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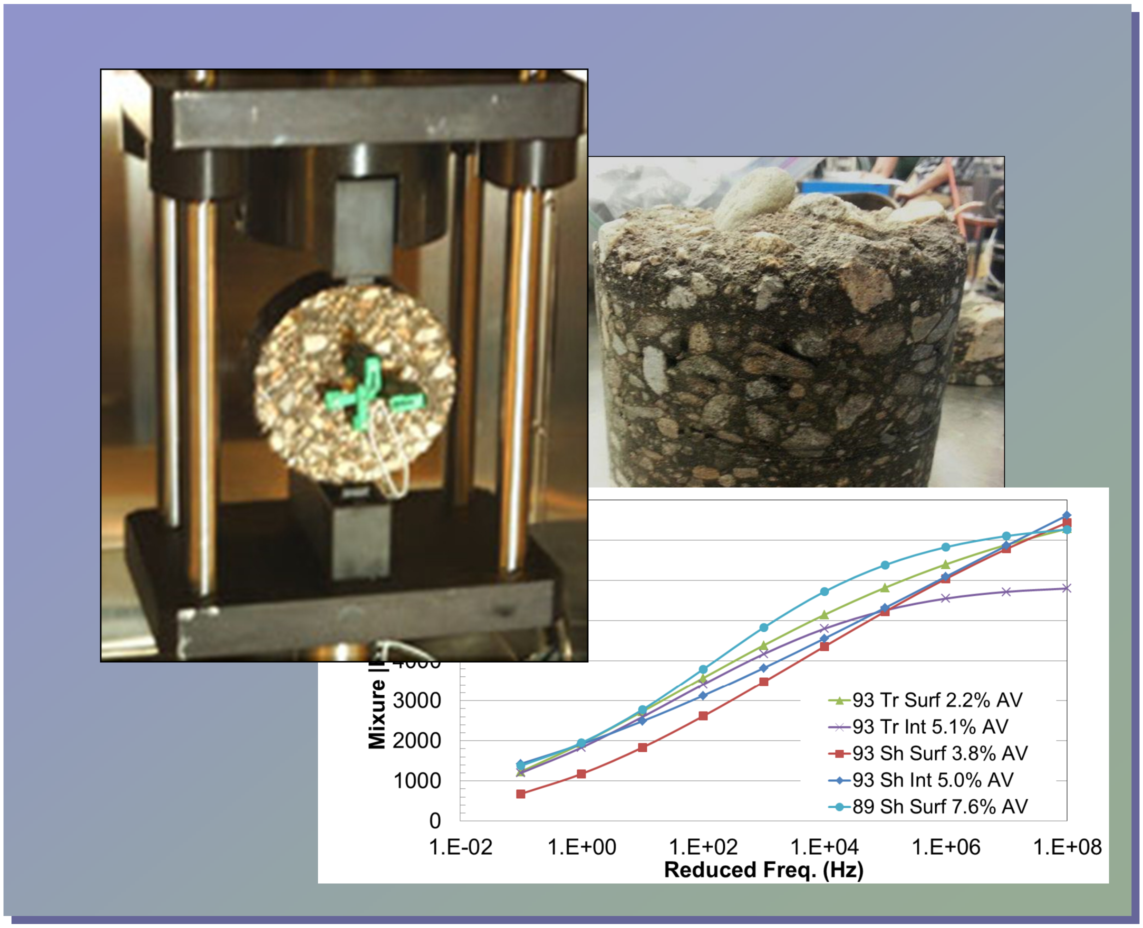

Performance of High RAP Pavement Sections in NH

Final Report

Prepared by the University of New Hampshire Department of Civil Engineering for the
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16. Abstract

This report summarizes the University of New Hampshire (UNH) results of test pavements used to determine the effect of using higher amounts of Recycled Asphalt Pavement (RAP) in Hot Mix Asphalt (HMA).

The New Hampshire Department of Transportation (NHDOT) has allowed RAP in HMA for over 20 years but has limited use to 15-20% of the mix. This study evaluated the changes in performance due to increased amounts of RAP as well as evaluating the impact of bumping the binder grade (to a softer binder) for higher RAP contents. The pavements tested were in place for approximately three years. Long-term performance was not evaluated. Binder testing included PG grade, shear modulus master curve, and the multiple stress creep recovery test. Mixture testing included complex modulus, flow numbers, Hamburg Wheel tracking, and fatigue. Test results for both binder and mixes using PG 58-28 demonstrated expected results with high RAP contents having a stiffer modulus, better rutting performance, and lower fatigue resistance. The PG 52-34 binder had unexpected trends. Testing did not include determining the presence of binder additives. The results of this project support the practical limitation of 1% total recycled binder (TRB) in NHDOT surface mixtures.

17. Key Words
Recycled asphalt pavement, RAP, high RAP pavement, asphalt pavement, HMA pavement, recycled pavement, asphalt binder, asphalt mixture, thermal cracking, fatigue cracking, rutting performance, Black Space, phase angle, total recycled binder (TRB)

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Performance of High RAP Pavement Sections in NH

NHDOT Project SPR 15680B
Phase II Final Report

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EXECUTIVE SUMMARY

This report presents the Phase II results of the Performance of High RAP Pavement Sections in NH project (NHDOT Project SPR 15680B). Six test sections were constructed in the southbound lanes on I-93 between Woodstock and Lincoln. The test sections included a range of RAP contents and two different virgin binders (PG 58-28 and PG 52-34) to evaluate the impact of bumping the binder grade at higher RAP contents and to provide guidance on the use of high RAP mixtures. Testing was conducted on both asphalt binders and mixtures. Binder testing included PG grading, shear modulus master curve, and the multiple stress creep and recovery test. Mixture testing included complex modulus, flow number, Hamburg wheel tracking, and fatigue. Differences in measured material properties due to specimen fabrication method were also investigated. The results of the binder and mixture testing for the materials with the PG 58-28 binder showed expected trends (stiffer modulus, lower phase angle, and warmer PG temperatures, better rutting performance, and lower fatigue resistance) with increasing RAP content. The materials with the PG 52-34 binder showed unexpected trends, particularly with phase angles. Similar trends were observed with specimens fabricated at the plant (not reheated), specimens fabricated in the lab, and field cores. Specimens that were fabricated from reheated plant mix showed different trends due to the impact of additional aging that occurred during reheating of the material. Performance of these mixtures to date in the field shows that the PG 58-28 mixtures are performing better than the PG 52-34 mixtures with respect to both thermal and fatigue cracking and that the amount of RAP does show performance differences. The results of this project in combination with the regional TPF 5(230) project support the practical limitation of 1.0% TRB in NH surface mixtures. Future work is needed to better understand the differences between binder and mixture test results and their relationship to field performance, the impact of aging, and the impact of various binder additives (such as REOB) on the long term performance of mixtures in NH.

1. INTRODUCTION

The use of RAP in HMA is routine in New Hampshire. The New Hampshire Department of Transportation (NHDOT) and local contractors are very comfortable using RAP percentages around 20% by total weight of mixture. However, the amount of RAP has typically been limited to the 15-20% range due to a lack of experience with, and understanding of, mixtures containing higher amounts of RAP. Specifically, there are concerns about low temperature and fatigue performance and the need to bump binder grades at the higher RAP contents. Additional research and study of high RAP mixtures in NH is necessary to establish the best practices and procedures necessary to produce high RAP mixtures that have equal or better performance than the routine mixtures currently used in the state.

The objectives of this project were to:

1. Conduct forensic analysis on the existing high RAP section and a comparable virgin section to evaluate the material properties and characteristics of the existing mixture with respect to the observed performance.
2. Evaluate the performance in terms of low temperature cracking, fatigue cracking, and moisture sensitivity of the new test section mixtures in the laboratory and field
3. Provide guidance on the use of high RAP mixtures to the NHDOT based on the results of the forensic and new material analysis.

The first objective was accomplished through Phase I of the project and results were detailed in the Phase I report. In summary, binders were extracted and recovered from field cores taken along paving projects that were constructed in 1987. This included 35% RAP mixtures from I-93 and virgin and low RAP mixtures along I-89. Field cores were obtained from the travel and shoulder lanes of the pavement sections and asphalt binder was extracted and recovered from different depths in the pavement structure. Testing of the recovered binder included shear modulus, phase angle, stiffness, m-value and critical cracking temperature. The field cores were tested in indirect tensile mode for dynamic modulus, creep compliance, and indirect tensile strength. The testing, in general, yielded trends among RAP contents, lane types and depths that were consistent with previous research, with increase in stiffness at the surface, in the shoulder lanes compared to travel lanes, and in high RAP mixtures compared to low RAP mixtures. The results indicate that the 35% RAP mixtures age more uniformly through depth and between travel and shoulder lanes compared to the virgin and 15% RAP mixtures.

Phase II of the project included the evaluation of six test sections that were constructed in 2011 in the southbound lanes on I-93 between Exits 30 and 32 in Woodstock and Lincoln. The test sections include a range of RAP contents and two different virgin PG binders to evaluate the impact of bumping the binder grade at higher RAP contents:

- Virgin PG 58-28
- 15% RAP with PG 58-28 binder
- 25% RAP with PG 58-28 binder

- 25% RAP with PG 52-34 binder
- 30% RAP with PG 52-34 binder
- 40% RAP with PG 52-34 binder

The FHWA Mobile Lab was onsite during production to conduct testing and materials were also collected for testing in the UNH laboratory. The FHWA lab collected raw materials to replicate the mix design and evaluate the properties of laboratory mixed, laboratory compacted (LMLC) specimens. FHWA also collected loose mix during production and compacted specimens without reheating (plant mixed, plant compacted PMPC) for testing. The NHDOT was also onsite to fabricate PMPC specimens for UNH testing and collect loose mix that was brought back to the laboratory and reheated to fabricate specimens (plant mixed, laboratory compacted PMLC). Finally, field cores were taken for testing as well.

Testing was conducted on both asphalt binders (tank sampled and extracted and recovered from mixtures) and mixtures. The binder testing was conducted by FHWA and mixture testing was conducted by both FHWA and UNH. Binder testing included PG grading, shear modulus master curve, and the multiple stress creep and recovery test. Mixture testing included complex modulus, flow number, Hamburg wheel track test, and fatigue.

This report summarizes the results of the Phase II study and is organized to present a description of the testing performed in Chapter 2, followed by the results in Chapter 3, and overall conclusions and recommendations in Chapter 4.

2. MATERIALS AND METHODS

The laboratory testing conducted during the study 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.

2.1 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 2.1 shows 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 2.1 and the gradations determined by ignition oven during production are shown in Figure 2.2. 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 2.3 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 2.1 Mixture Volumetric Data

Mix		Mixing/Discharge Temp (°C)	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

