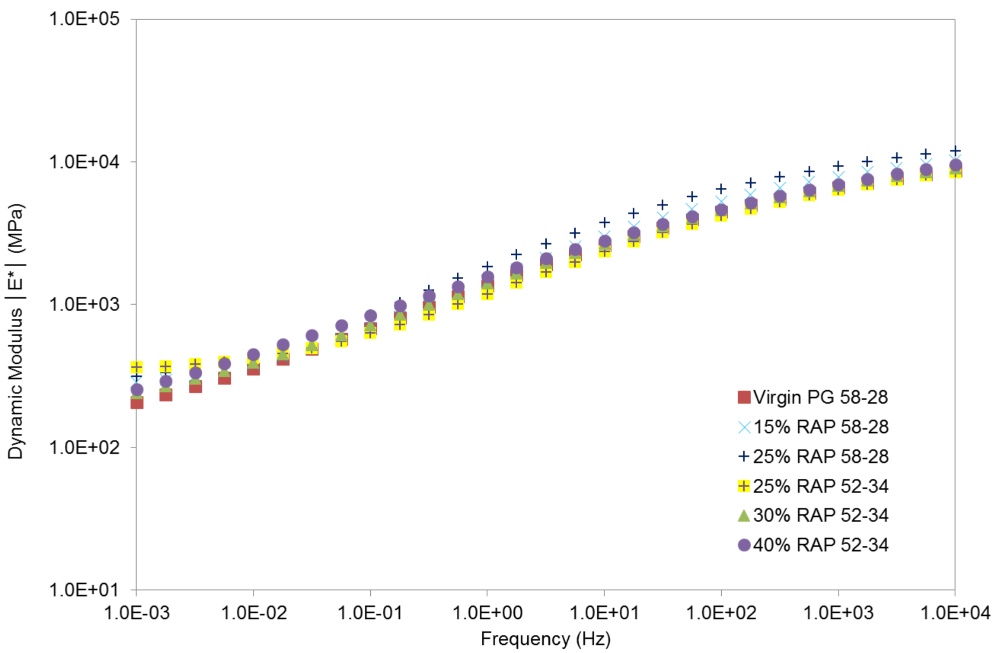

Figure 3.21 Average Dynamic Modulus Master Curves at 21^{o}C for UNH PMPC Specimens

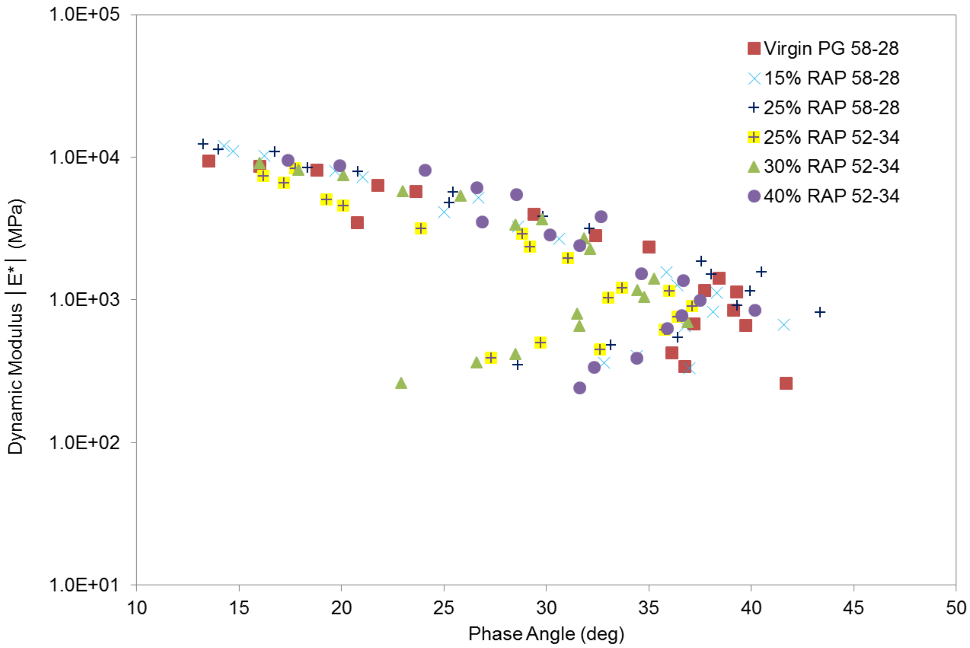

Figure 3.22 Average Black Space Curves for UNH PMPC Specimens

3.4.1.3 Plant Mixed, Laboratory Compacted (PMLC)

The loose mixture sampled at the plant during production was brought back to the lab and reheated to produce three replicate specimens for each mixture. The average dynamic modulus curves for the six mixtures are shown in Figure 3.23. The stiffness of both the PG 58-28 and PG 52-34 base binder mixtures show a decrease in average stiffness as the RAP content increases. The 25% RAP 52-34 mixture has a higher stiffness than the 25% RAP 58-28 mixture. The dynamic modulus for the 25% RAP 58-28 and 40% RAP 52-34 mixtures are statistically similar over the intermediate and high frequency range, as are the 25% RAP 52-34 and 30% RAP 52-34 mixtures. The others are statistically different over most of the intermediate to high frequency range. The phase angle measurements are statistically different at the intermediate temperature for most mixtures, but are similar at the low and high test temperatures. These results do not follow expected trends with RAP content and binder grade; the differences are likely a result of the reheating process that was required to fabricate specimens from loose mix. The average Black Space curves for the six mixtures are shown in Figure 3.24. There are no discernable trends with respect to RAP content or base binder grade with these results.

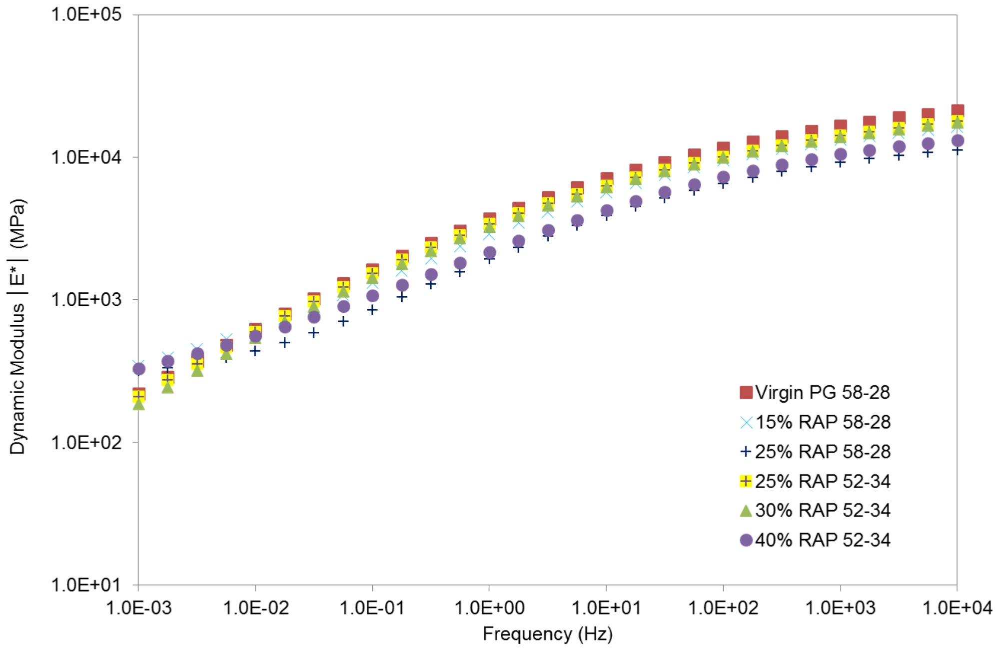

Figure 3.23 Average Dynamic Modulus Master Curves at 21°C for PMLC Specimens

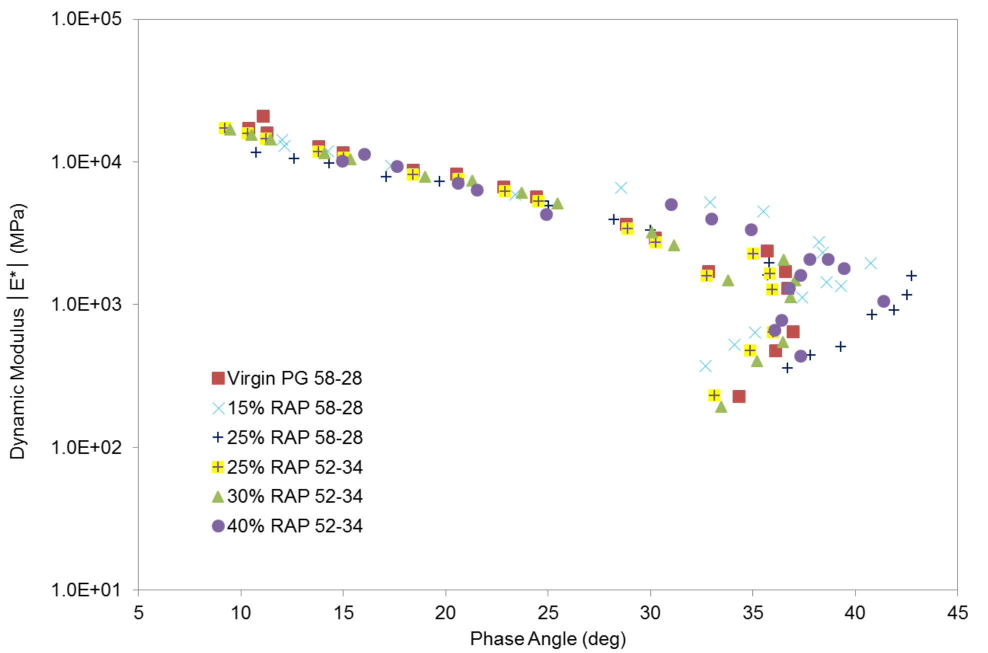

Figure 3.24 Average Black Space Curves for PMLC Specimens

3.4.1.4 Field Cores

Cores were taken from each of the test sections in the field and then two small geometry specimens were fabricated from each field core. There were challenges testing the small geometry specimens at high temperatures; the small cross sectional area required small loads that were close to the minimum capacity for AMPT control and resulted in a significant amount of creep in the specimens. For that reason, there is a large degree of uncertainty in the dynamic modulus and phase angle values at the low frequency/high temperature range. The average dynamic modulus master curves created from three replicate specimens are shown in Figure 3.25 below. Air void contents were not controlled for these specimens; the average air void contents for the mixtures are shown in the legend. At the intermediate and high frequency range, both the PG 58-28 and PG 52-34 base binder mixtures show an increase in stiffness with RAP content, and a decrease in stiffness for the mixtures with the softer base binder. The only exception is the 25% RAP 58-28 mixture, for which higher air void content may be contributing to the response. The differences in air void contents may also contribute to the magnitude of difference between the 30% and 40% RAP mixtures as well. The PG 58-28 base binders are statistically similar to one another, except at the high frequencies where the 15% RAP 58-28 mixture is significantly different. The PG 52-34 base binder mixtures are all statistically similar. Differences between the two different base binders are significant for the 25% RAP 52-34 mixture, but not at the higher RAP contents. The phase angles are statistically similar.

The average Black Space curves for the field cores are shown in Figure 3.26. The phase angles from the 30°C test temperature are not shown on this figure. The PG 58-28 base binder mixtures show a slight decrease in phase angle with higher RAP contents and overall have higher phase angles than the PG 52-34 base binder mixtures. The PG 52-34 base binder mixtures show an increase in phase angle with higher RAP content. The trends with the PG 52-34 base binders are not expected, but do follow the observations from the other specimen types.