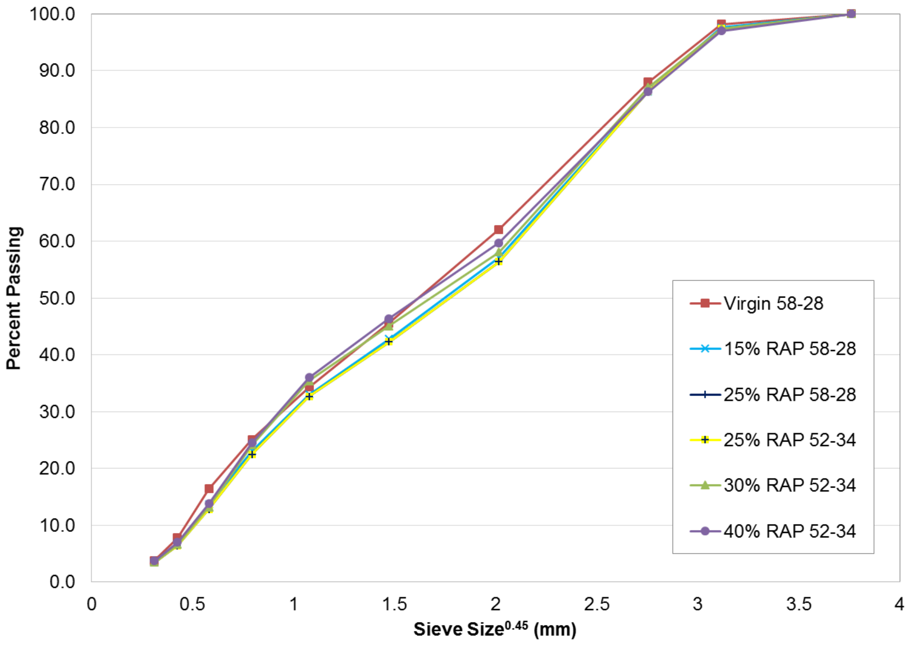

Figure 2.1 Mix Design Gradations

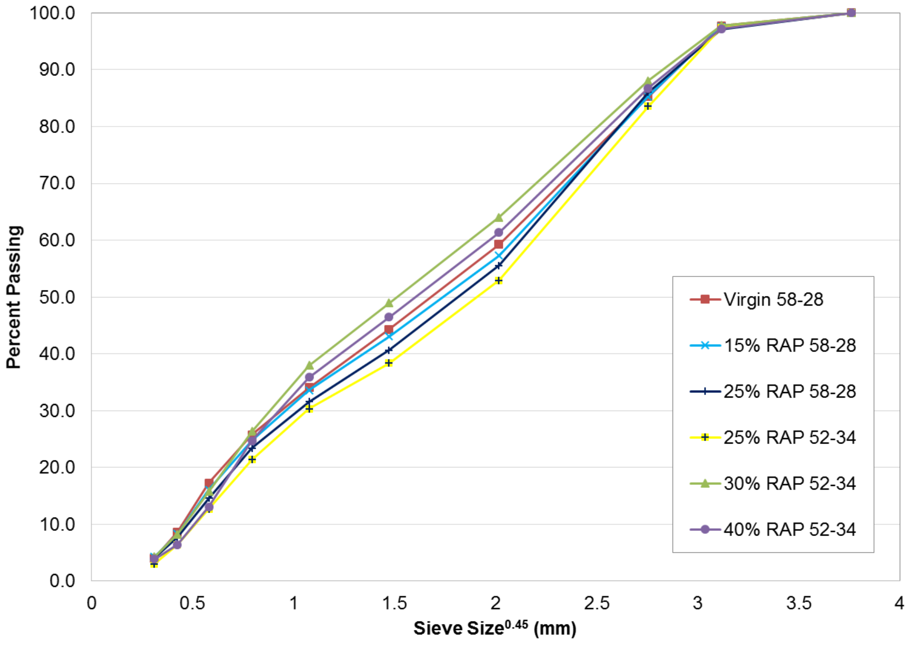

Figure 2.2 Production Gradations

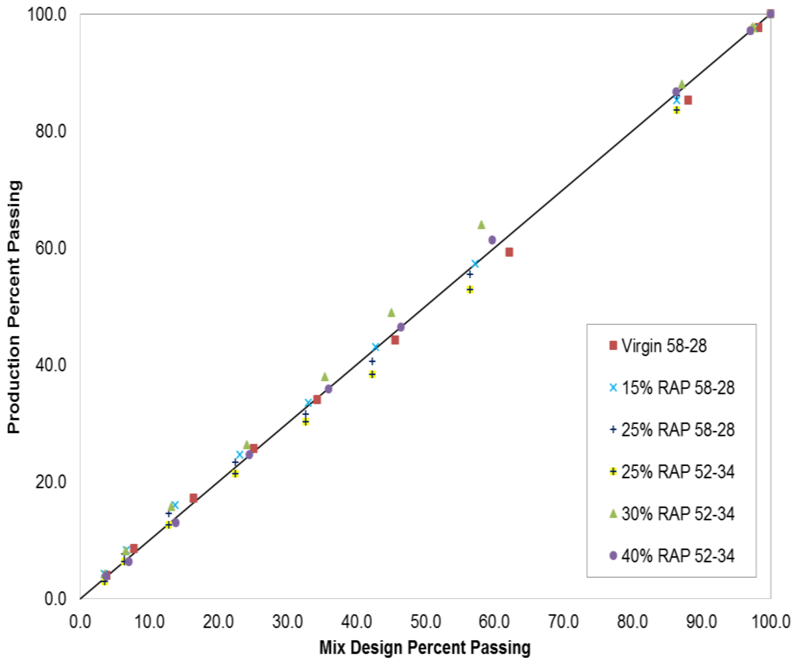

Figure 2.3 Comparison of Production and Mix Design Gradations

2.2 Specimen Fabrication

2.2.1 *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°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.

2.2.2 *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.

2.2.3 *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°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%.

2.2.4 *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 2.4 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 2.5. The air void content of the tested specimens ranged from 4.2% to 6.7%.

Figure 2.4 Two small specimens produced from one field core

Figure 2.5 Comparison of standard size (left) vs. small geometry specimens (right)

2.3 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.

2.4 Mixture Tests

2.4.1 *Dynamic Modulus*

The AMPT (Asphalt Mixture Performance Tester) machine was used for the dynamic modulus testing in this study. The temperature control systems in the AMPT can achieve the required testing temperatures, ranging from 2.9°C to 37.8°C. 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 for the TPF 5(230) High RAP project 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; these were followed in this project as well. Table 2.2 summarizes 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 2.2 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 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^{o}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.

2.4.2 *Fatigue Using 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.

$$Test\ Temp = \frac{High\ PG - Low\ PG}{2} - 3 \tag{2.1}$$

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 2.6 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 2.6 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 2.7. For all the mixtures, the exponential form shown in Equation (2.1 was used to fit the C versus S characteristic curves.

$$C(S) = e^{aS^b} \tag{2.1}$$

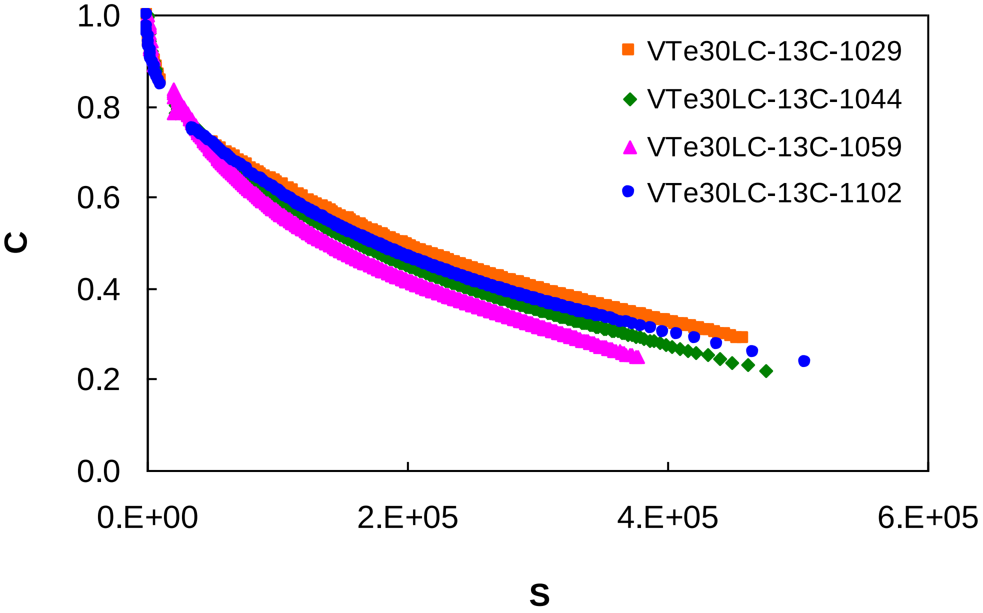

Figure 2.7 Example SVECD Fatigue Results

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 elsewhere. 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 2.8 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.

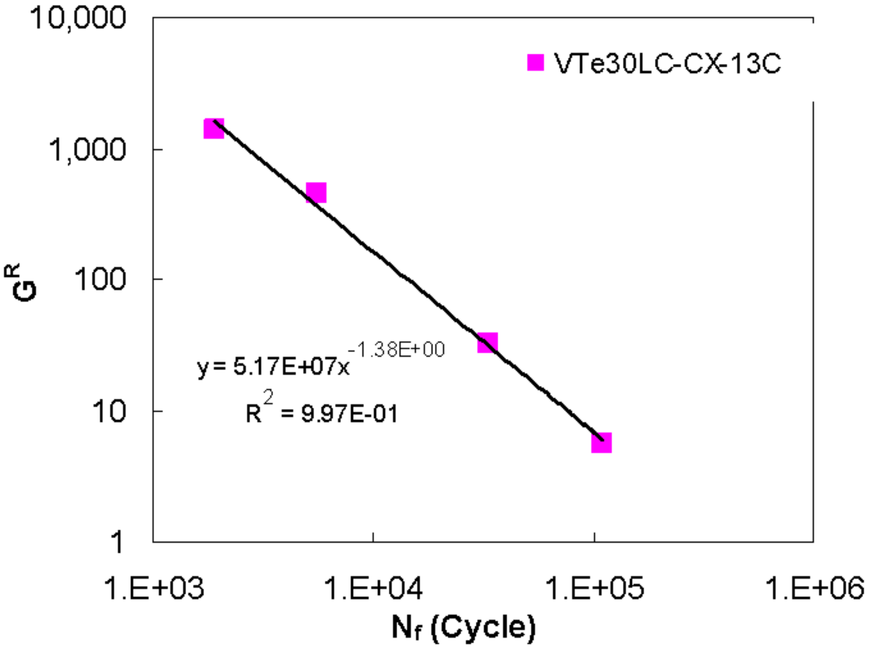

Figure 2.8 Relationship between G^R and N_f

2.4.3 *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 mixtures, based on the climactic location, was 44.7°C. Testing was performed on both mix design and production specimens. The test conditions for each specimen type are shown in Table 2.3 below.

Table 2.3 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	

2.4.4 *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°C. The tests were run until the number of passes reached 20,000 or an average displacement of 20mm was reached. The stripping inflection point was determined for each mixture.

3. RESULTS AND DISCUSSION

3.1 Binder Testing

3.1.1 *PG Grading*

The continuous PG grades and critical cracking temperatures were measured by FHWA on both the virgin and extracted and recovered binders. Figure 3.1 and Figure 3.2 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 3.3 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.

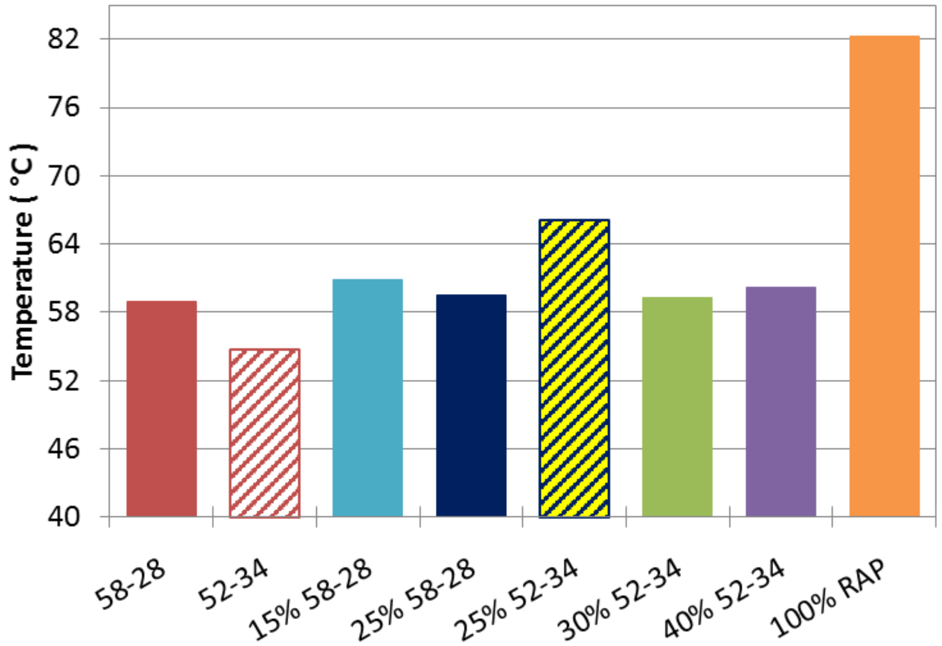

Figure 3.1 Continuous High Temperature Grade for Virgin and Extracted and Recovered Binders

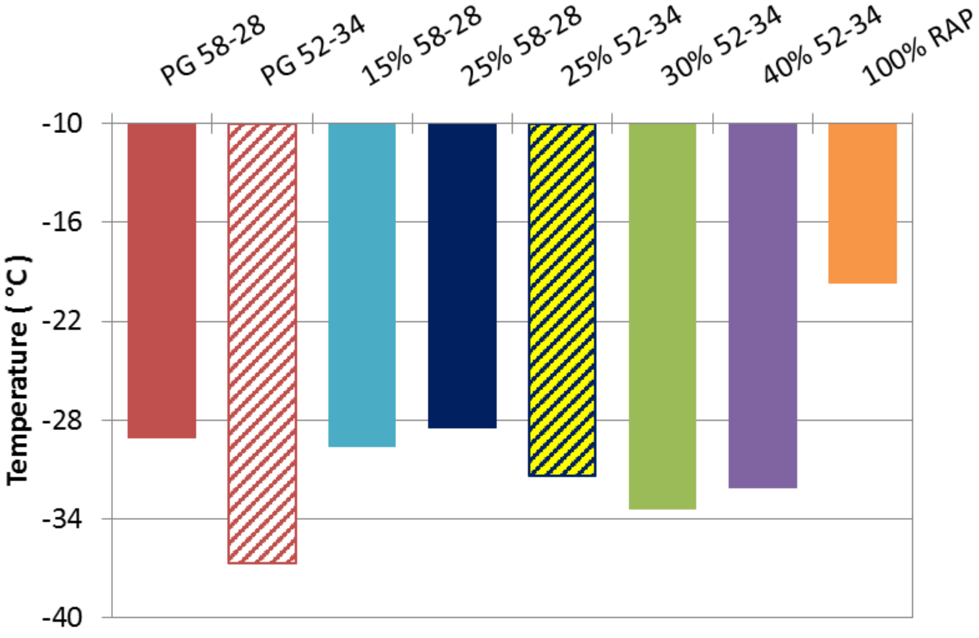

Figure 3.2 Continuous Low Temperature Grade for Virgin and Extracted and Recovered Binders

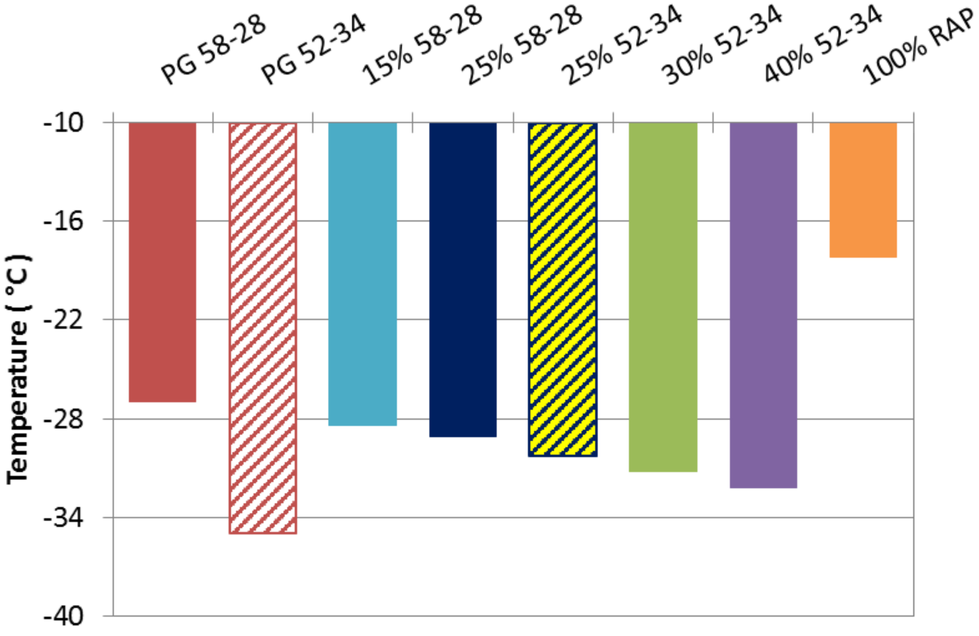

Figure 3.3 Critical Cracking Temperature for Virgin and Extracted and Recovered Binders

3.1.2 *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 3.4. 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 3.5. 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.

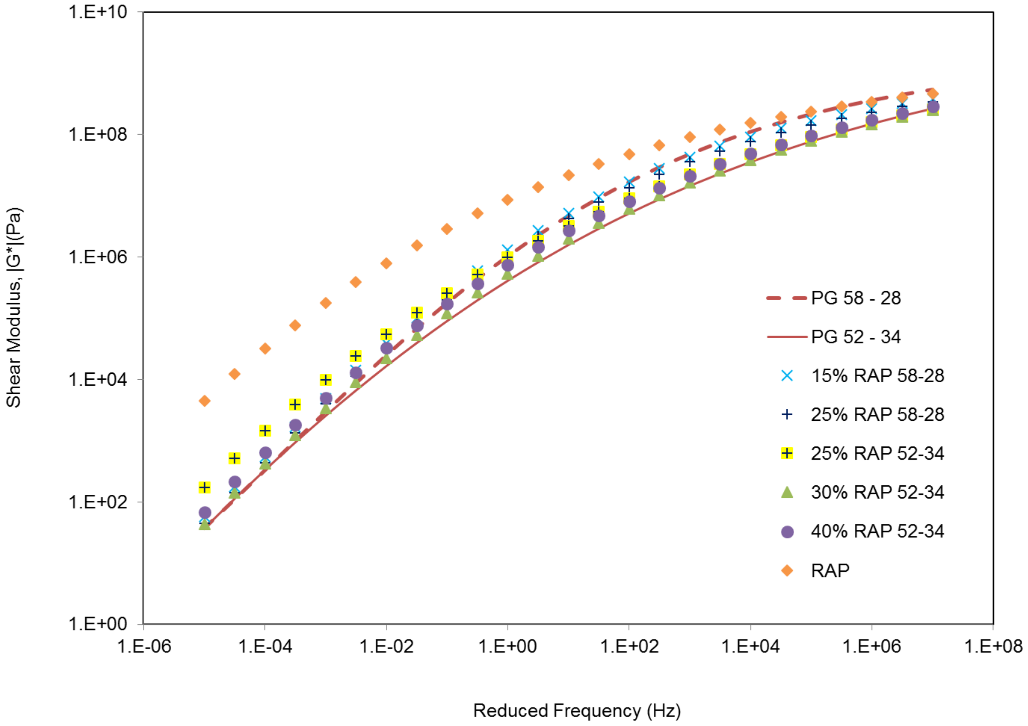

Figure 3.4 Shear Modulus Master Curves at 21°C for Virgin and Extracted and Recovered Binders

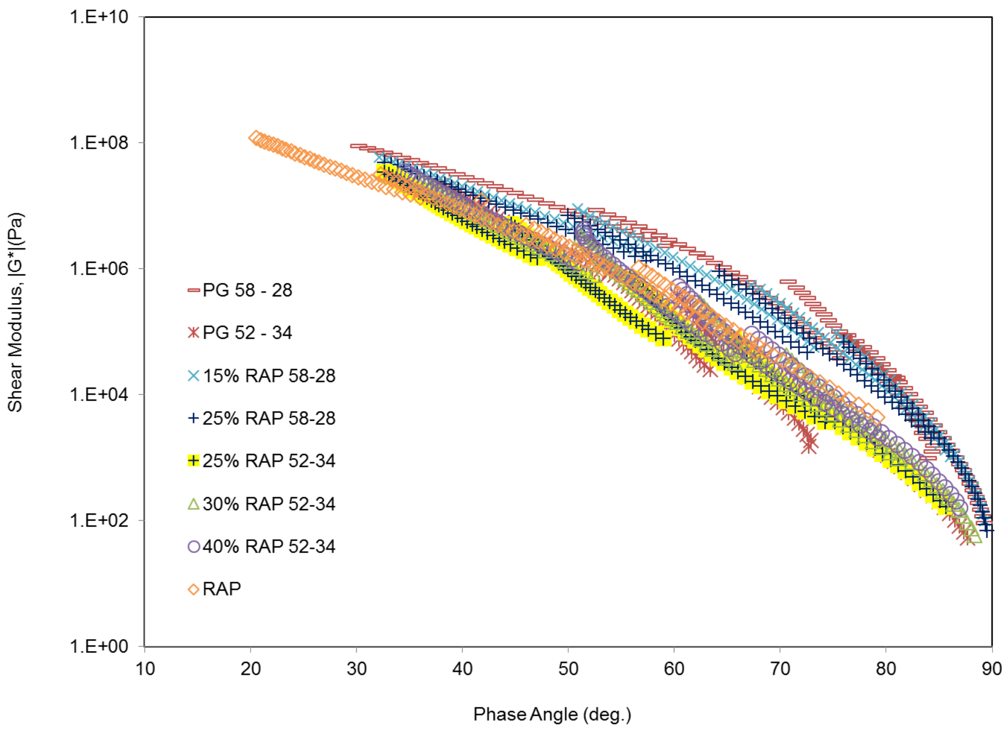

Figure 3.5 Black Space Curves for Virgin and Extracted and Recovered Binders

3.1.3 *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 3.1 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 3.1 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

3.2 Mixture Testing

3.2.1 *Dynamic Modulus*

3.2.1.1 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 3.6 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 3.7 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.

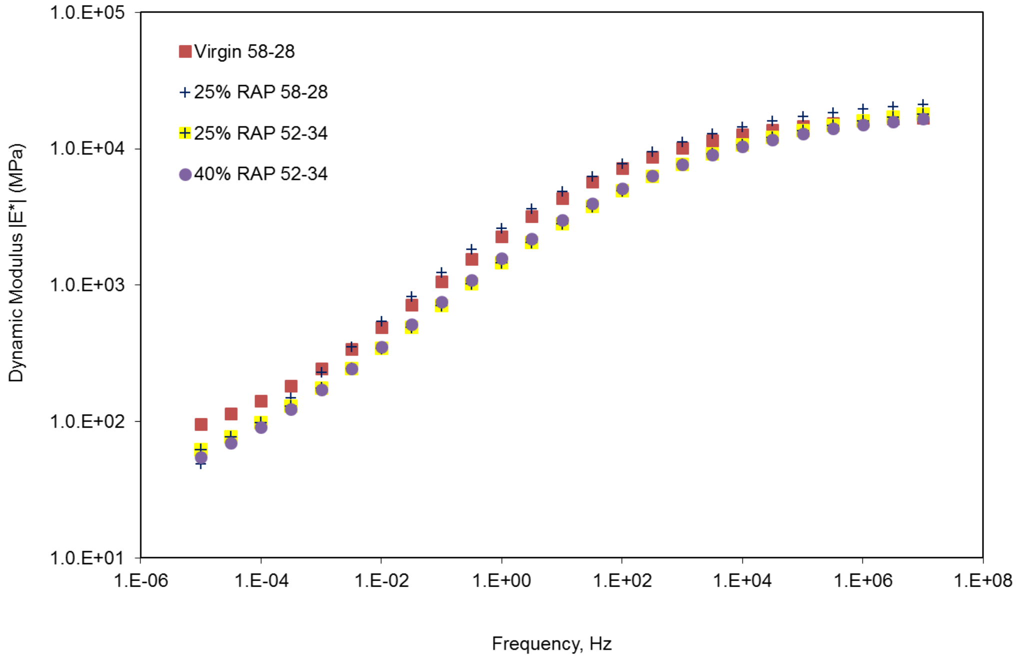

Figure 3.6 Average Master Curves at 21°C for LMLC Specimens

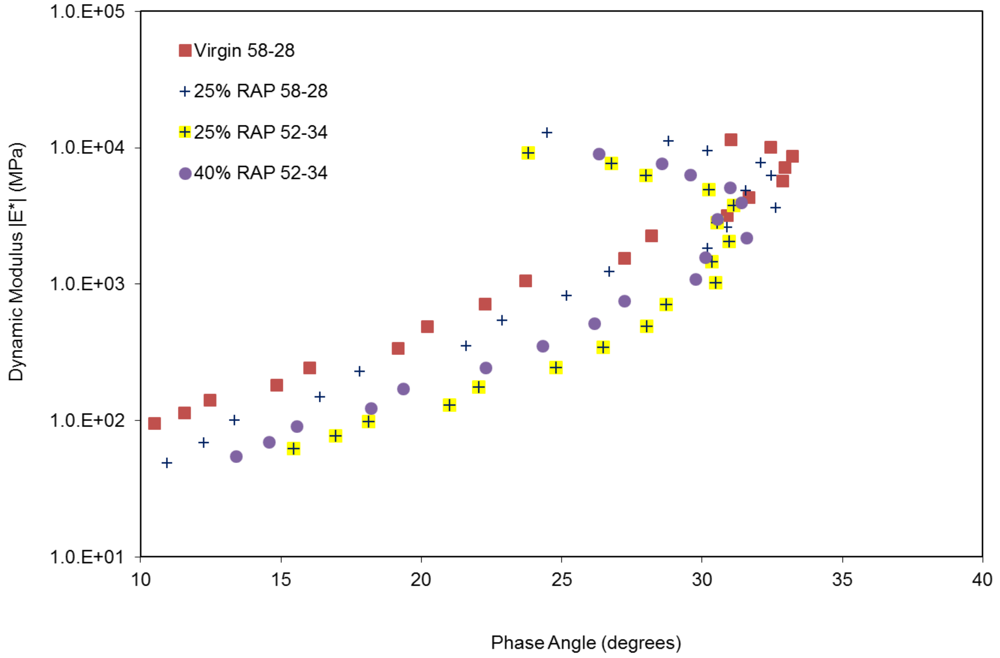

Figure 3.7 Average Black Space Curves for LMLC Specimens

3.2.1.2 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 3.8. 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 3.9. 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 3.10 through Figure 3.15. 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 3.2.1.5 below.

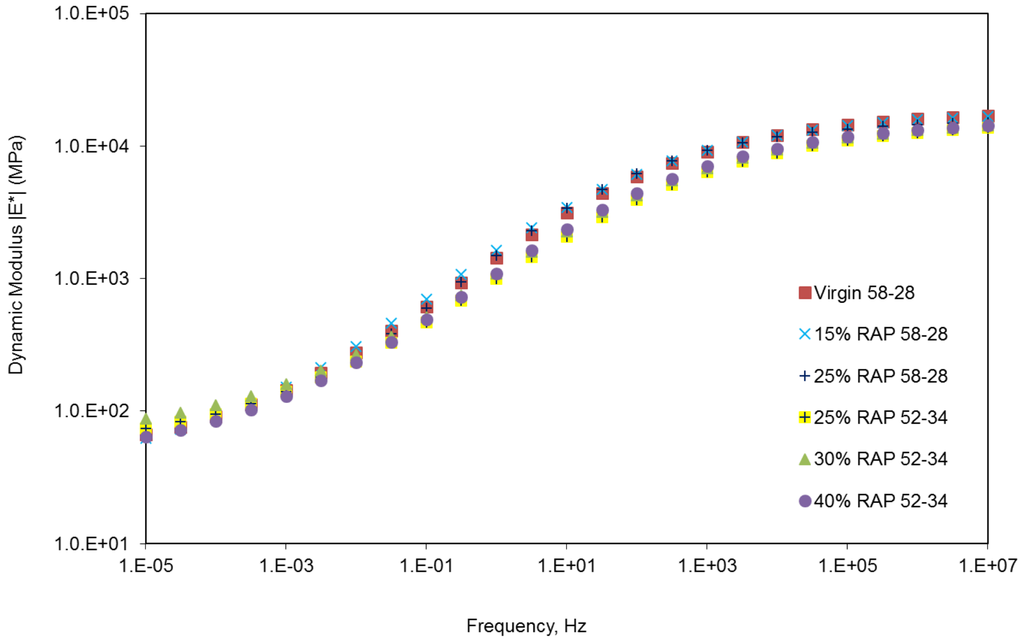

Figure 3.8 Average FHWA PMPC Dynamic Modulus Master Curves at 21^{o}C for All Production Days