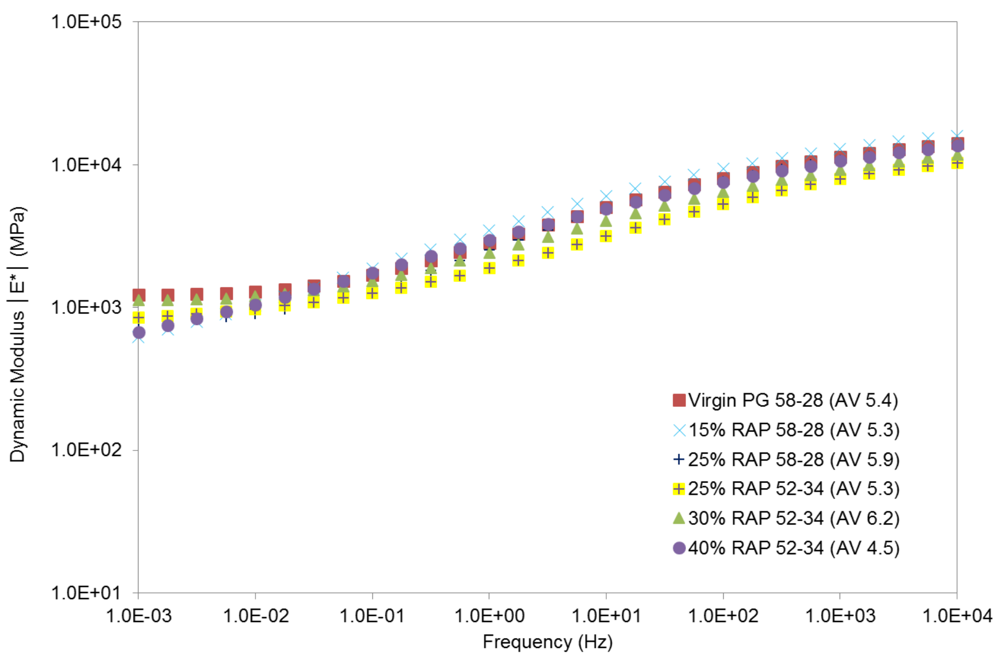

Figure 3.25 Average Dynamic Modulus Master Curves at 21°C for Field Cores

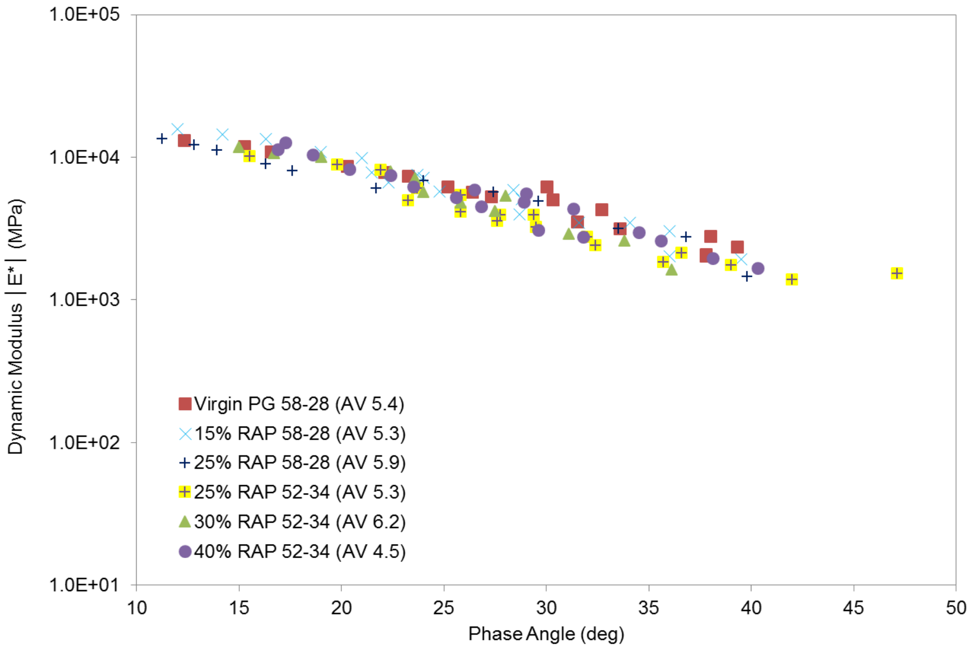

Figure 3.26 Average Black Space Curves for Field Cores

3.4.1.5 Comparison of All Dynamic Modulus Results

In this section, the dynamic modulus and black space curves for all of the different specimen types (LMLC, PMLC, PMPC, and field cores) are compared. The LMLC, PMLC, and PMPC specimens all have air void contents that were controlled in the laboratory and are in the 6.5% to 7.5% range. Specimens fabricated from field cores have lower air void contents, as noted on each graph. The field cores were tested at different temperatures than the other specimen types, and therefore statistical comparisons are not possible.

Comparison of FHWA and UNH Results

The dynamic modulus curves for PMPC specimens measured by FHWA and UNH are compared in Figure 3.27. Generally, the measured dynamic modulus values are very similar except in the low frequency range. This is likely because the FHWA testing included a higher temperature of 54.4°C. The FHWA curves therefore include measured data in that low frequency range while the UNH curves have extrapolated points from the dynamic modulus master curve construction. The comparison between the Black Space curves is shown in Figure 3.28. The FHWA phase angle measurements are consistently a few degrees lower than the UNH phase angle measurements. This may be due to the instrumentation that was used; FHWA uses spring-loaded LVDTs whereas loose core LVDTs were used in the UNH testing.

Impact of Reheating Loose Mix (PMLC vs PMPC)

The comparison between dynamic modulus master curves measured on LMLC, PMLC, PMPC, and field cores for all six mixtures are shown in Figure 3.29 and the Black Space curves are shown in Figure 3.30. The impact of reheating the loose mixture for compaction in the laboratory is shown by comparing the PMLC and PMPC specimens. The lab compacted specimens (PMLC) have higher stiffness and the difference between the lab compacted and plant compacted stiffnesses decreases with higher RAP contents; for the 25% RAP 58-28 mixture, there is little difference between the PMPC and PMLC master curves. The differences are larger for the mixtures with the PG 52-34 binder. The PMPC and PMLC dynamic modulus curves are statistically different over the whole frequency range for all mixtures except the 25% RAP 58-28 mixture. The phase angles for the virgin 58-28, 25% RAP 52-34 and 30% RAP 52-34 mixtures are significantly different at the low and intermediate temperatures; all other phase angles are statistically similar. Figure 3.30 shows the comparison between Black Space curves for all of the mixtures; the curves for the PMPC and PMLC specimens are similar for all six mixtures.

Mix Design vs Production

The difference between measurements that would be made during the mix design process and those made on the material actually produced can be evaluated by comparing the LMLC and PMPC specimens. This comparison was only done for the virgin 58-28, 25% RAP 58-28, 25% RAP 52-34, and 40% RAP 52-34 mixtures. All of the LMLC master curves are stiffer than the PMPC master curves, and are statistically different. The PG 58-28 mixtures show larger differences than the PG 52-34 mixtures between the LMLC and PMPC master curves. The mixtures with lower RAP contents also show larger differences between the LMLC and PMPC master curves. One likely reason for the differences in LMLC and PMPC master curves is the differences in aging; the LMLC mixtures were subject to short term oven aging while the PMPC mixtures were subject to aging through plant production. The higher asphalt content and finer gradations during production likely also contribute the differences observed. The Black Space curves for the LMLC specimens are significantly different than all of the other specimen types.

Field Compaction vs Laboratory Compaction

The impact of compaction method can be evaluated by comparing the PMPC specimens and the field cores. The dynamic modulus master curves for the field cores are consistently stiffer than those measured from the PMPC specimens, however the average air void contents of the field cores are lower, which will contribute to the differences observed. The 25% RAP 58-28 and 30% RAP 52-34 have air void contents close to the laboratory compacted specimens, and slightly higher dynamic modulus values are observed for these mixtures. The Black Space curves are similar for the field cores and PMPC specimens.

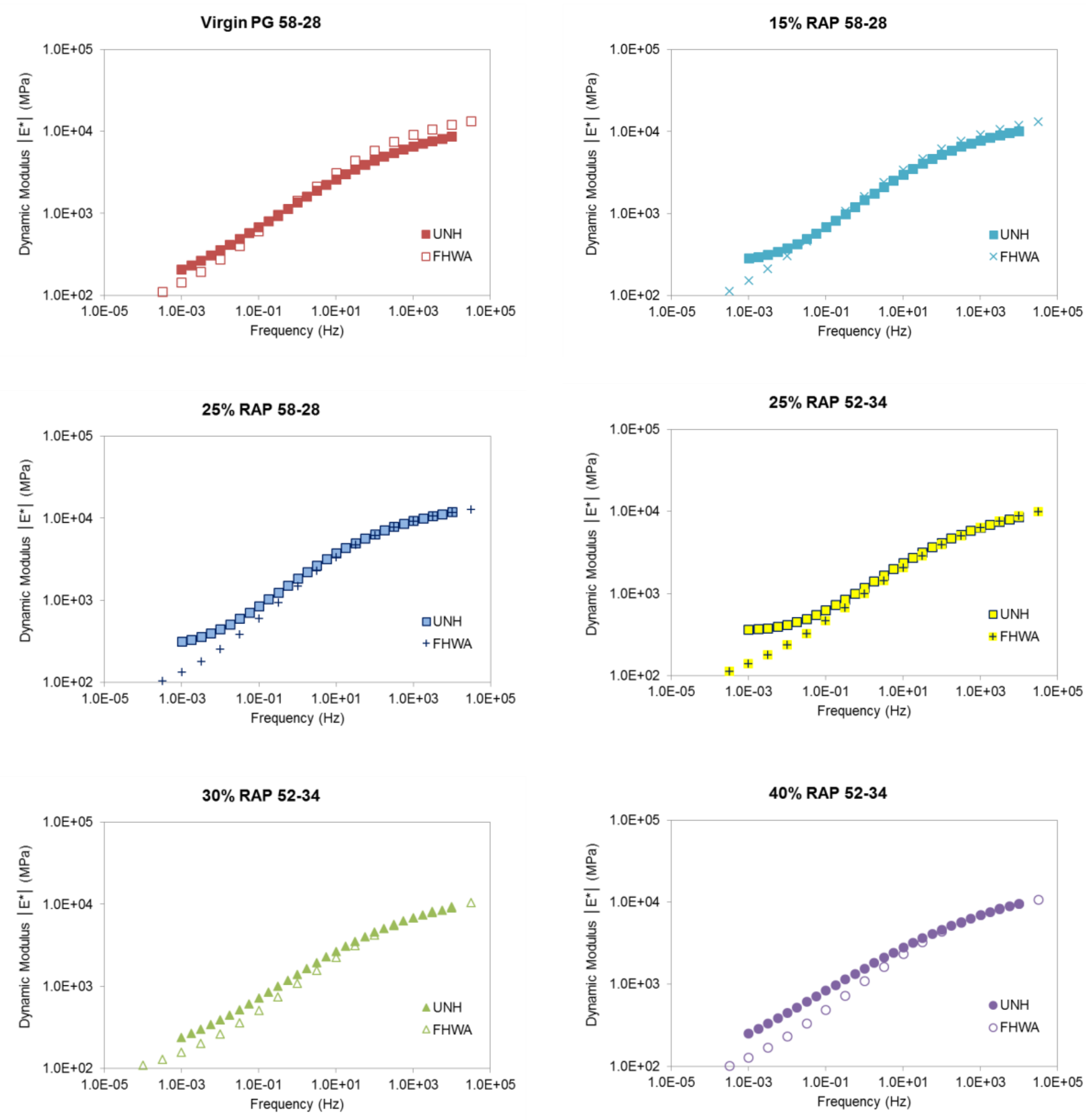

Figure 3.27 Comparison between UNH and FHWA PMPC Dynamic Modulus Master Curves at 21°C