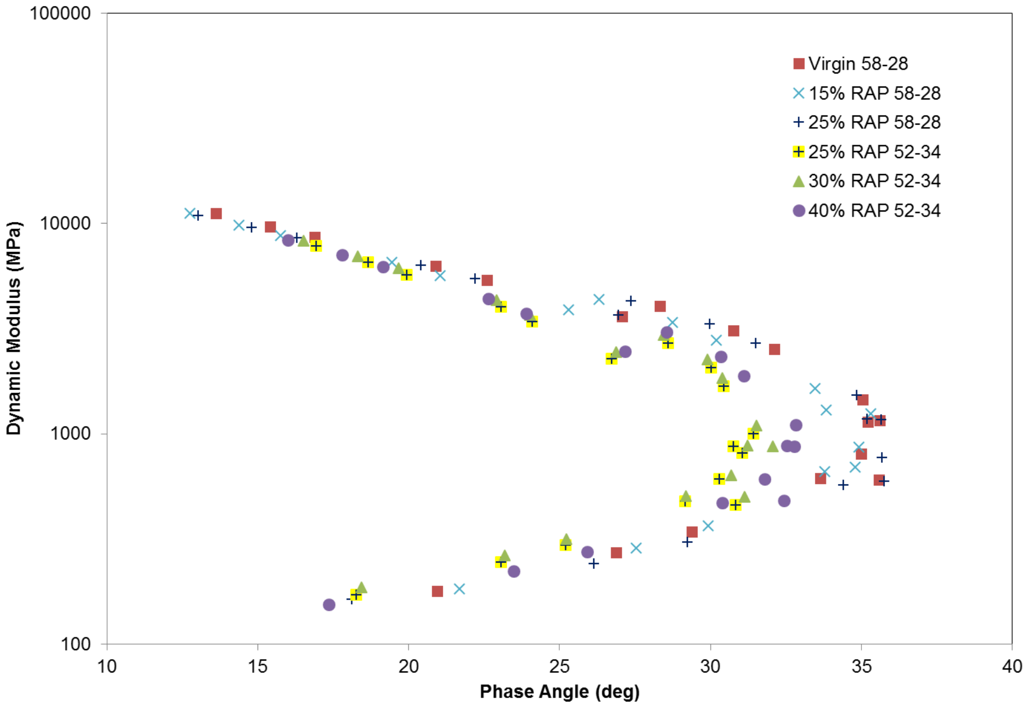

Figure 3.9 Average Black Space Curves for FHWA PMPC Specimens

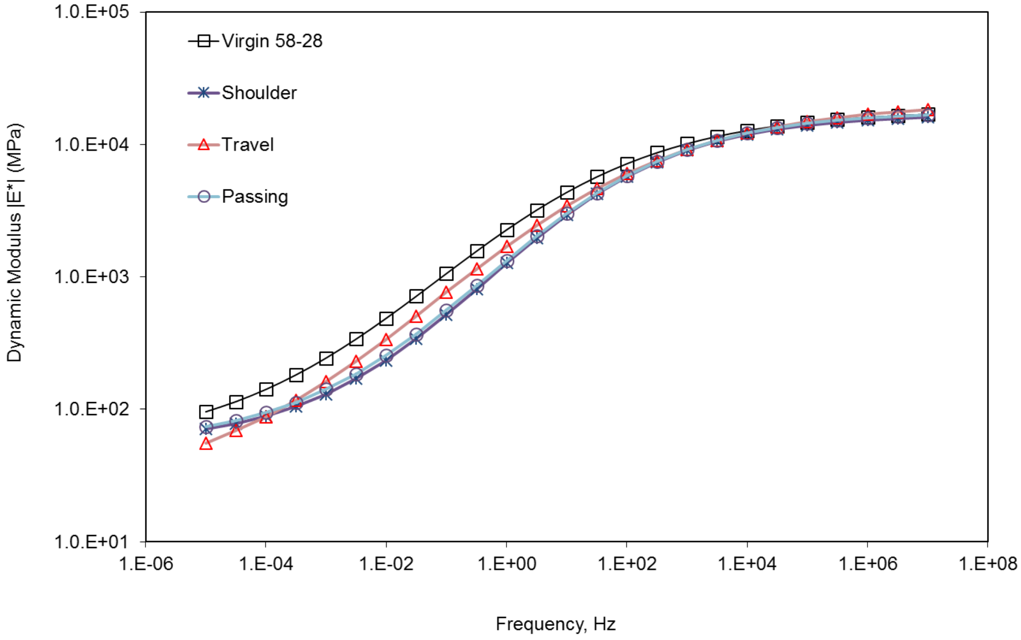

Figure 3.10 Virgin PG 58-28 Average Dynamic Modulus Curves at 21°C for LMLC and all PMPC Production Days

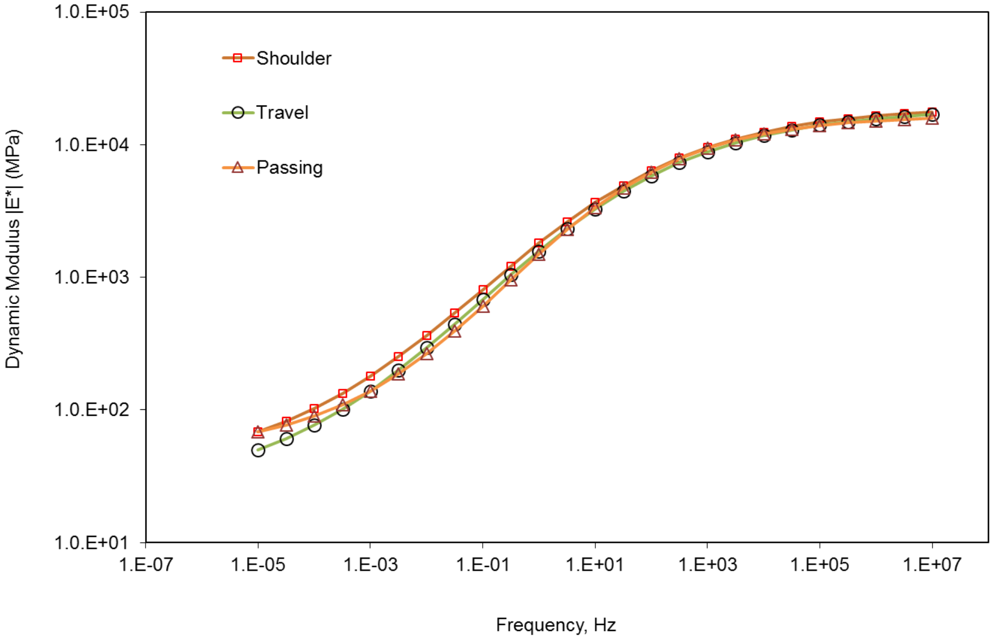

Figure 3.11 15% RAP PG 58-28 Average Dynamic Modulus Curves at 21°C for all PMPC Production Days

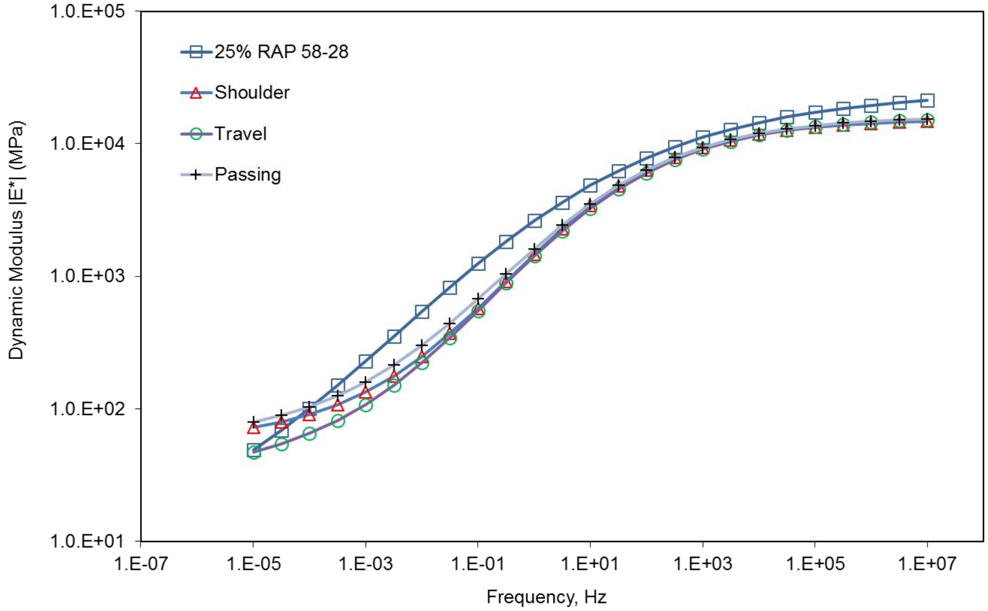

Figure 3.12 25% RAP PG 58-28 Average Dynamic Modulus Curves at 21°C for LMLC and all PMPC Production Days

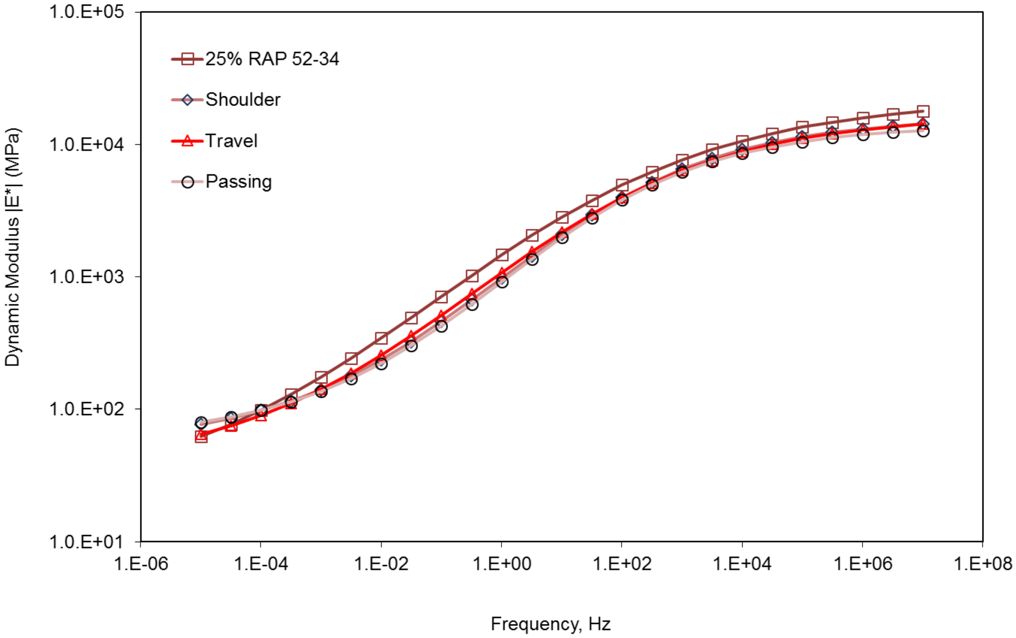

Figure 3.13 25% RAP PG 52-34 Average Dynamic Modulus Curves at 21°C for LMLC and all PMPC Production Days

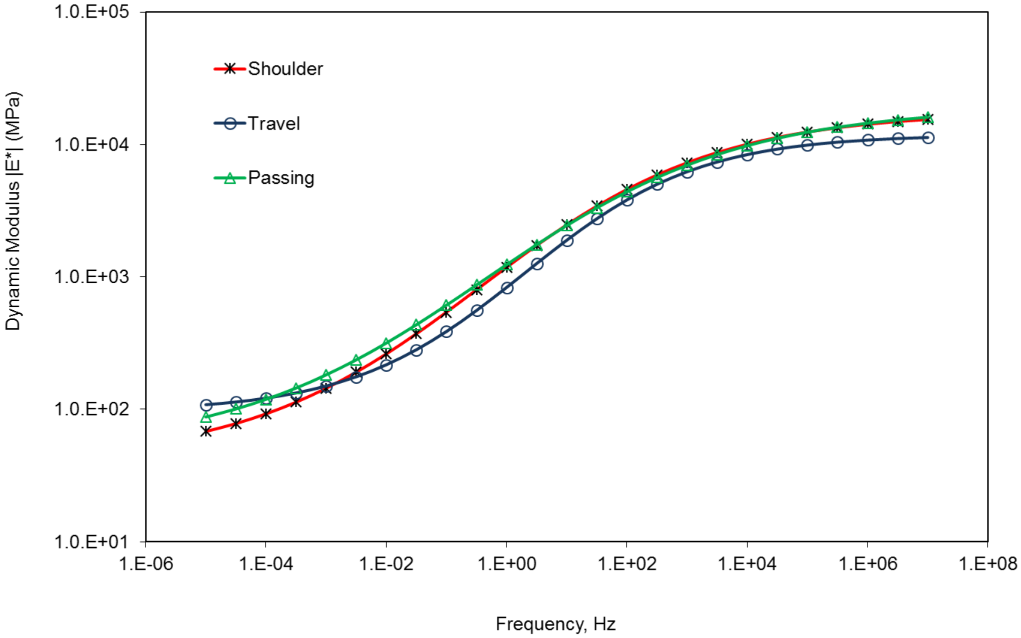

Figure 3.14 30% RAP PG 52-34 Average Dynamic Modulus Curves at 21°C for all PMPC Production Days

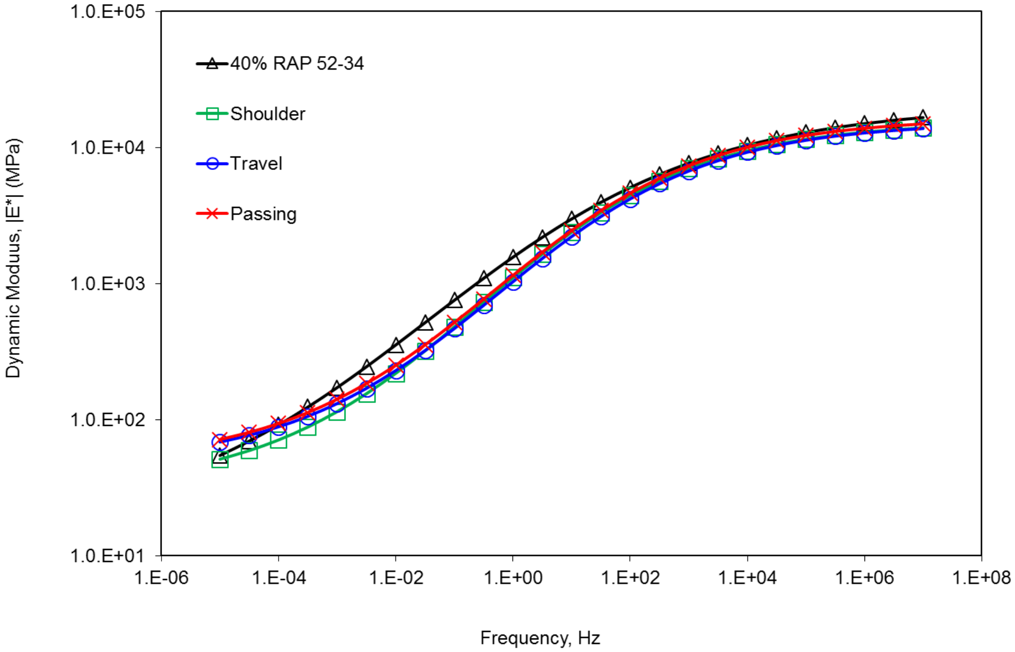

Figure 3.15 40% RAP PG 52-34 Average Dynamic Modulus Curves at 21°C for LMLC and all PMPC Production Days

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 3.16. 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 3.17. 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.

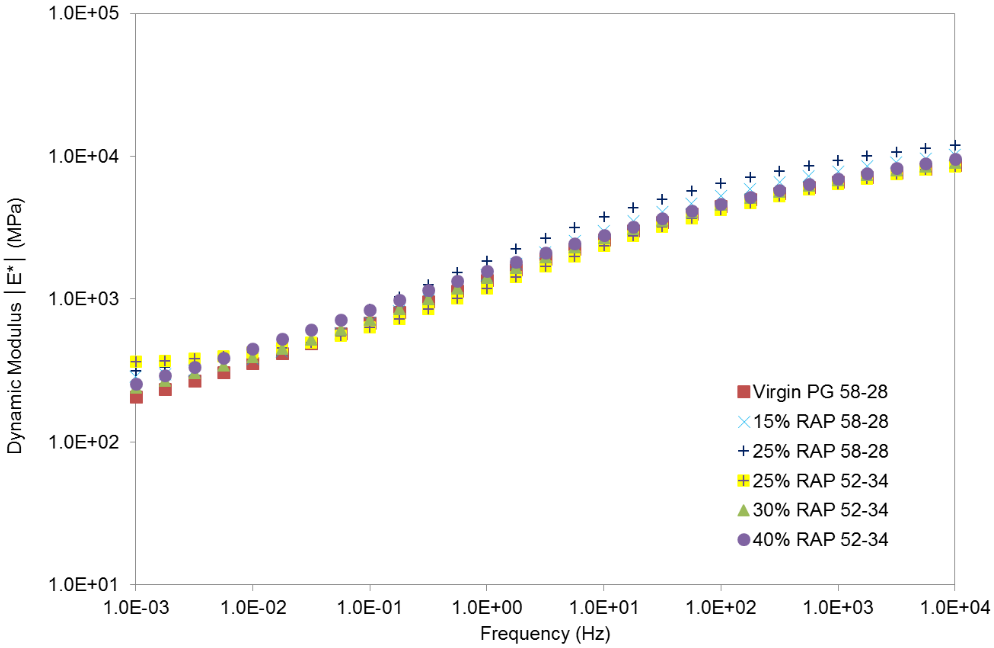

Figure 3.16 Average Dynamic Modulus Master Curves at 21°C for UNH PMPC Specimens

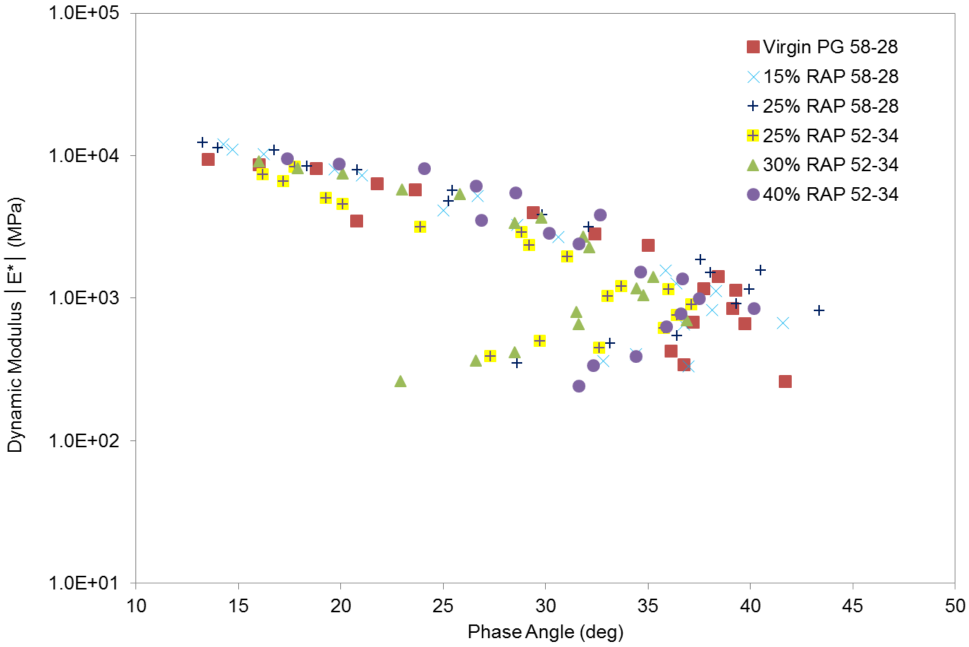

Figure 3.17 Average Black Space Curves for UNH PMPC Specimens

3.2.1.3 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 3.18. 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 3.19. There are no discernable trends with respect to RAP content or base binder grade with these results.

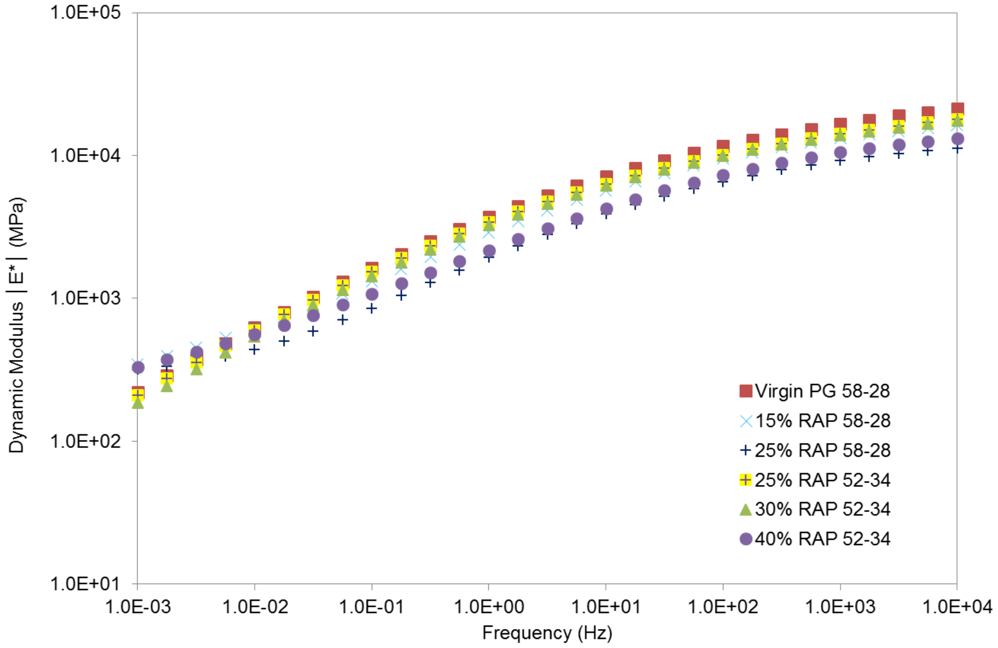

Figure 3.18 Average Dynamic Modulus Master Curves at 21^{o}C for PMLC Specimens

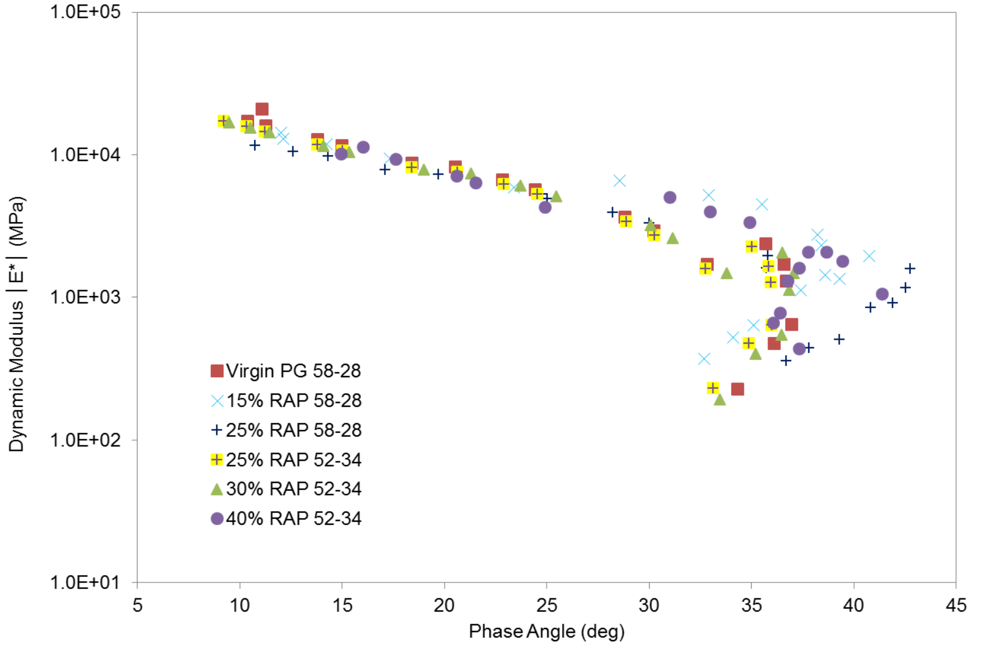

Figure 3.19 Average Black Space Curves for PMLC Specimens

3.2.1.4 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 3.20 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 3.21. The phase angles from the 30^{o}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.

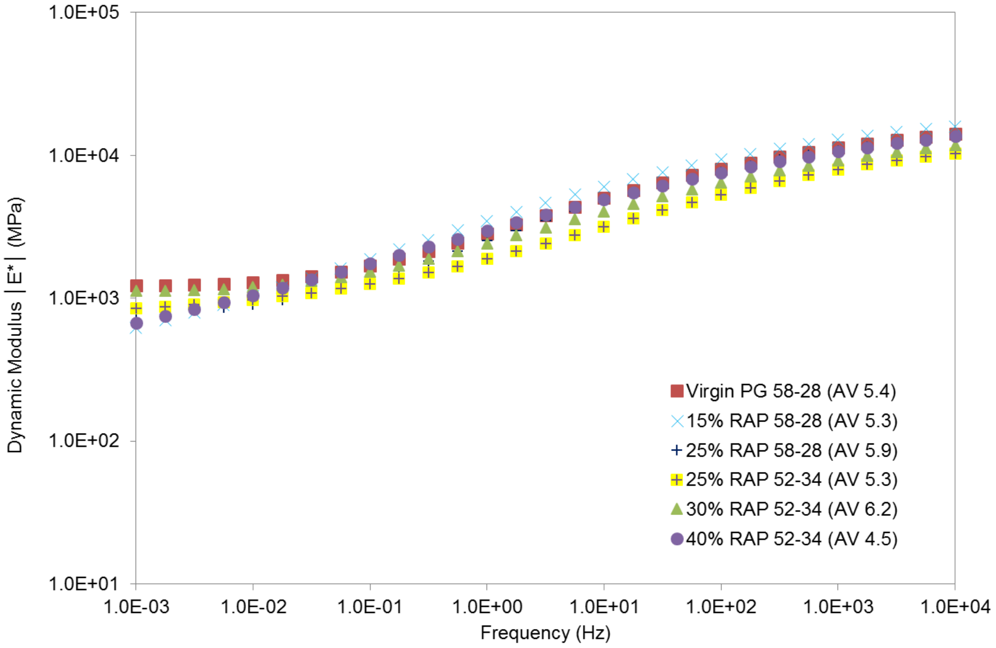

Figure 3.20 Average Dynamic Modulus Master Curves at 21^{o}C for Field Cores

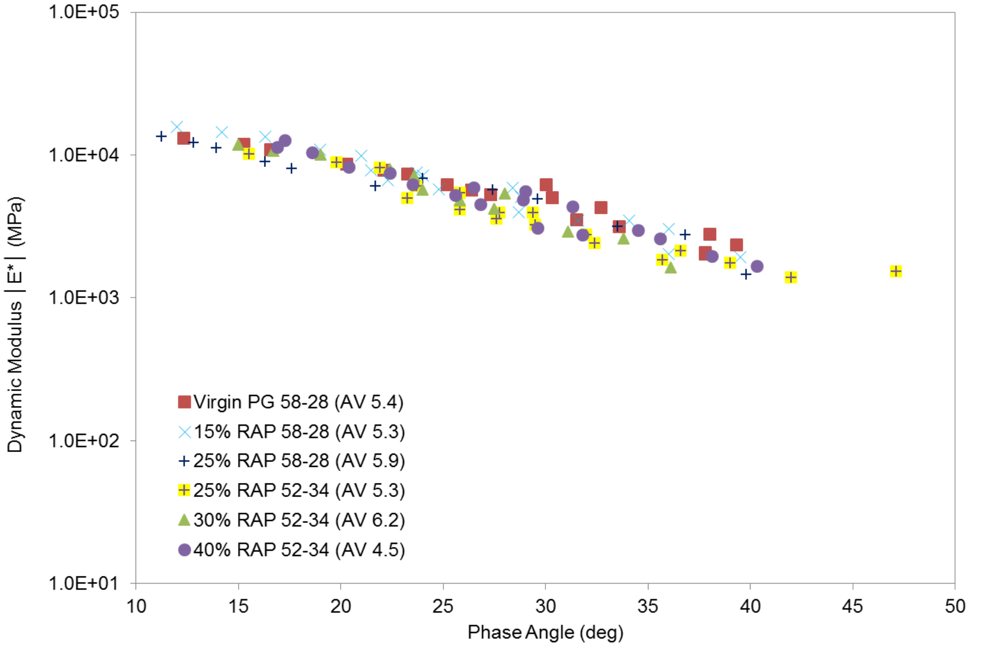

Figure 3.21 Average Black Space Curves for Field Cores

3.2.1.5 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 3.22. 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^{o}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 3.23. 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 3.24 and the Black Space curves are shown in Figure 3.25. 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 3.25 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.