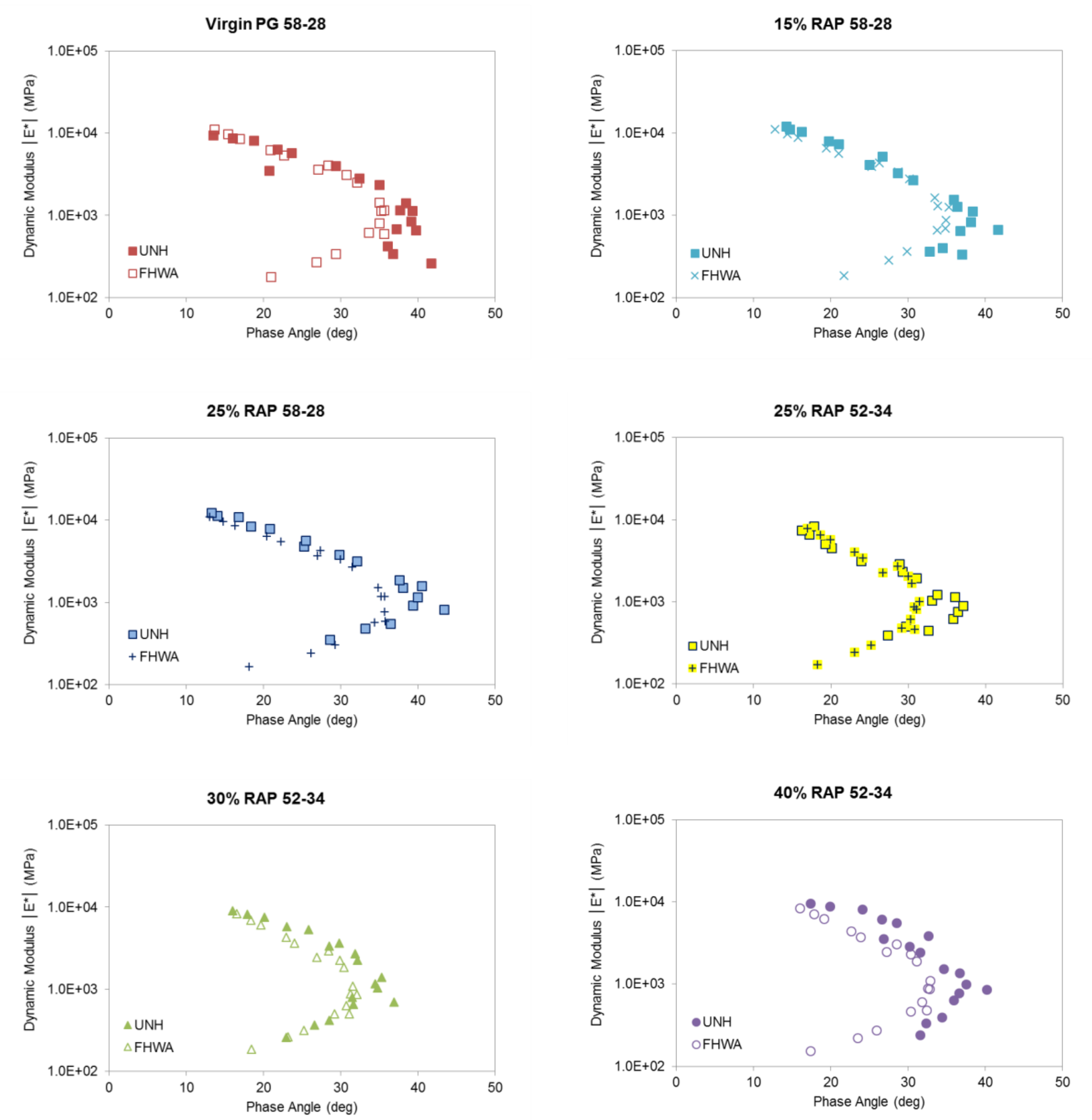

Figure 3.28 Comparison between UNH and FHWA PMPC Black Space Curves

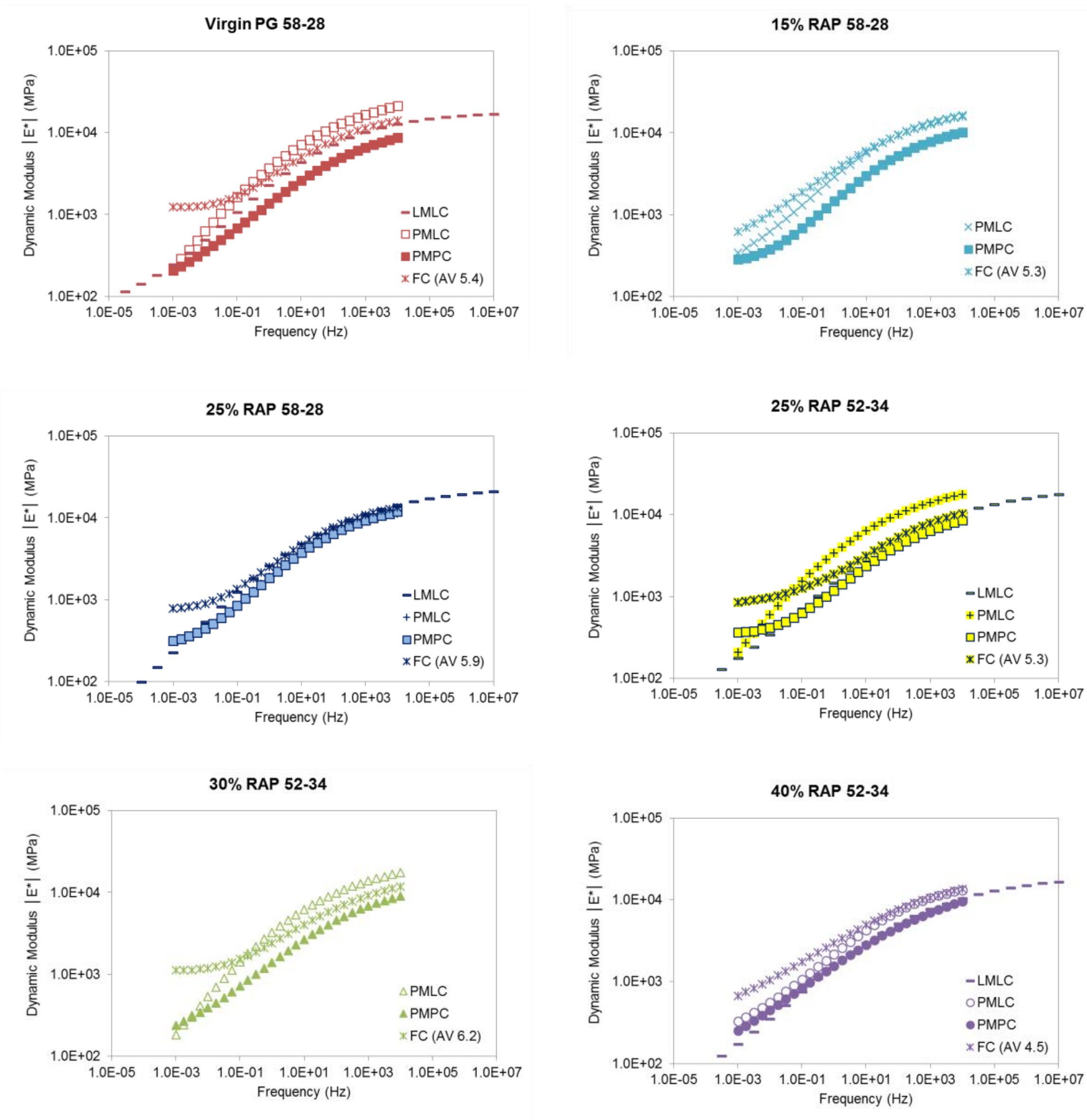

Figure 3.29 Average Dynamic Modulus Master Curves at 21°C for LMLC, PMLC, PMPC, and Field Cores

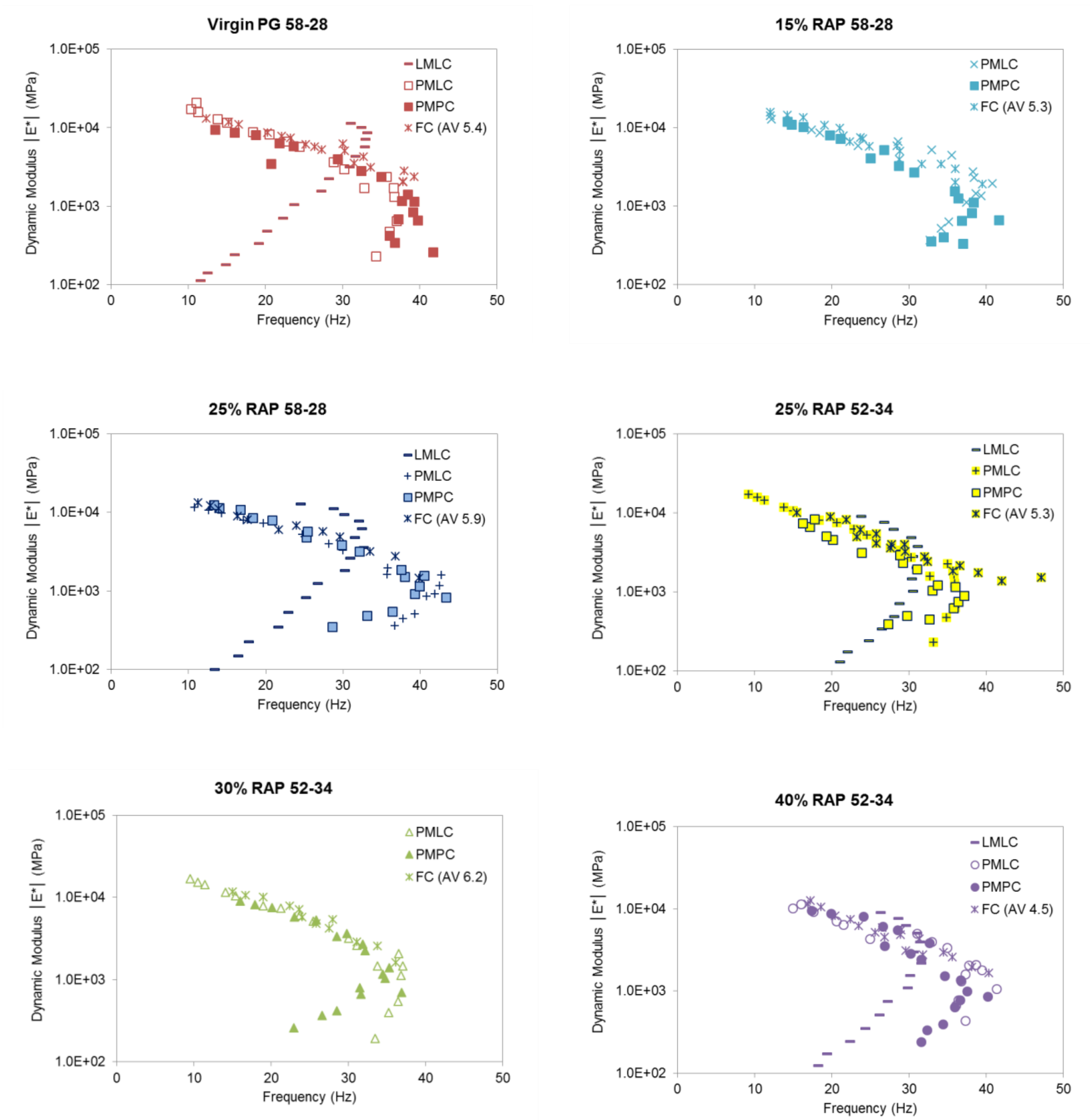

Figure 3.30 Average Black Space Curves for LMLC, PMLC, PMPC, and Field Cores

3.4.2 *Fatigue*

Fatigue behavior of the mixtures was evaluated using three different tests: S-VECD and beam fatigue to evaluate crack initiation and the overlay tester to evaluate crack propagation.

3.4.2.1 S-VECD

Fatigue testing was conducted in uniaxial tension mode using the AMPT. Analysis was performed using the S-VECD approach. The damage characteristic curves for the PMPC and PMLC specimens in **Error! Reference source not found.** and **Error! Reference source not found.**, respectively. The PMLC specimen curves fall into two groups while the PMPC specimen curves are spread out; there is no specific trend with respect to RAP content or virgin binder grade for either set of specimen types. The damage characteristic curves for the PMPC and PMLC specimens are similar for the mixtures with up to 25% RAP. The PMLC curve for the 30% and 40% RAP mixtures is much different than the PMPC curve. The relationship between the SVECD failure criterion, G^R, and the number of cycles to failure for the PMPC and PMLC mixtures are shown in Figure 3.33 and Figure 3.34, respectively. In general, mixtures that have shallower slopes and are further towards the upper right would be expected to have better fatigue performance. However, the actual field performance will depend upon the structure in which the mixture is placed and the traffic and environmental loadings. The PMLC specimens do not show any trends with respect to RAP content or virgin PG grade, however the virgin mixture has a shallower slope than the RAP mixtures. The virgin and 15% RAP PMPC specimens are grouped together with a shallower slope than the remaining RAP specimens that show similar expected performance. There are no trends with the direct comparison of the PMPC and PMLC specimen types in Figure 3.35 and Figure 3.36; in some cases the two are similar and in others one type shows better expected fatigue performance than the other.