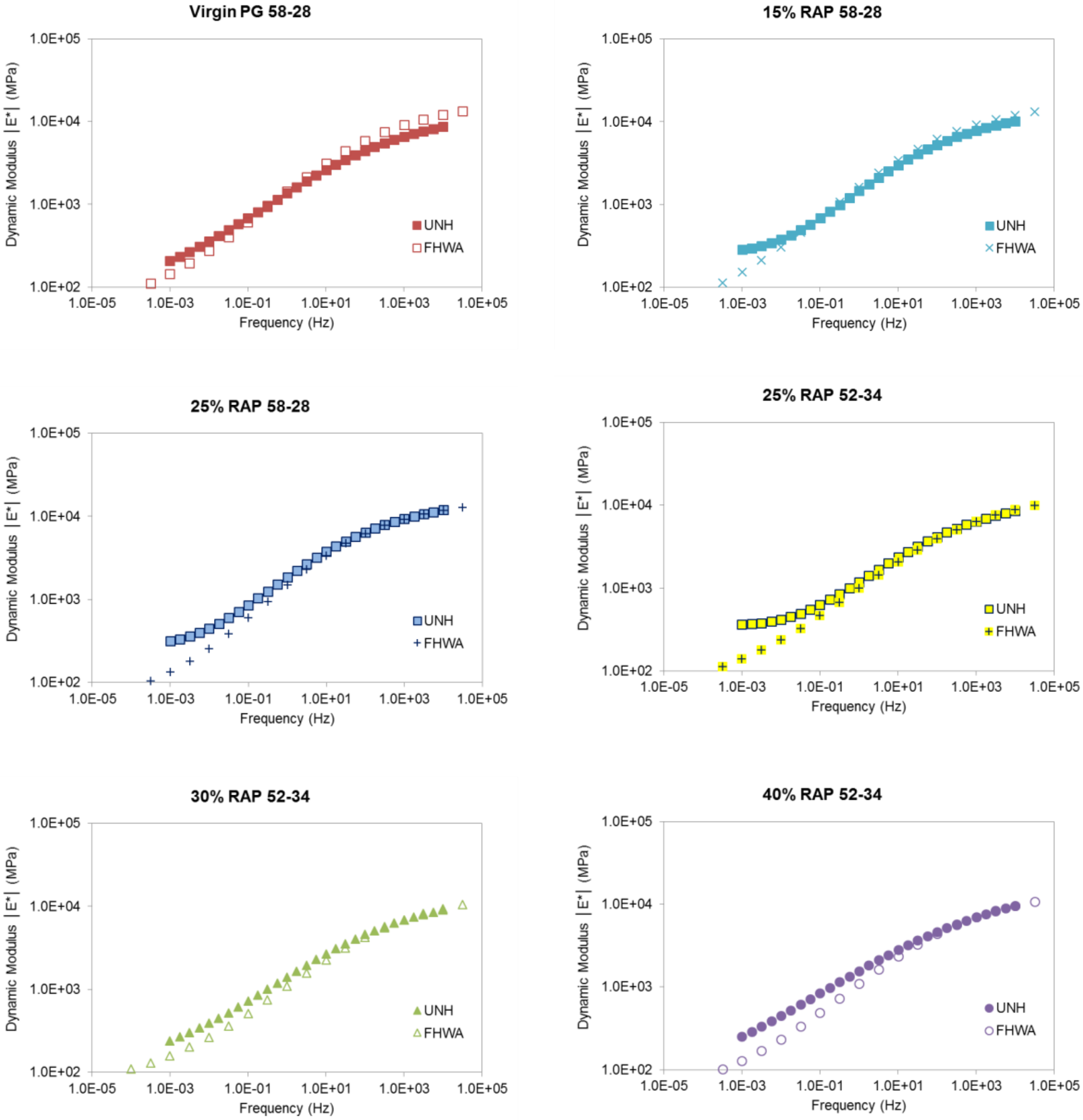

Figure 3.22 Comparison between UNH and FHWA PMPC Dynamic Modulus Master Curves at 21°C

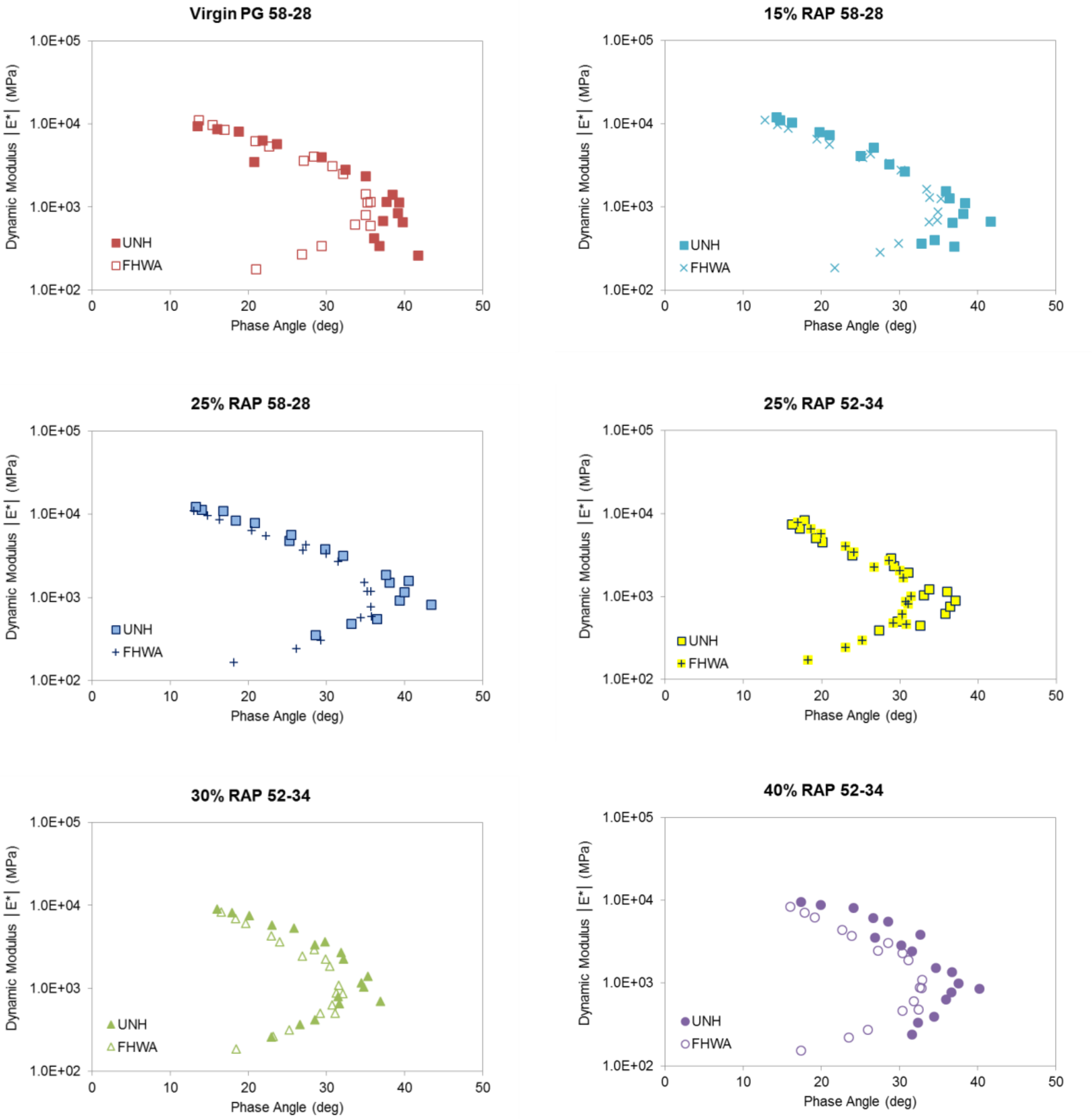

Figure 3.23 Comparison between UNH and FHWA PMPC Black Space Curves

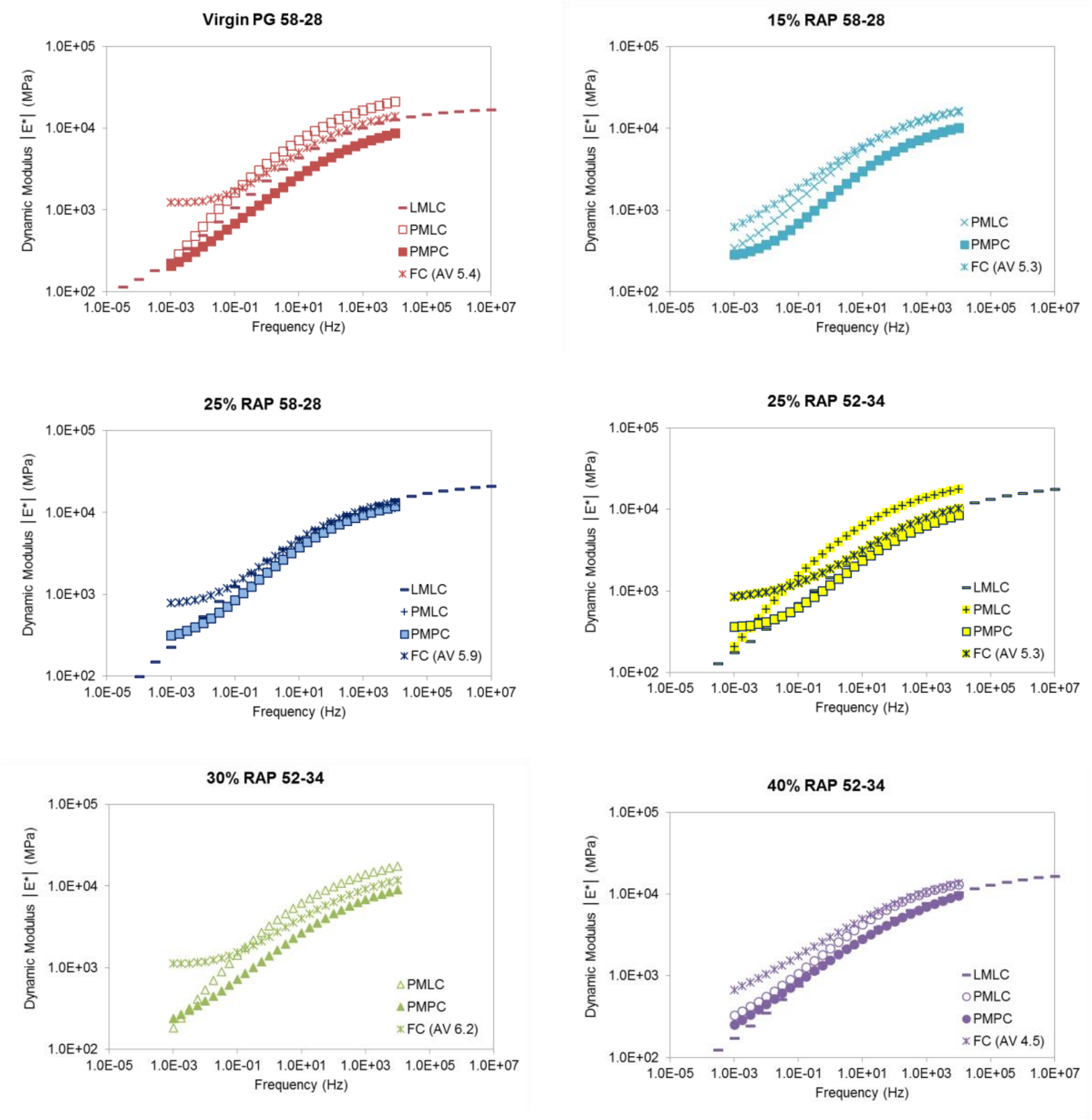

Figure 3.24 Average Dynamic Modulus Master Curves at 21°C for LMLC, PMLC, PMPC, and Field Cores

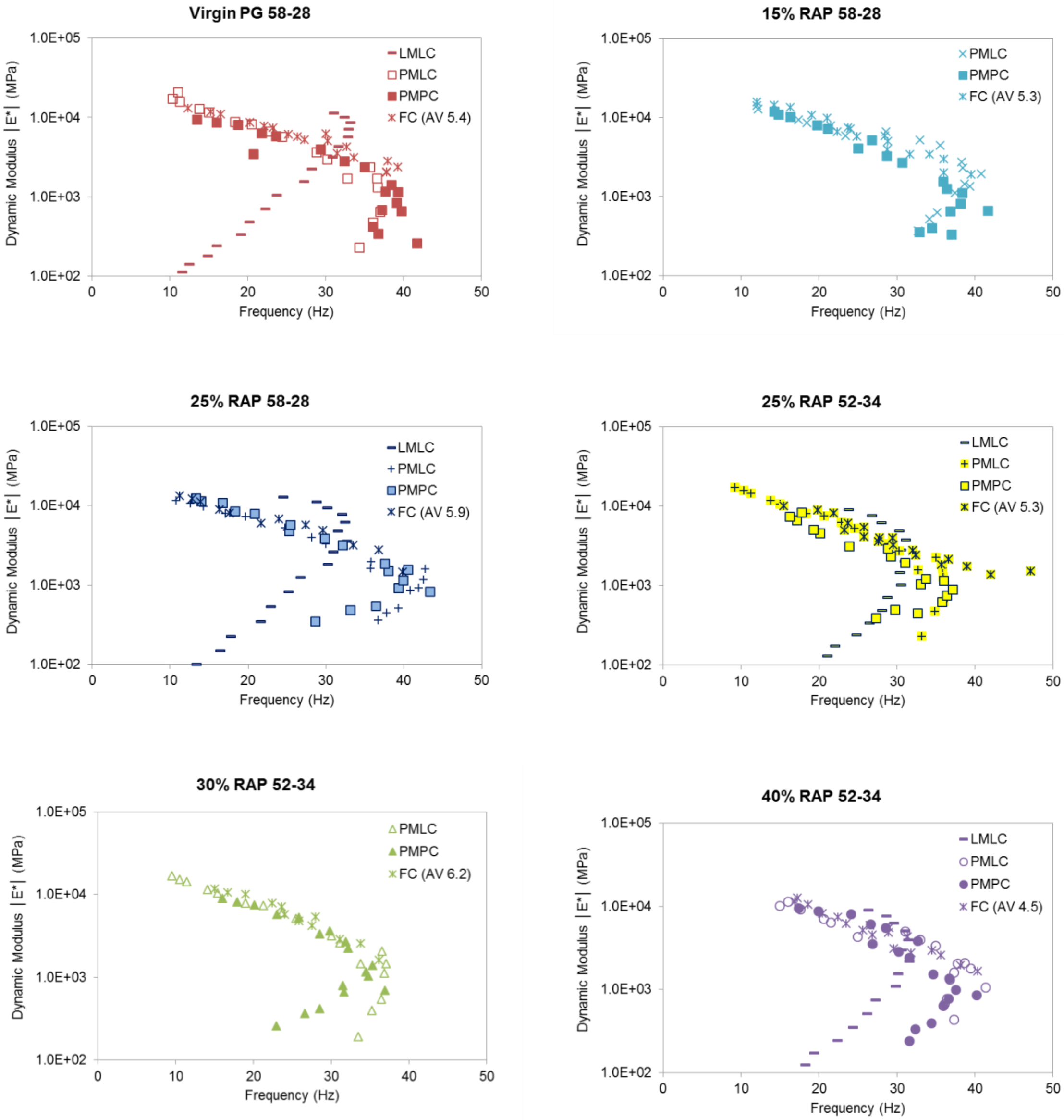

Figure 3.25 Average Black Space Curves for LMLC, PMLC, PMPC, and Field Cores

3.2.2 *SVECD Fatigue*

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 Figure 3.26 and Figure 3.27, respectively. 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 3.28 and Figure 3.29, 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 results of the fatigue testing is inconclusive due to a limited number of specimens that were tested. It appears that the higher RAP contents will be more susceptible to fatigue, however additional tests would be required to confirm this with laboratory testing.

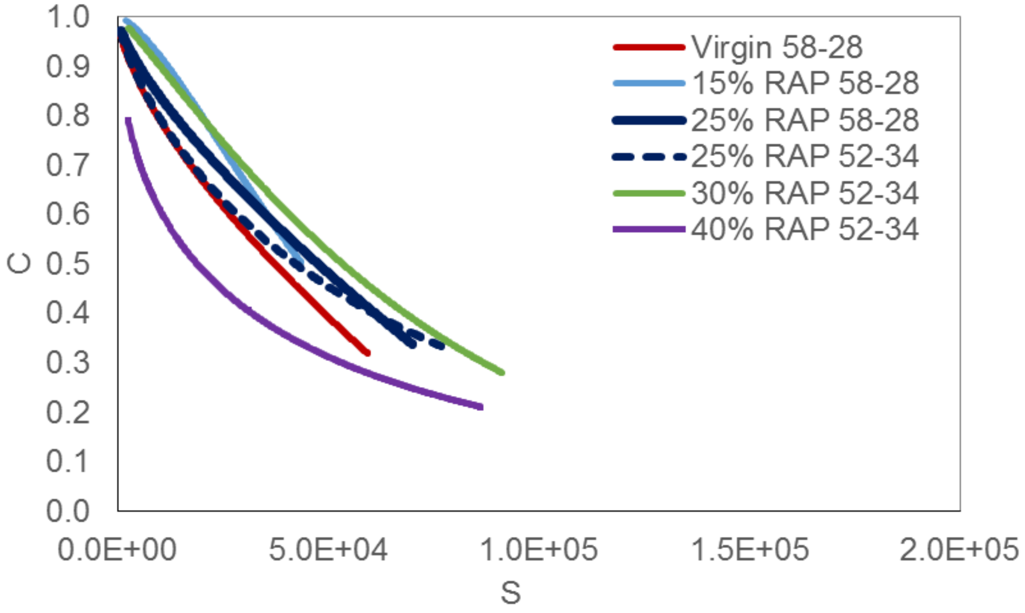

Figure 3.26 Damage Characteristic Curves for PMPC Specimens

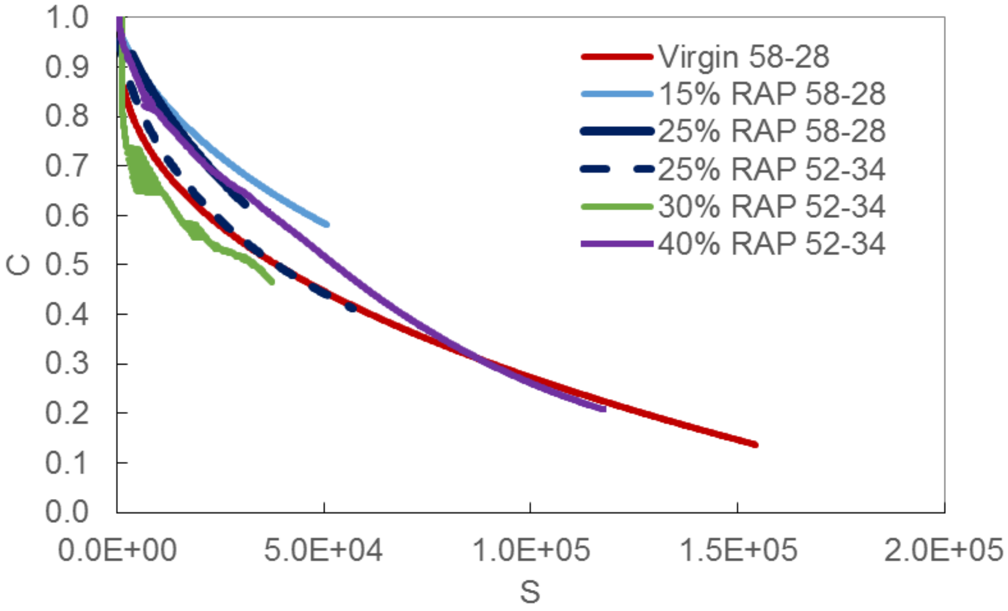

Figure 3.27 Damage Characteristic Curves for PMLC Specimens

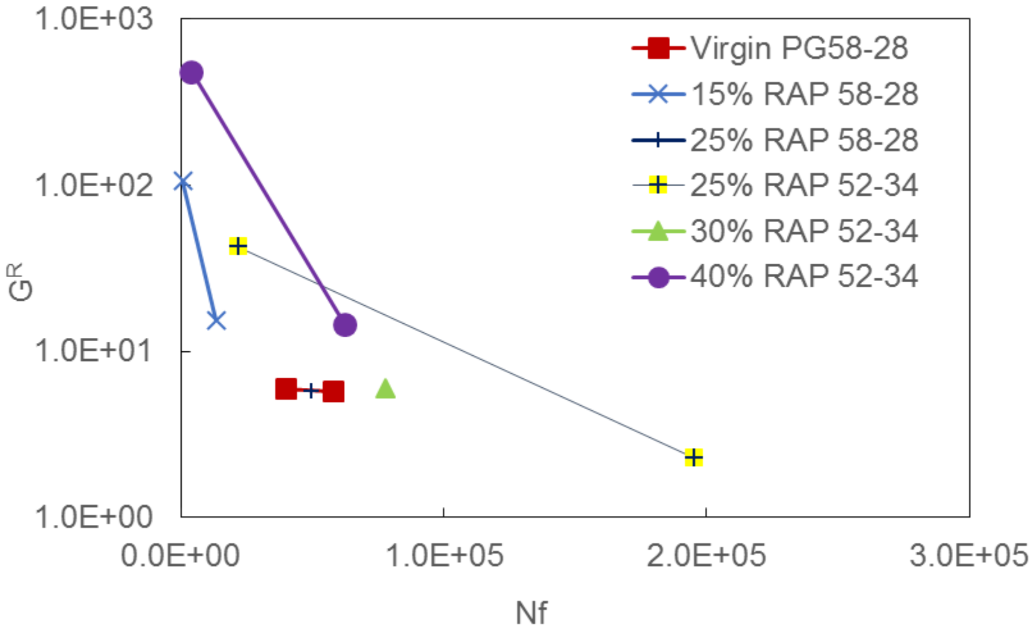

Figure 3.28 G^R versus Number of Cycles to Failure for PMPC Specimens

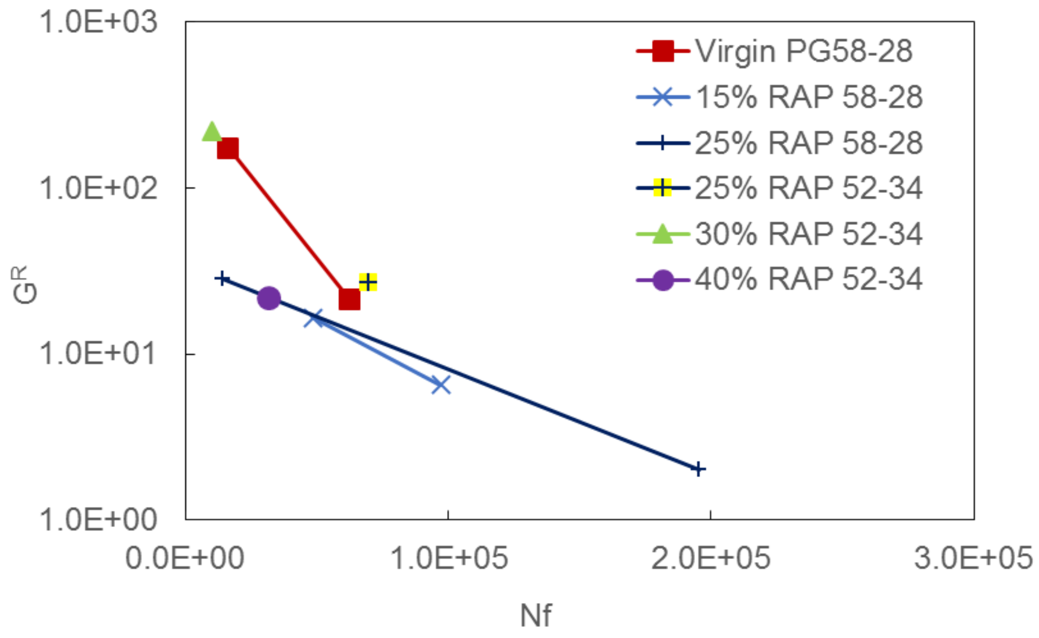

Figure 3.29 G^R versus Number of Cycles to Failure for PMLC Specimens

3.2.3 *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 3.30 through Figure 3.33 show the average of four replicate tests. Figure 3.30 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 3.32), 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 3.32), 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.