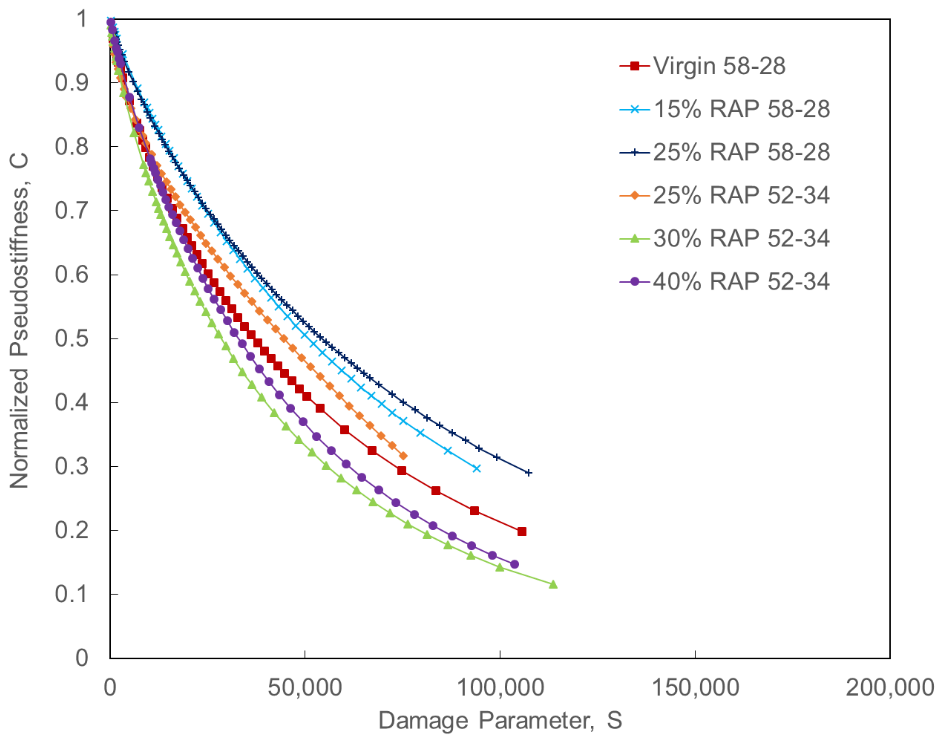

Figure 3.31 Damage Characteristic Curves for PMPC Specimens

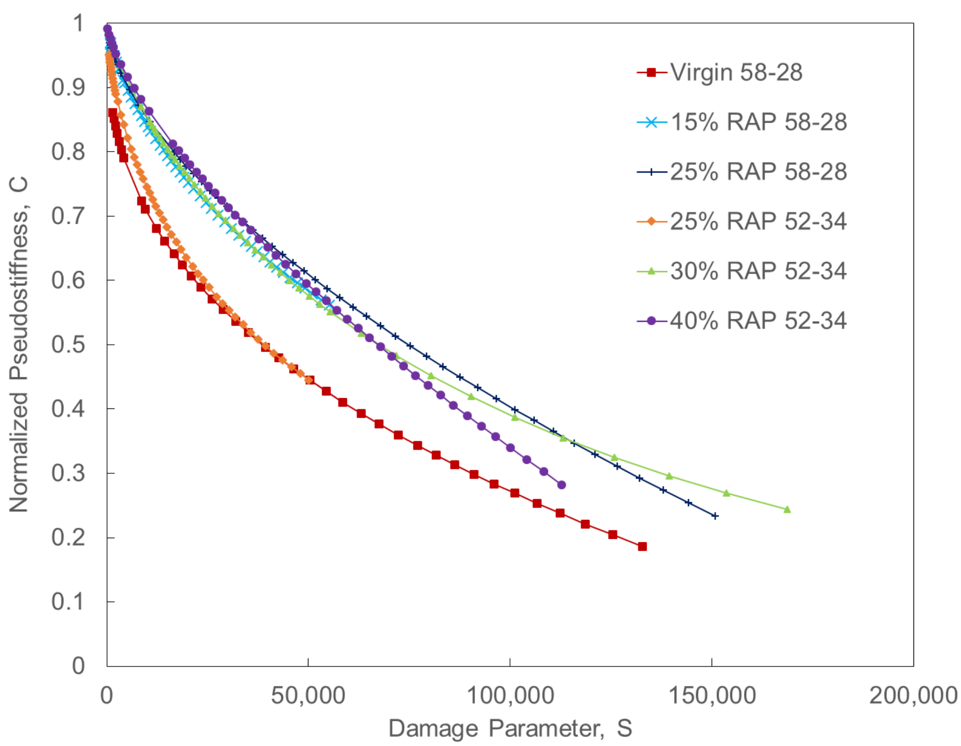

Figure 3.32 Damage Characteristic Curves for PMLC Specimens

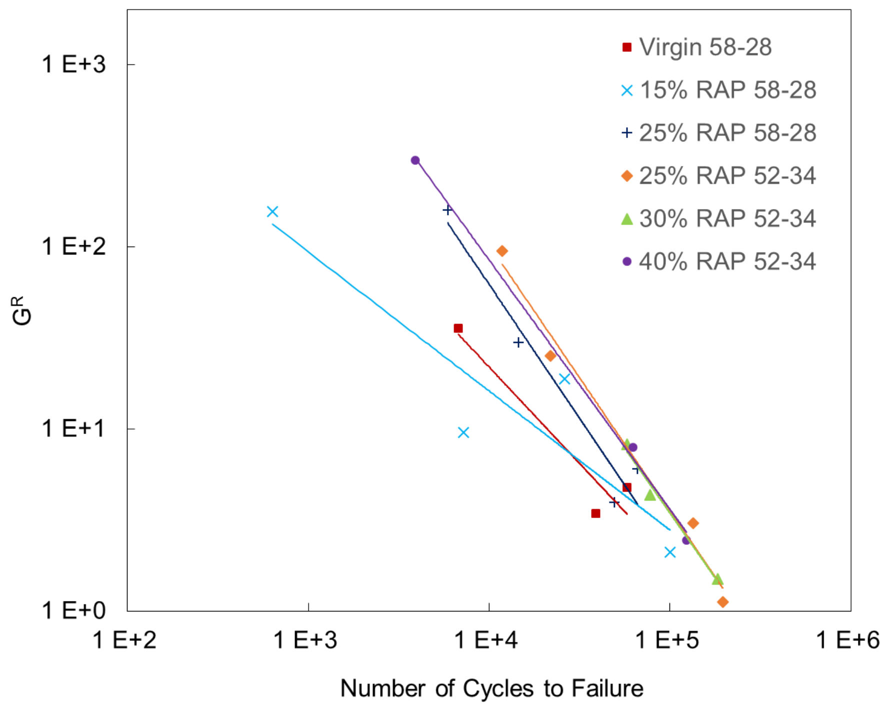

Figure 3.33 G^R versus Number of Cycles to Failure for PMPC Specimens

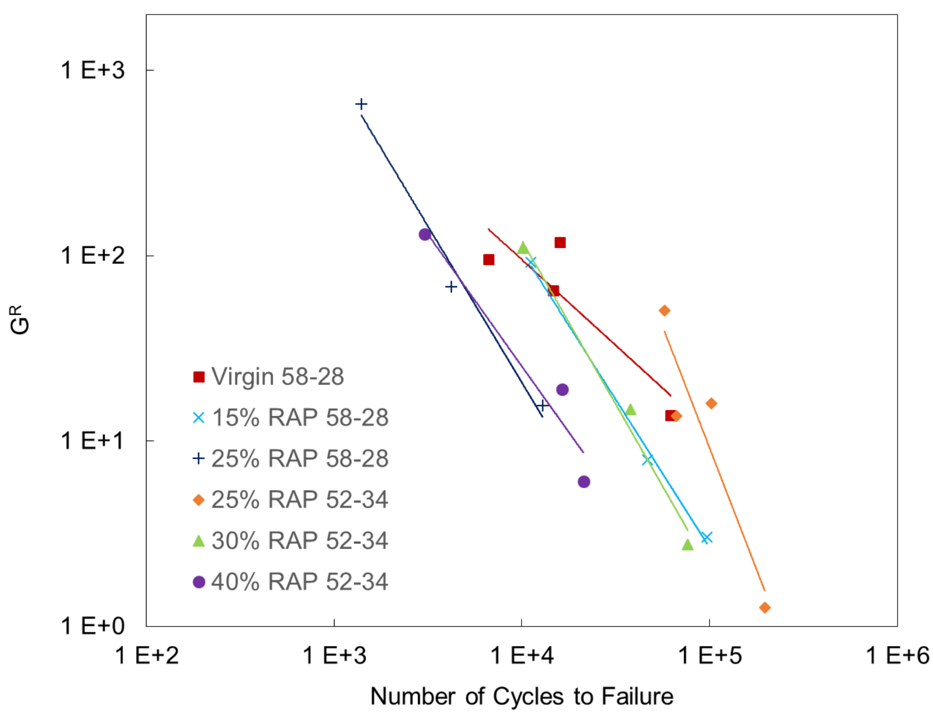

Figure 3.34 G^R versus Number of Cycles to Failure for PMLC Specimens

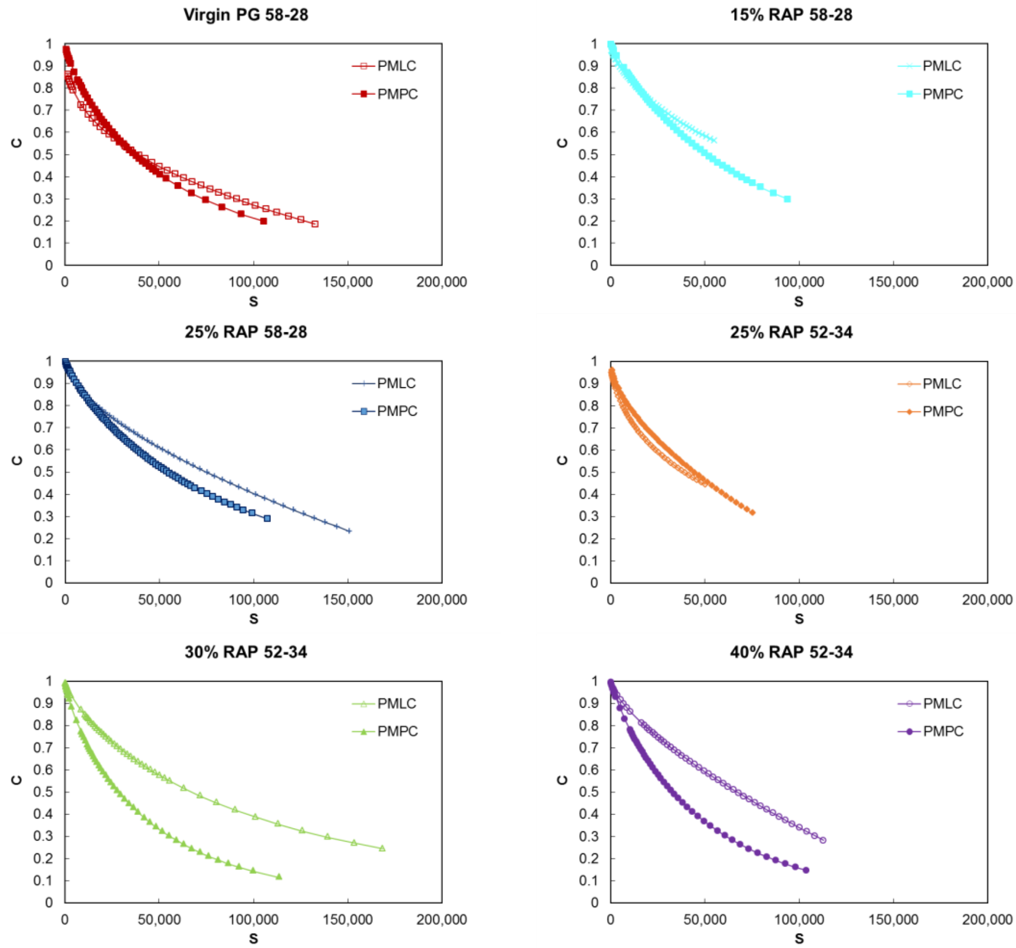

Figure 3.35 Comparison of PMLC and PMPC damage characteristic curves for each mixture

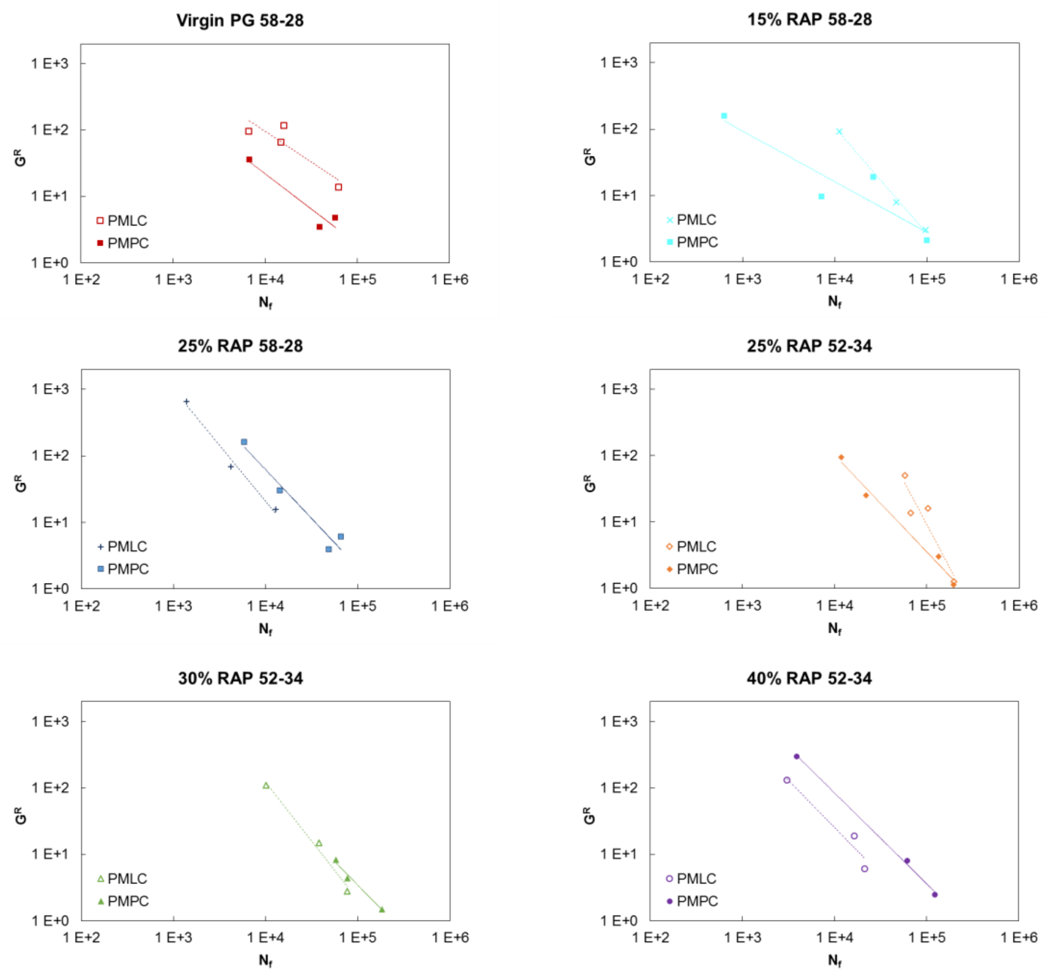

Figure 3.36 Comparison of PMLC and PMPC G^R versus number of cycles to failure curves for each mixture

3.4.2.2 Flexural Beam Fatigue

Flexural beam fatigue testing was performed on four of the NH mixtures; there was not sufficient material for the testing to be performed on the virgin and 15% RAP PG 58-28 mixtures. The results, shown in Figure 3.37, show that the use of the softer binder for the 25% RAP mixture improved the laboratory flexural fatigue performance. All of the mixtures with the PG 52-34 base binder had a greater number of cycles to failure than the PG 58-28 mixture, and there is not much difference in laboratory flexural fatigue performance with RAP content for the PG 52-34 base binder mixtures.

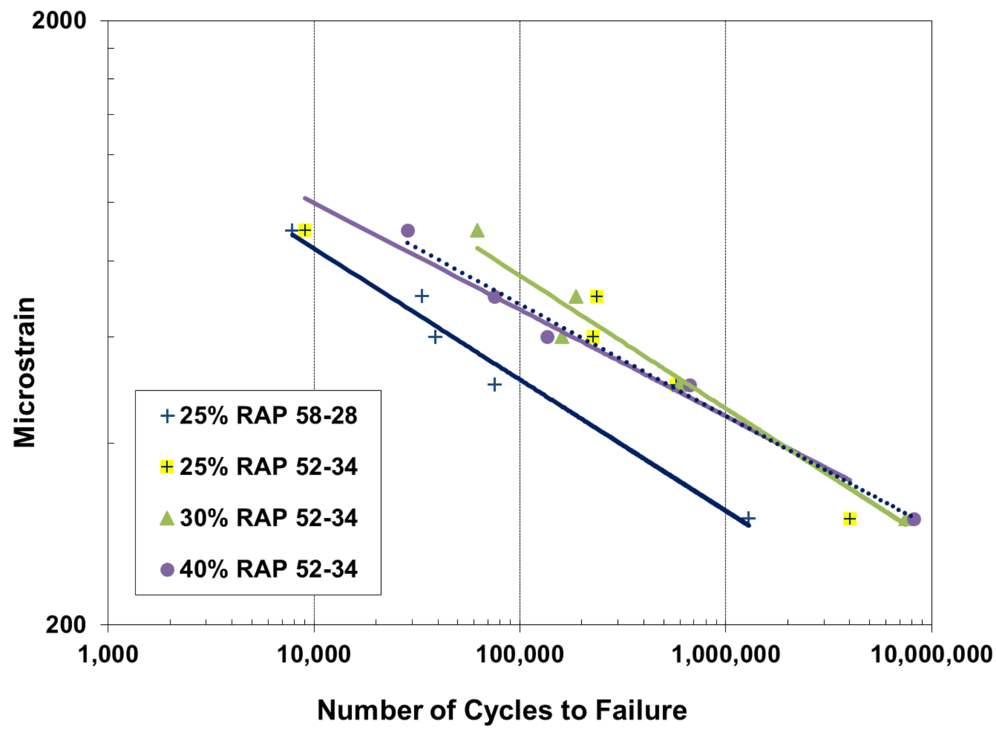

Figure 3.37 Flexural Beam Fatigue Results for NH Mixtures

3.4.2.3 Overlay Tester

The overlay test results for all six mixtures are shown in Figure 3.38. As with other mixtures, the performance in the overlay tester appears to be a function of the RAP content. The mixture that performed the best was the virgin PG 58-28, while the worst performing mixtures were the 30 and 40% RAP PG 52-34 mixtures. In contrast to the flexural beam fatigue test results, the overlay tester shows that the use of the softer PG grade may not improve the resistance to crack propagation.

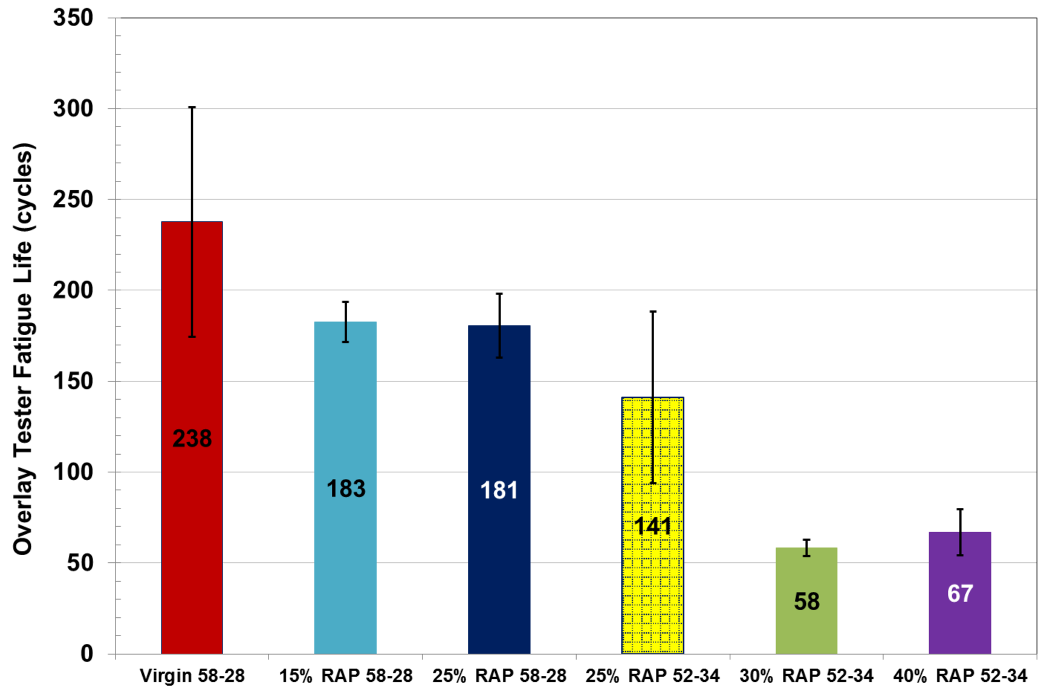

Figure 3.38 Overlay Tester Results for NH Mixtures

3.4.3 *Flow Number*

Flow number tests were conducted by the FHWA mobile lab on both LMLC and PMPC specimens at several confining states and deviator stresses. Figure 3.39 through Figure 3.42 show the average of four replicate tests. Figure 3.39 shows that the flow number for the LMLC specimens in the unconfined state increases with RAP content for both base virgin binder grades and that use of the softer PG 52-34 binder decreases the flow number for the 25% RAP mix, as expected. However, when the materials are confined (Figure 3.41), the flow number decreases with the higher RAP content for the PG 52-34 base binder materials. The production mixtures show different trends depending on the deviator stress that is applied. All three deviator stresses show that the 25% RAP PG 52-34 mixture performs better than the 25% RAP PG 58-28 mixture and the 30% RAP PG 52-34 mixture. With the exception of the virgin mix, the LMLC specimens show significantly higher flow numbers than the PMPC specimens (Figure 3.41), indicating a difference in the aging condition of the two sets of specimens and the differences in asphalt content and gradation. The trends within each PG base binder grade are the same with the LMLC and PMPC specimens, but the trend between the two 25% RAP mixtures reverses.

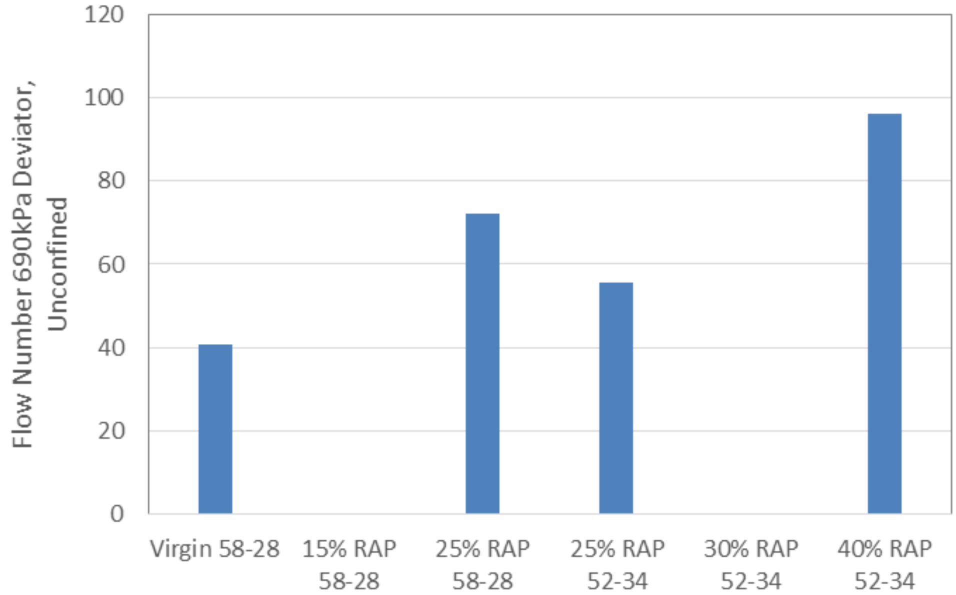

Figure 3.39 Average Flow Number for LMLC Specimens Unconfined and 690 kPa Deviator Stress

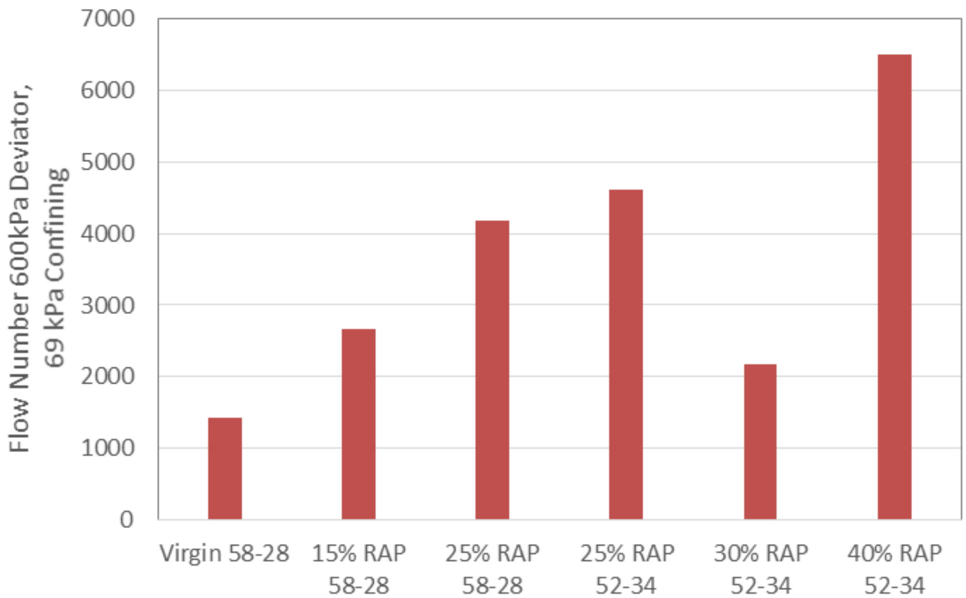

Figure 3.40 Average Flow Number for PMPC Specimens at 69 kPa Confining Pressure and 600 kPa Deviator Stress

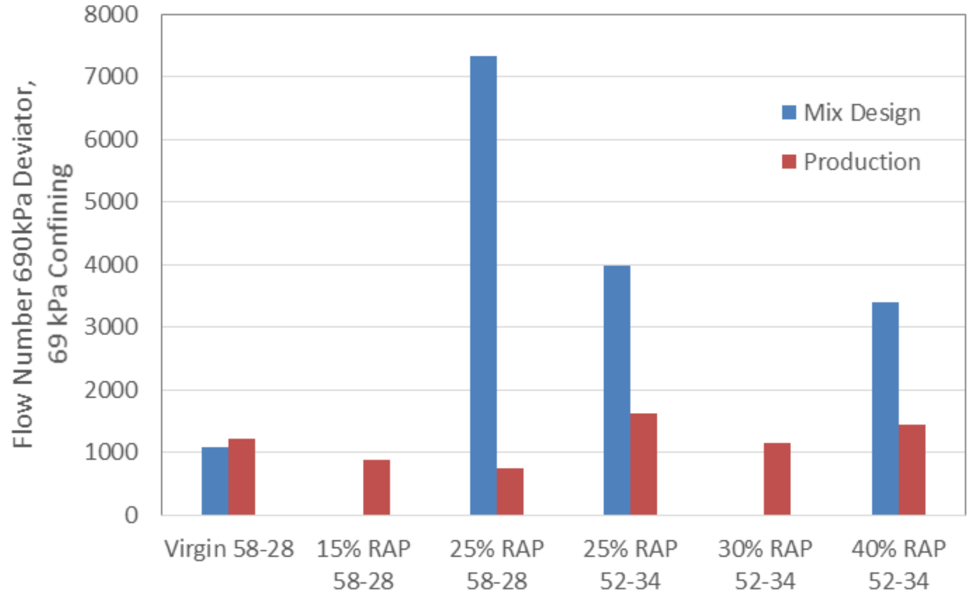

Figure 3.41 Average Flow Number for LMLC and PMPC Specimens at 69 kPa Confining Pressure and 690 kPa Deviator Stress

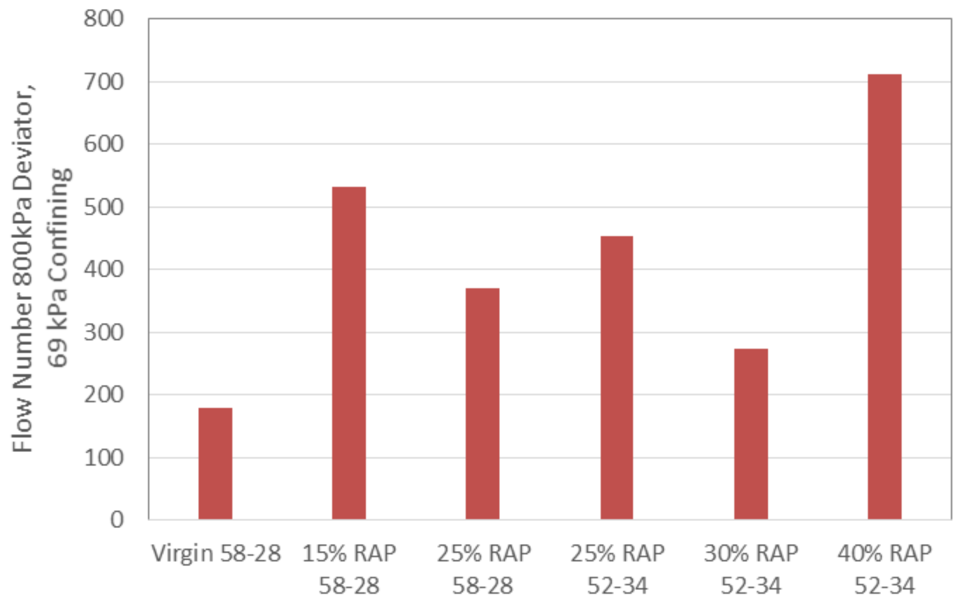

Figure 3.42 Average Flow Number for PMPC Specimens at 69 kPa Confining Pressure and 800 kPa Deviator Stress

3.4.4 *Moisture Hamburg Wheel Tracking Device*

The stripping inflection point (SIP) determined from the HWTD testing are shown in Figure 3.43. Higher SIP values indicate an increased resistance to moisture damage and rutting. The LMLC specimens exhibited higher SIP values than the PMPC specimens. The higher RAP contents have slightly improved SIP values and the performance of the PG 58-28 base binder mixtures is better than the PG 52-34 base binder mixtures, with larger differences observed for the LMLC specimens than the PMPC specimens.

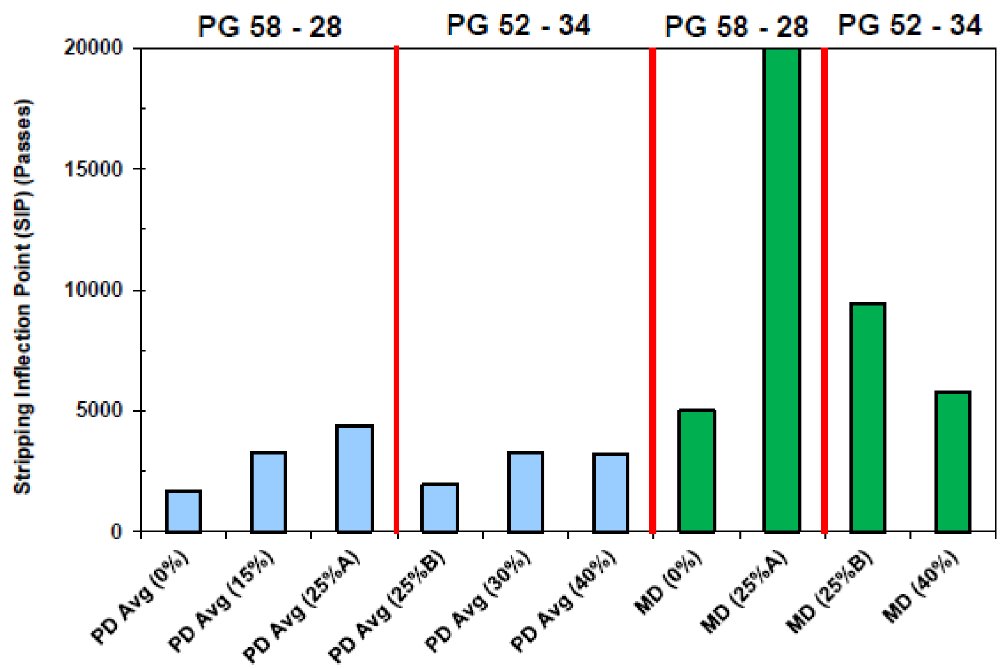

Figure 3.43 Stripping Inflection Point for PMPC (PD) and LMLC (MD) specimens

3.5 Field Performance

Field performance of the sections was qualitatively evaluated by NHDOT in December of 2014, after approximately 3.5 years of service. A summary of the findings are shown in Table 3.3. All sections are showing longitudinal cracking along the construction joints. There are transverse cracks in all shoulder sections, with the amount of cracking increasing with higher RAP contents. Fatigue cracking was observed at RAP levels of 25% and higher. The mixtures with the PG 58-28 base binder are performing better than those with the PG 52-34 base binder. The 30% RAP 52-34 section appears to have the worst performance overall, which may also be due to the higher air void content (as measured in from the field cores).

Table 3.3 Field Performance Evaluated December 2014

Section	Longitudinal joint cracking	Transverse cracking	Fatigue cracking	Other
Virgin PG 58-28	Centerline and shoulder	Infrequent through shoulder	none	n/a
15% RAP PG 58-28	Centerline and shoulder	Regular through shoulder	none	n/a
25% RAP PG 58-28	Centerline and shoulder	Regular through shoulder	One in right wheelpath	n/a
25% RAP PG 52-34	Centerline and shoulder	Regular through shoulder, extend mid-full lane	Occasional	n/a
30% RAP PG 52-34	Centerline and shoulder	Full width 10-20 ft apart	Occasional	Coarse texture in travel late, aggregate pop outs in both lanes
40% RAP PG 52-34	Centerline and shoulder	Mostly full width, some not reaching shoulder in passing lane, 20-30 ft apart	Occasional	Some aggregate pop outs

CHAPTER 4 VIRGINIA MIXTURES

4.1 Mixture Design Information

The Virginia mixtures were produced in a 1993 Astec double barrel drum plant with 270 tons per hour capacity owned by Superior Paving Corporation and located in Centreville, Virginia (VA). Mixing times were determined to be approximately 250-260 seconds. The general mixture design information for the VA mixtures is shown in Table 4.1 and Table 4.2. The mixtures were designed with a nominal maximum aggregate size of 9.5 mm with a varying optimum asphalt content based on RAP percentage. The design high PG grades were decreased as RAP content increased to offset the stiff RAP material; the design low PG grades were constant among all four mixtures. The gradations were similar across the four mixtures.

4.2 Plant Production Information

The plant production information for the VA mixtures is shown in Table 4.3. The asphalt mixtures were produced between 310 to 315°F. All mixtures were stored in the silo for 20-30 minutes prior to discharging into the delivery trucks. The haul time for the four mixtures was between 15 and 20 minutes, resulting in compaction temperatures that were consistent among the mixtures, ranging from 290-300°F.

Table 4.1 Mix design information – all VA mixtures

Mix	PG Grade	NMAS (mm)	Design Asphalt Content (%)	% RAP	VMA	VFA
VA PG 76-22 0 % RAP	76-22	9.5	5.6	0	15.2	83.2
VA PG 70-22 20 % RAP	70-22	9.5	5.2	20	15.2	79.6
VA PG 64-22 30 % RAP	64-22	9.5	5.2	30	14.6	84.6
VA PG 64-22 40 % RAP	64-22	9.5	5.4	40	15.0	84.4

Table 4.2 Mixture gradations - all VA mixtures

Mix	PG	Mixture Gradation								
		12.5	9.5	#4	#8	#16	#30	#50	#100	#200
VA PG 76-22 0 % RAP	76-22	99.9	92.0	61.7	42.3	30.9	22.5	15.1	10.1	6.5
VA PG 70-22 20 % RAP	70-22	99.3	89.2	57.6	41.8	31.8	22.9	14.4	9.4	6.1
VA PG 64-22 30 % RAP	64-22	99.1	90.8	58.3	40.3	30.5	22.6	14.7	9.6	6.4
VA PG 64-22 40 % RAP	64-22	99.0	91.1	58.6	42.5	32.5	23.4	14.6	9.3	6.2

Table 4.3 Plant production information - all VA mixtures

Mix	PG Grade	Plant Type	Discharge Temp. (ºC/ºF)	Compaction Temp. (ºC/ºF)	Silo Storage time (hrs)
VA PG 76-22 0 % RAP	76-22	Drum	154.4/310	148.9/300	0.33
VA PG 70-22 20 % RAP	70-22	Drum	157.2/315	146.1/290	0.50
VA PG 64-22 30 % RAP	64-22	Drum	157.2/315	146.1/295	0.42
VA PG 64-22 40 % RAP	64-22	Drum	154.4/310	143.3/290	0.50

4.3 Mixture Testing

4.3.1 *Dynamic Modulus*

Tall test specimens compacted at the asphalt plant were not available for this set of mixtures. Sampled asphalt mixtures from this project only consisted of short gyratory specimens for indirect tensile testing and loose mix. The loose mix was reheated and compacted to form tall gyratory specimens for dynamic modulus testing.

The master stiffness curves generated from the test data are shown in Figure 4.1. The virgin PG 76-22 mixture was the softest. The three RAP mixtures have very similar dynamic modulus master curves; the use of the PG 64-22 virgin binder with the 30% and 40% RAP contents offset the higher RAP contents and produced stiffness similar to the 20% RAP mixture with the PG 70-22 binder. The Black Space plots, in Figure 4.2, show that the addition of the 20% RAP decreases the phase angle, but the use of the softer PG 64-22 binder with the 30% and 40% RAP mixtures brings the phase angle back to a position similar to that of the virgin mixture.

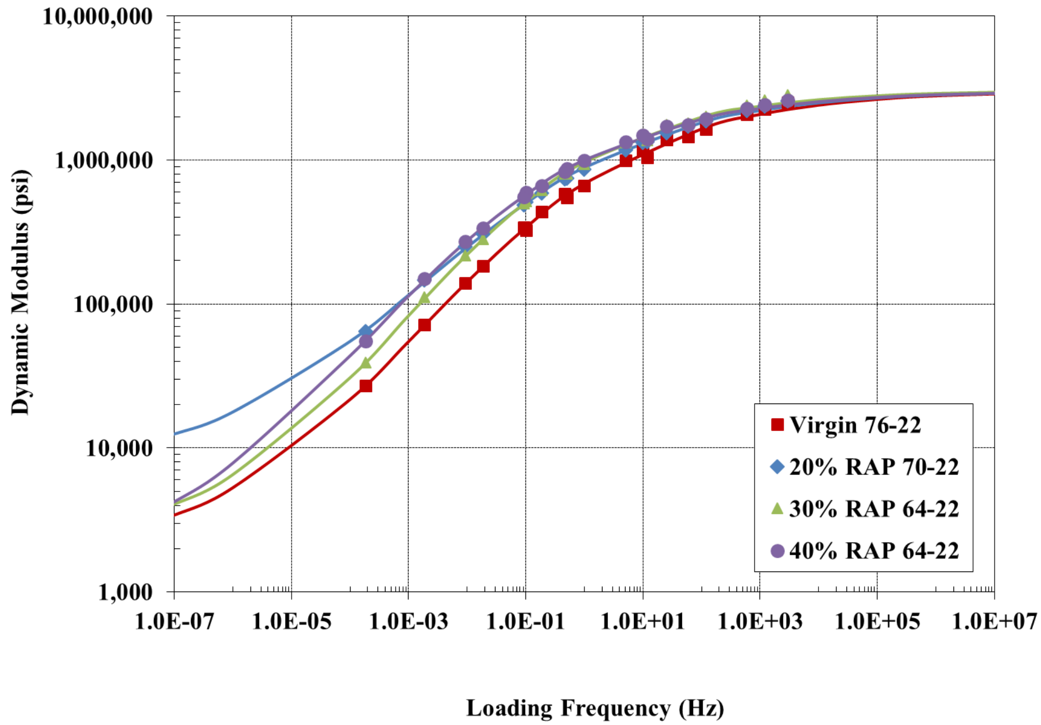

Figure 4.1 Dynamic Modulus Master Curves for VA PMLC Specimens

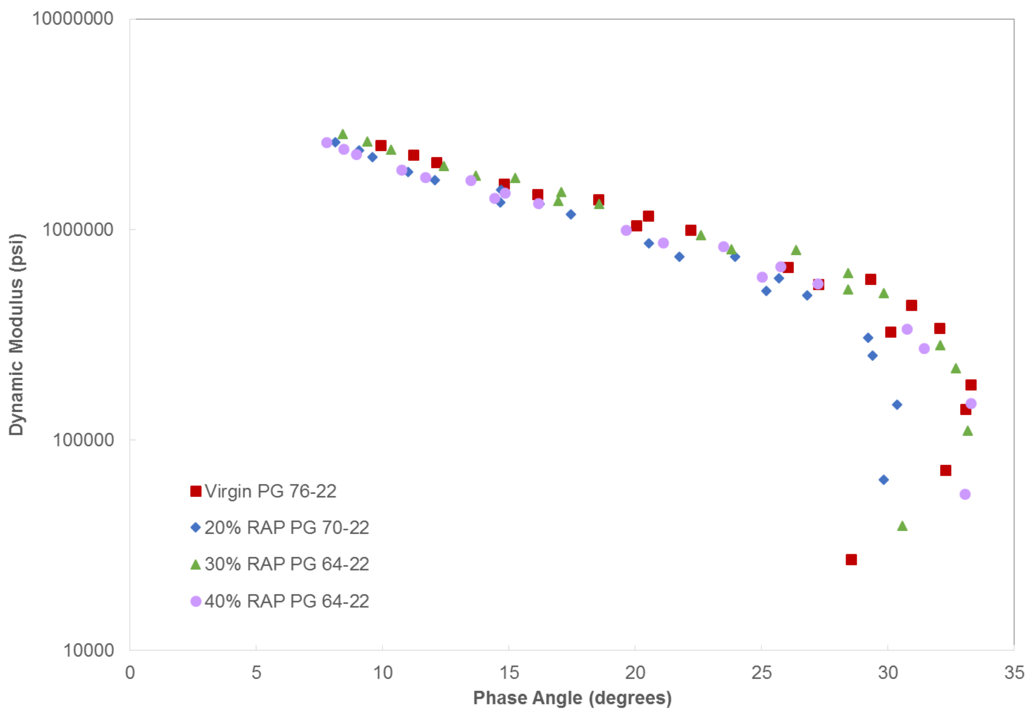

Figure 4.2 Black Space Curves for VA PMLC Specimens

4.3.2 *Fatigue*

Fatigue behavior of the mixtures was evaluated using three different tests: S-VECD and beam fatigue to evaluate crack initiation and the overlay tester to evaluate crack propagation. All of the fatigue evaluation was conducted on specimens that were fabricated from reheated plant mix.

4.3.2.1 S-VECD

S-VECD testing on the VA mixtures was conducted in crosshead-controlled (CX) mode of loading. In accordance with recent recommendations from AASHTO TP107, virgin and 20% RAP mixtures were tested at 21°C, while the 30 and 40% mixtures were tested at 18°C. The testing frequency was 10 Hz. Table 4.4 shows the exponential fit parameters for the S-VECD model for the VA mixtures.

Table 4.4 Exponential Fit Parameters for VECD Model for VA Mixtures

Mix Type	**Alpha**	**a**	**b**	**C_f**
VA PG 76-22 0% RAP	3.420	-1.117E-03	5.768E-01	0.168
VA PG 70-22 20% RAP	3.946	-1.019E-04	7.664E-01	0.388
VA PG 64-22 30% RAP	3.321	-2.214E-04	7.075E-01	0.341
VA PG 64-22 40% RAP	3.307	-2.6332E-04	6.991E-01	0.408

Figure 4.3 shows the fitted damage characteristic curves for all of the VA mixtures. The virgin mixture exhibits the lowest damage at a given pseudostiffness value, while the 20% RAP mixture produces the highest damage value at a given pseudostiffness. The PG 64-22 mixtures (30% and 40% RAP) lie between the PG 76-22 (virgin) and PG 70-22 (20% RAP), indicating that the binder grade change at higher RAP contents may influence the placement of the damage characteristic curve.

The S-VECD failure criterion using the stable rate of pseudo strain energy release (G^R) and the loading mode-independent secant G^R for the mixtures are presented in Figure 4.4 and Figure 4.5. At a given G^R value, the virgin material performs the best, while the three RAP mixtures show similar performance.

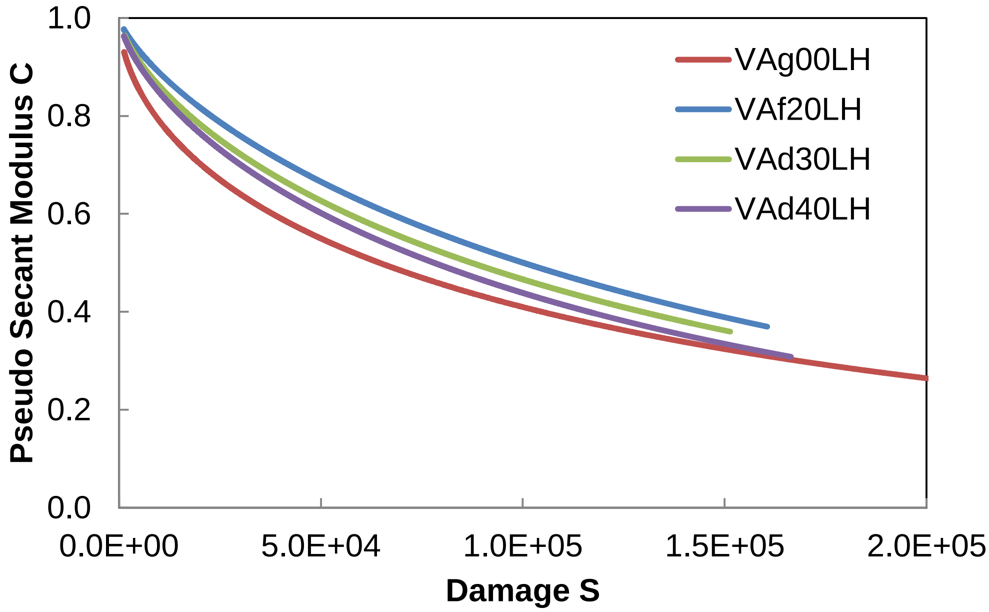

Figure 4.3 Characteristic curve C vs. S - all VA mixtures

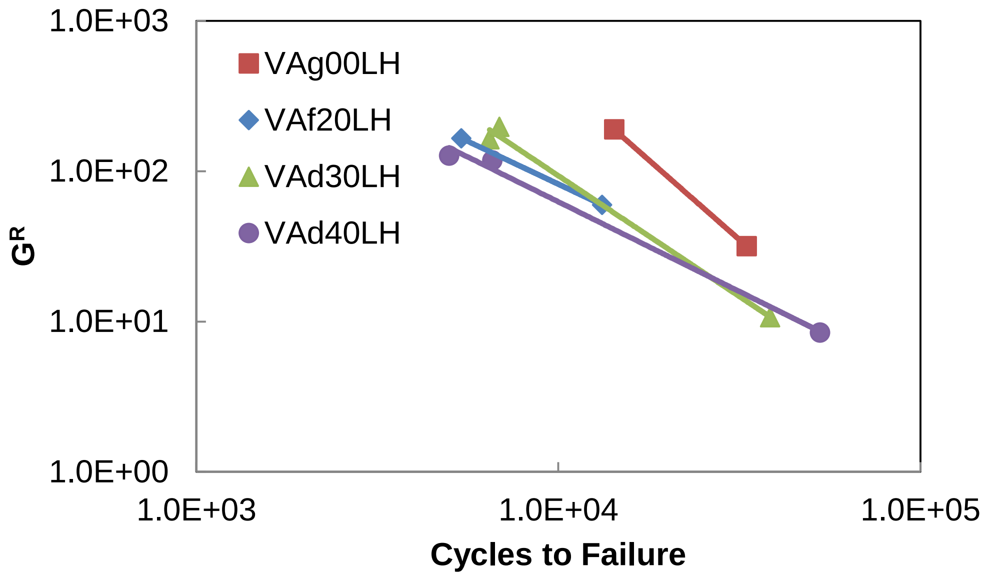

Figure 4.4 Failure Criterion for VA mixtures using G^R method

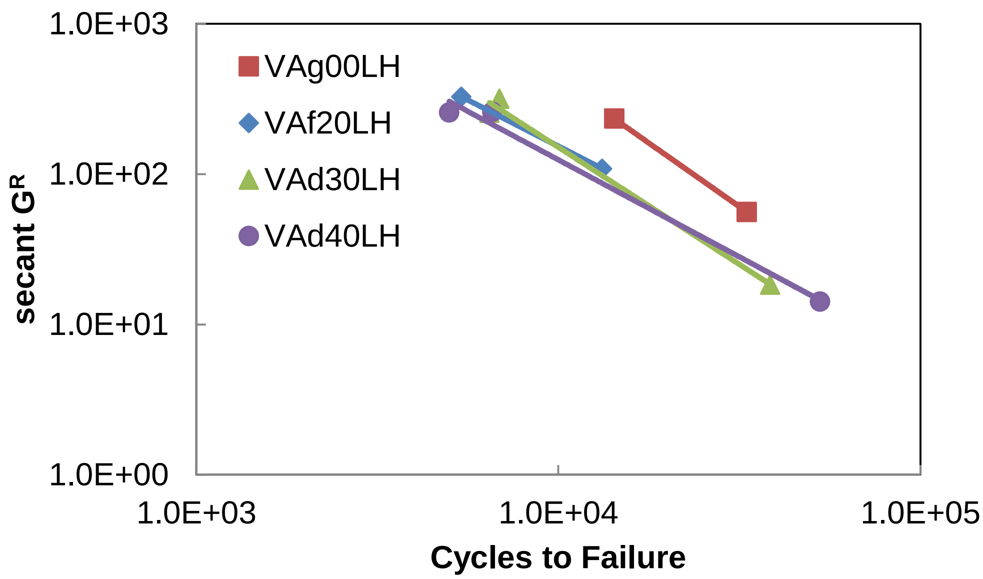

Figure 4.5 Failure Criterion for VA mixtures using secant-GR method

4.3.2.2 Flexural Beam Fatigue

The flexural beam fatigue results for the four VA mixtures are shown in Figure 4.6. The virgin mixture shows the best performance. At the 20% RAP, the number of cycles to failure decreases. The 30% and 40% RAP mixtures show similar performance.

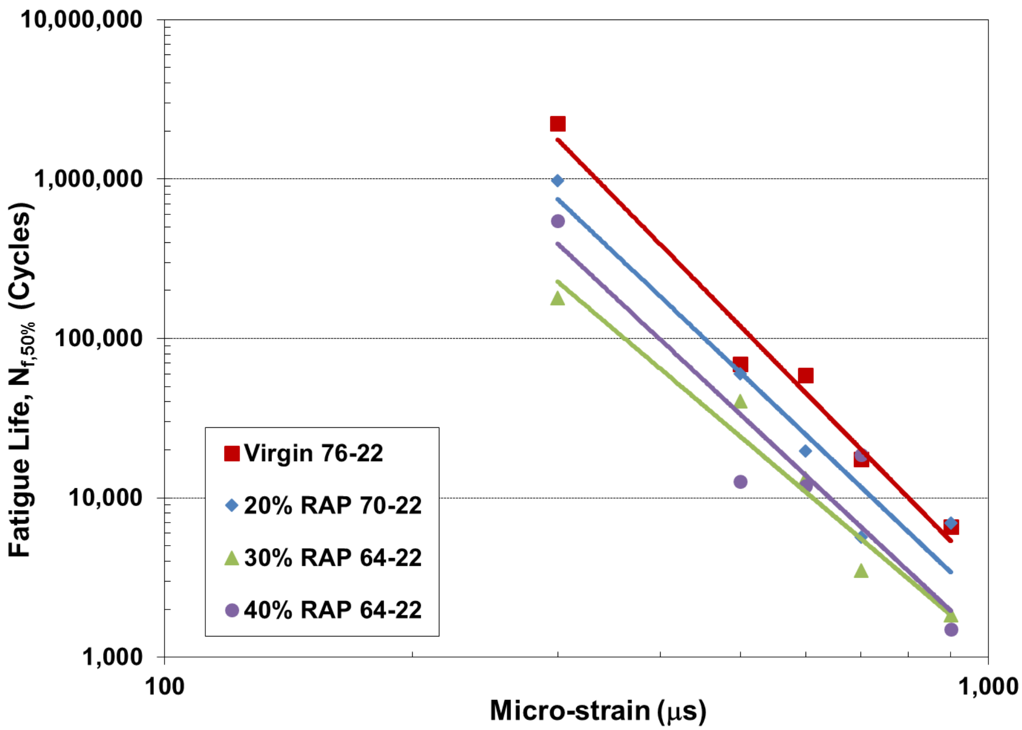

Figure 4.6 Flexural Beam Fatigue Test Results for Virginia RAP Mixtures

4.4.2.3 Overlay Tester

The overlay tester results for the VA mixtures (Figure 4.7) show that the three RAP mixtures have similarly poor performance with respect to crack propagation. The virgin mixture clearly outperforms the RAP mixtures and the use of the softer base binder grades does not help to improve the performance.

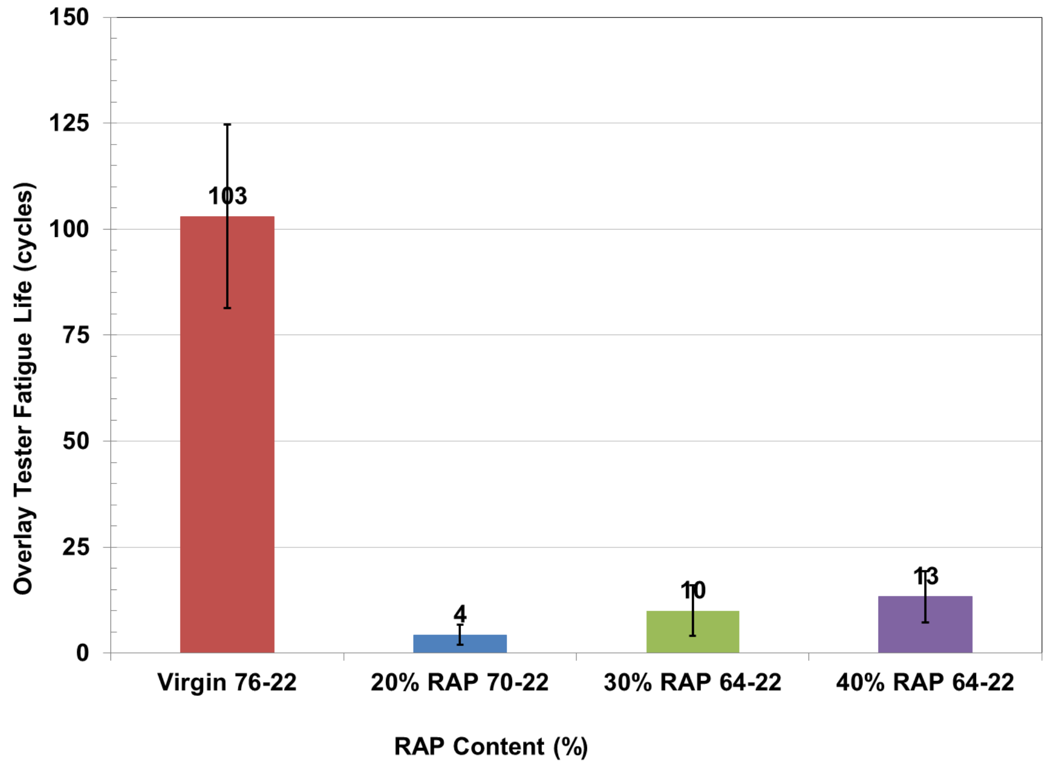

Figure 4.7 Overlay Tester Results for Virginia Mixtures

4.3.3 *Low Temperature*

4.3.3.1 TSRST

The failure temperature and load measured from the TSRST test on the PMLC specimens are shown in Figure 4.8 and Figure 4.9, respectively. The increasing RAP content results in a warmer failure temperature and a lower failure load, although the failure loads are not very different for the RAP mixtures. This indicates that the use of the softer virgin binder does offset the increase in stiffness from the RAP.

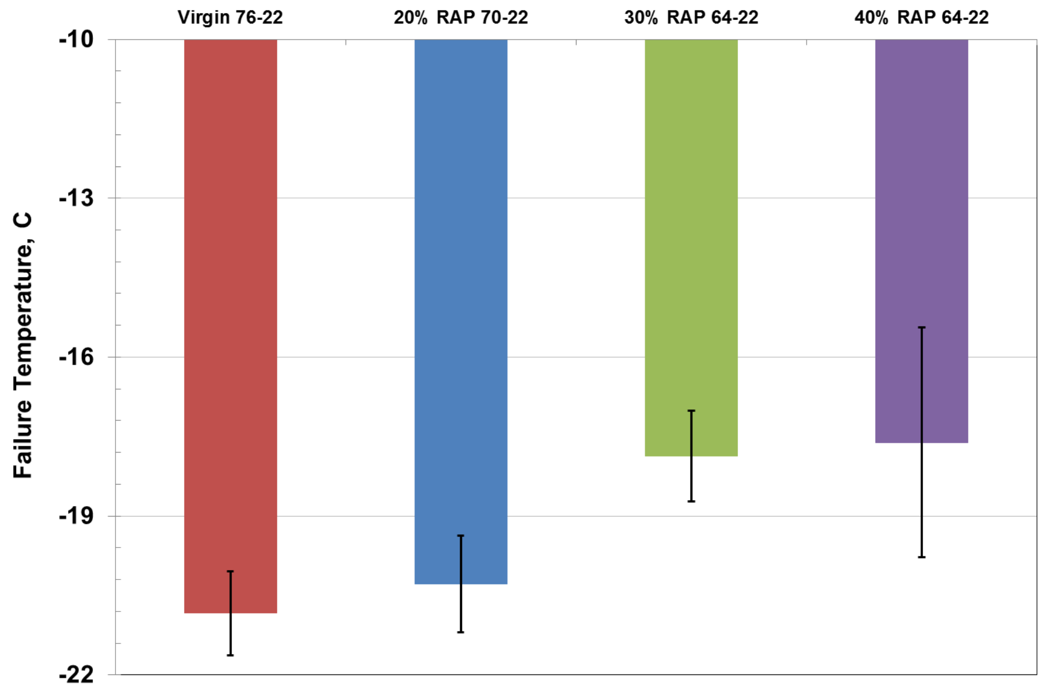

Figure 4.8 TSRST Failure Temperature for VA PMLC Mixtures

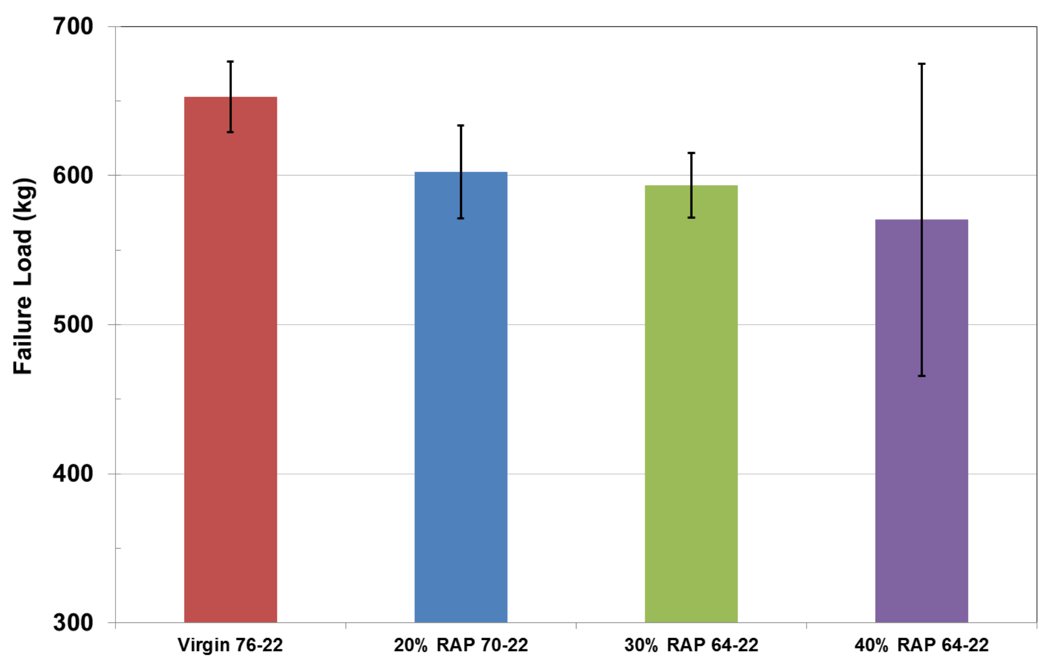

Figure 4.9 TSRST Failure Load for VA PMLC Mixtures

4.3.3.2 Low Temperature Creep and IDT Strength

The low temperature IDT strength measured at -10ºC for the VA mixtures are shown in Figure 4.10 and Figure 4.11 for the lab compacted and plant compacted specimens, respectively. The virgin mixture shows the highest strength. The RAP mixtures have similar strengths, with no distinct trend with increasing RAP content. This indicates that the softer virgin binder grades offset the increase in RAP content in terms of low temperature strength for these mixtures. These results generally agree with those from the TSRST testing.

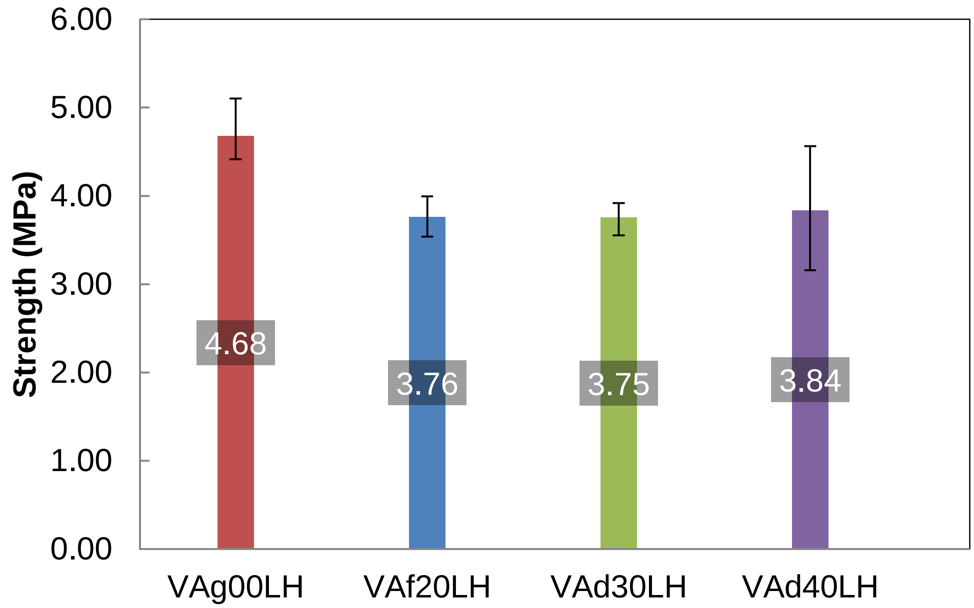

Figure 4.10 Low temperature strength results for VA PMLC Specimens

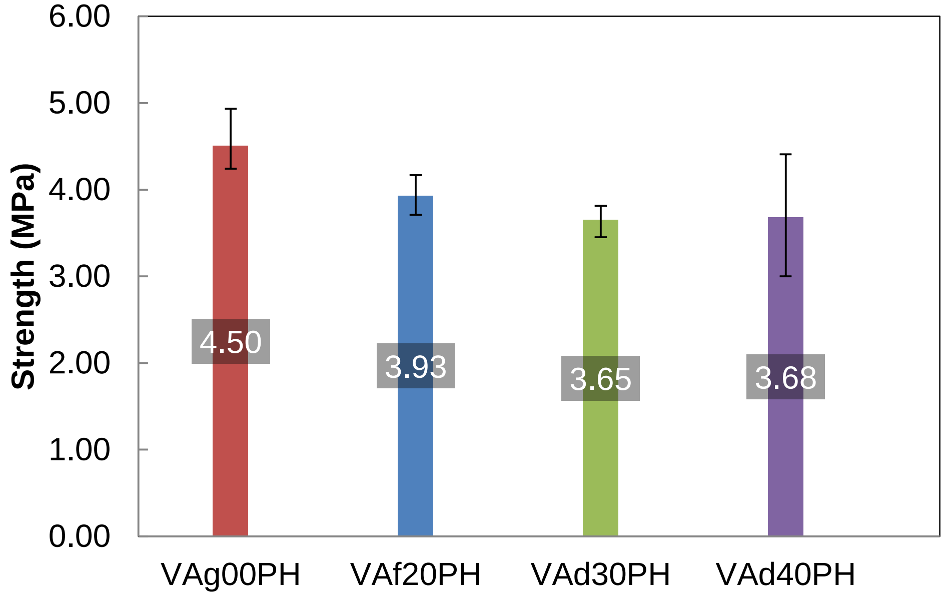

Figure 4.11 Low temperature strength results for VA PMPC Specimens

CHAPTER 5 OVERALL CONCLUSIONS FROM PHASE I AND PHASE II

In this chapter the overall conclusions from the 28 mixtures that have been tested as part of Phase I and Phase II are presented.

5.1 Impact of RAP Percentage

In general, the addition of RAP stiffens the mixture as expected; however, the magnitude of the impact of higher RAP percentages varies with each set of mixtures and the test used to evaluate stiffness. The amount of increase in stiffness with RAP appears to be impacted by several factors:

- Specimen preparation method: specimens compacted at the plant (PMPC) show larger differences with increases in RAP content than specimens reheated and compacted in the lab (PMLC). This may be due to the additional aging that occurs when mixture is reheated in the lab; the mixtures with more virgin binder are susceptible to more aging during this process and will stiffen more than the higher RAP mixtures.
- Mix design and materials: Mixtures that used a softer RAP or had a higher virgin asphalt content showed less impact of RAP on the stiffness. Virgin binder grade also had an impact, with lower PG grades generally showing larger impacts from increasing levels of RAP. This is likely due to the amount of interaction and comingling of the virgin and RAP binders.
- Production parameters: the results indicate apparent effects of mix temperatures and silo storage time on the measured dynamic modulus values. Lower mix temperatures may result in softer mixtures as less aging happens during the mixing process and longer storage times may result in stiffer mixtures as additional aging occurs as the material is stored for longer times at high temperature.

The TSRST tests on the mixtures showed that slightly warmer cracking temperatures occurred with increases in RAP content, with some apparent effects of mixture and production parameters.

Fatigue cracking was evaluated using several test methods: S-VECD, beam fatigue, and overlay tester. The S-VECD test yields the cracking resistance in both initiation and propagation stages and the energy-based failure criteria are sensitive to mixture parameters. The beam fatigue test is a measure of crack initiation while the overlay tester is a measure of crack propagation. True comparisons of fatigue performance of different mixtures should also consider the pavement structure in which the mixture is placed. The comparison of the S-VECD failure criteria show poorer fatigue performance for higher RAP content using the same binder in general and this decrease in the cracking resistance depends on virgin binder grade and content, RAP binder grade, and other production parameters. Flexural fatigue results showed different results depending on the mixture; in some cases the different RAP mixtures performed similarly to the comparison virgin mixtures and in others there were clear decreases in flexural fatigue performance with increase in RAP content. The overlay test results show that the addition of any amount of RAP significantly decreases the mixture resistance to crack propagation for some mixtures and others there is not a drop in performance until RAP levels above ~20% are used.

5.2 Impact of PG Grade

The impact of dropping the PG grade of the virgin binder to compensate for the addition of higher levels of RAP shows varied results based on the mixtures tested in Phases I and II of this study. The extracted binder results show that a softer virgin binder grade generally improves both the high and low PG grades, but the magnitude of the improvement varies with RAP content and mixture. The exception is the NH Phase II mixtures where the addition of the softer PG 52-34 binder did not have the expected effects.

The use of a softer virgin PG grade did decrease the dynamic modulus for the VT, NY, and Phase II NH mixtures. However, there was also a significant difference in binder contents for the VT mixtures that would also contribute to the difference in stiffness. The softer virgin grade did result in an improvement in low temperature cracking by several degrees, or appears to offset the RAP stiffness, as measured by the TSRST test.

Fatigue testing showed that the softer virgin binder helped the flexural performance some mixtures, but had negligible effect with others. The S-VECD analysis showed better fatigue performance for the stiffer virgin binders. The NY and NH Phase II mixtures showed worse overlay test results with the softer virgin binder, while the VT mixtures showed a benefit, especially with the 20% RAP mixture. The higher asphalt contents in the softer VT mixtures likely also contributed to the better performance observed.

From the mixtures tested in this study, the impact of using a softer virgin binder grade varies from mix to mix and for different mixture properties. It appears to help improve some properties, has negligible effect on others, and may make others worse.

5.3 Impact of Plant Production

Plant production parameters such as mixture temperature and silo storage time show apparent impacts on mixture properties measured in this project. Specifically, lower initial stiffness and more stiffening upon reheating were observed with the NH Phase I and NY 20% mixtures that were stored in the silo for shorter periods than the companion virgin mixtures. The Phase I NH 20% mixture also had a lower discharge temperature. Because neither mix temperature nor storage time was controlled for these mixtures, it is difficult to separate out the effects as they may cancel out for some mixtures that had lower mix temperatures but longer storage times, or vice versa. The impact of silo storage time is explored further in the Silo Storage Study Additional Task that is described in a separate report.

5.4 Phase III and Silo Storage Study Additional Task

Phase III focused on a detailed laboratory investigation. The mixture designs from the NH Phase I 12.5 mm mixtures (50 gyration Superpave design) were used for Phase III; nine mixtures were produced in the laboratory with varying RAP content and total asphalt content, as shown in Table 5.1. The asphalt content ranges were chosen to cover typical allowable production tolerances. Testing consisted of both binder and mixture testing. Results are summarized in the Phase III report.

Table 5.1 Phase III mixtures

Mixture	**Asphalt content**	**RAP Content (total weight)**		
		0	**20**	**40**
NH Phase I	5.2 (opt-0.5%)	PG 64-28	PG 64-28 PG 58-28	PG 64-28 PG 58-28
	5.7 (optimum)	PG 64-28	PG 64-28	PG 64-28
	6.2 (opt+0.5%)	-	-	PG 64-28

The Silo Storage Study Additional Task evaluated a virgin mixture and a 25% RAP mixture that were produced, stored in a silo and sampled at storage times up to 10 hours. Testing was performed on the mixtures and extracted and recovered binders. Results are summarized in the Silo Storage Study Additional Task report