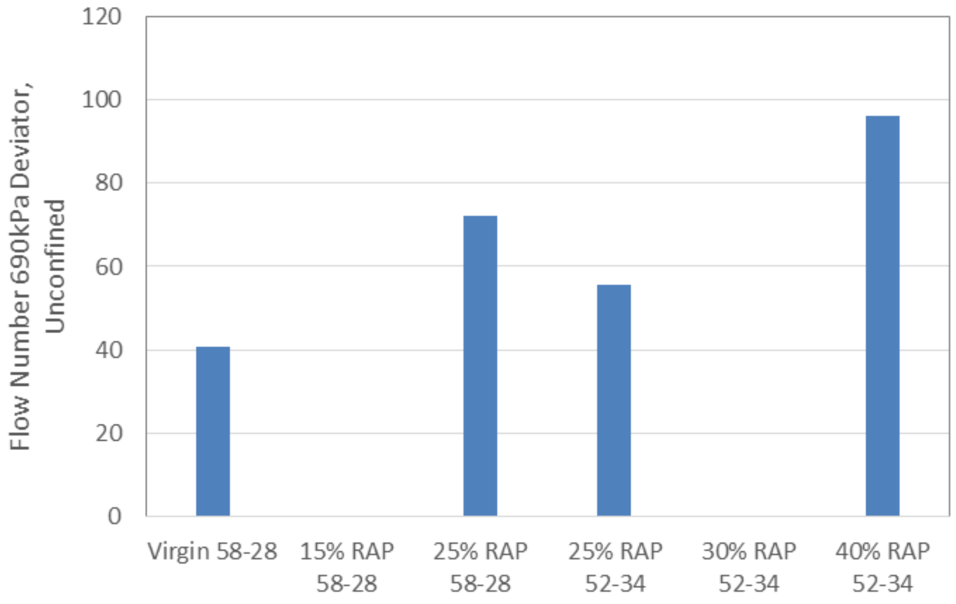

Figure 3.30 Average Flow Number for LMLC Specimens Unconfined and 690 kPa Deviator Stress

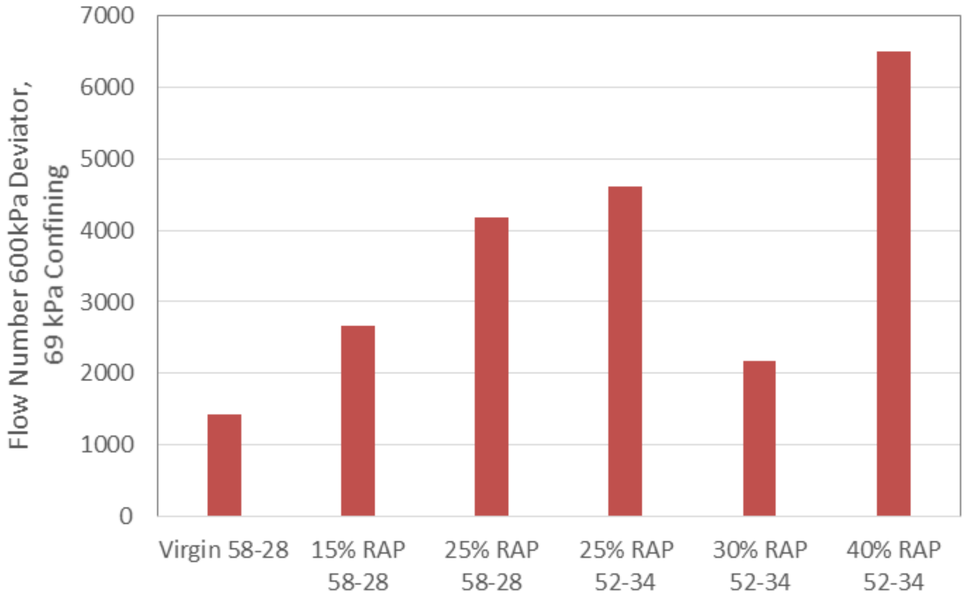

Figure 3.31 Average Flow Number for PMPC Specimens at 69 kPa Confining Pressure and 600 kPa Deviator Stress

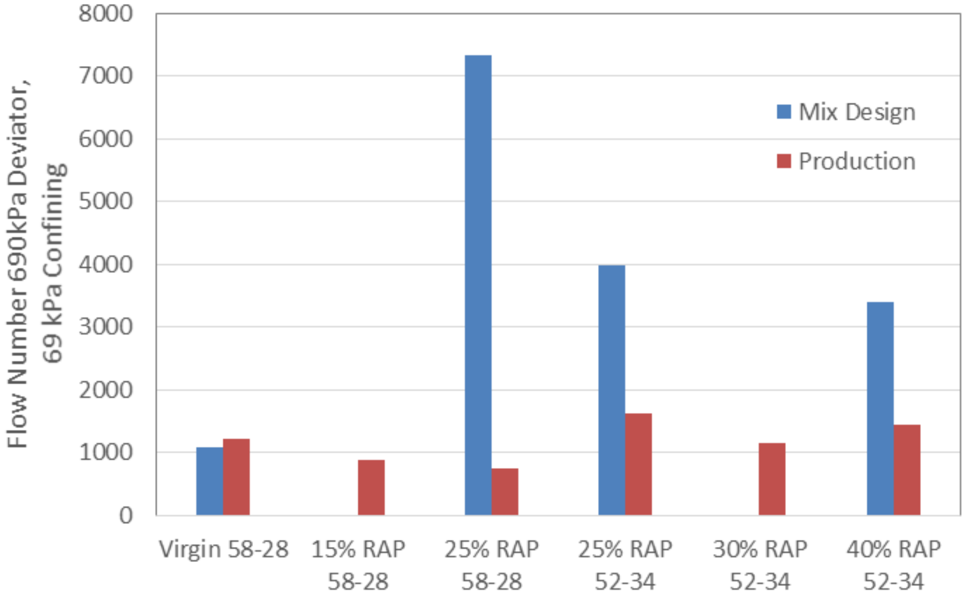

Figure 3.32 Average Flow Number for LMLC and PMPC Specimens at 69 kPa Confining Pressure and 690 kPa Deviator Stress

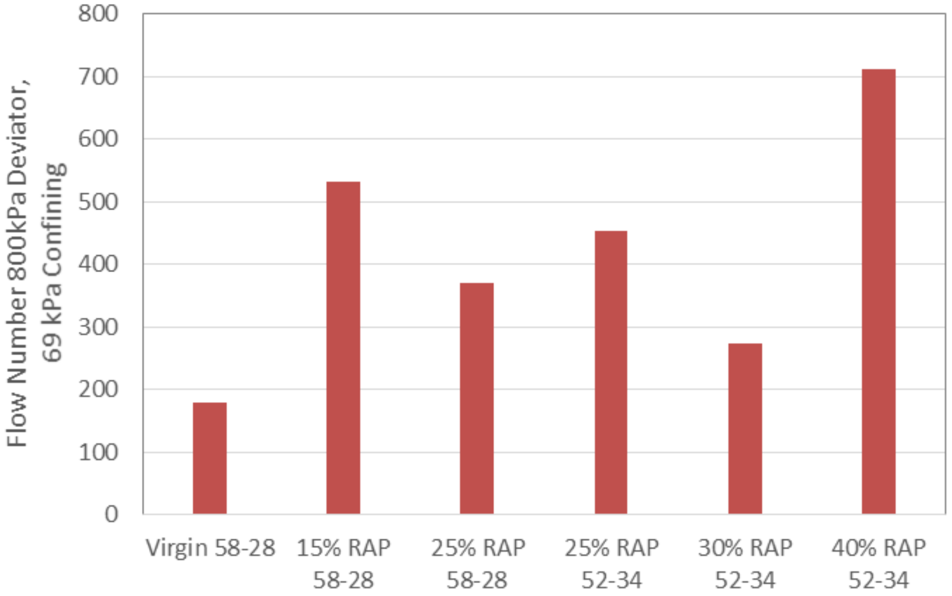

Figure 3.33 Average Flow Number for PMPC Specimens at 69 kPa Confining Pressure and 800 kPa Deviator Stress

3.2.4 *Hamburg Wheel Track Testing*

The stripping inflection point (SIP) determined from the HWTD testing are shown in Figure 3.34. 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.

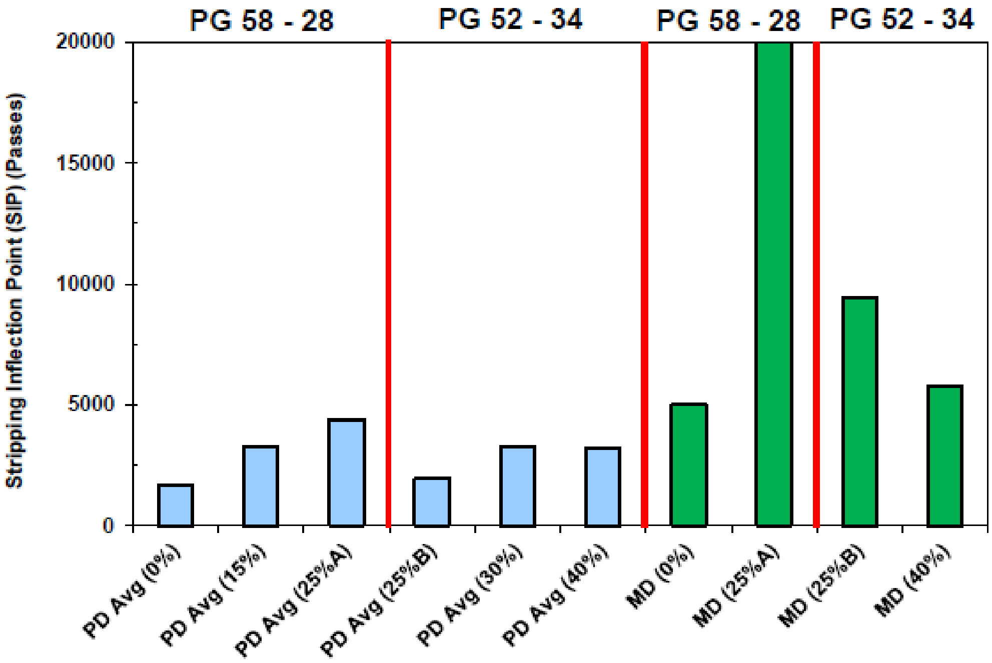

Figure 3.34 Stripping Inflection Point for PMPC (PD) and LMLC (MD) specimens

3.3 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 3.2. 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 3.2 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

4. SUMMARY AND CONCLUSIONS

In Phase II of this project, six test sections were constructed in the southbound lanes on I-93 between Exits 30 and 32 in Woodstock and Lincoln. The test sections included a range of RAP contents and two different virgin PG binders to evaluate the impact of bumping the binder grade at higher RAP contents and to provide guidance on the use of high RAP mixtures:

- Virgin PG 58-28
- 15% RAP with PG 58-28 binder
- 25% RAP with PG 58-28 binder
- 25% RAP with PG 52-34 binder
- 30% RAP with PG 52-34 binder
- 40% RAP with PG 52-34 binder

Testing was conducted on both asphalt binders (tank sampled and extracted and recovered from mixtures) and mixtures. Binder testing included PG grading, shear modulus master curve, and the multiple stress creep and recovery test. Mixture testing included complex modulus, flow number, Hamburg wheel tracking, and fatigue. Four different specimen fabrication methods were used to evaluate differences in measured material properties:

- laboratory mixed, laboratory compacted (LMLC)
- plant mixed, laboratory compacted (PMLC)
- plant mixed, plant compacted (PMPC)
- field cores

The results of the binder testing showed expected trends for the mixtures with the PG 58-28 base binder: stiffer response, lower phase angle, warmer PG temperatures, and better rutting resistance with increasing RAP contents. The results for the PG 52-34 base binder mixtures were mixed, with some trends the opposite of what would be expected with respect to RAP content and in comparison with the PG 58-28 mixtures. In particular, the phase angle values for the PG 52-34 mixtures were much lower in comparison to the PG 58-28 mixtures than what would be expected from the softer binder. This may be due to the method by which the PG 52-34 binder was produced. The use of a paraffinic oil (such as recycled engine oil bottoms (REOB)) to produce the PG 52-34 could possibly cause the observed behavior, however testing for the presence of REOB in the binder was not done.

Mixture testing shows that mixtures with the PG 58-28 base binder are stiffer than those with the PG 52-34 base binder and mixtures with both binders show increasing stiffness with increasing RAP content. The impact of the change in binder grade on stiffness was greater than the impact of the change in RAP content. This trend was observed for the LMLC, PMPC, and field core specimens. The trends observed with the PMLC specimens were different, likely due to the impact of reheating the material in the laboratory; the lower RAP content mixtures and PG 52-34 base binder mixtures were affected by the reheating to a greater extent. This is because the larger proportion of virgin binder and softer binders will undergo a greater change in stiffness due to the reheating than already aged RAP material. This has also been observed with various mixtures in the TPF 5(230) Evaluation of Plant-Produced High-Percentage RAP Mixtures in the Northeast project; additional details can be found in the TPF 5(230) reports.

The combination of stiffness and phase angle, as evaluated in Black Space, can indicate a material's resistance to cracking. The PG 58-28 base binder mixtures show a decrease in phase angle with increasing RAP content, whereas the mixtures with the PG 52-34 base binder have lower phase angles and show an increase in phase angle with increasing RAP content. This trend is not expected behavior for a softer binder; it was observed over the multiple specimen types and in the binder testing. Similar to the behavior observed from the binders, this may be explained if REOB is found to be present in the materials.

Evaluation of the rutting and moisture resistance of the mixtures generally shows the expected trends with increasing rutting resistance at higher RAP contents. The differences between the PG 58-28 and PG 52-34 mixtures changed slightly depending upon the specimen fabrication type and the testing conditions, however, none of the results indicated that these materials would be susceptible to rutting or moisture damage. The available fatigue results are inconclusive, but indicate that the higher RAP mixtures may be more susceptible to fatigue.

Performance of these mixtures to date in the field shows that the PG 58-28 mixtures are performing better than the PG 52-34 mixtures with respect to both thermal and fatigue cracking and that the amount of RAP does show performance differences. The laboratory testing and analysis that was conducted in this project was able to identify the relative differences in the performance of the mixtures, particularly the Black Space analysis. However, thresholds for the laboratory measurements do not exist in relation to the magnitude of distress that would be expected in the field.

The use of the softer PG 52-34 binder at the higher RAP contents did not help improve the performance of these materials, and in fact, appeared to make it worse. This is likely due to the chemistry of the PG 52-34 base binder material (possible presence of REOB) and how the material ages; this was especially evident when comparing the modulus values of the plant mixed materials that had been reheated for specimen fabrication and those that had not (PMLC vs PMPC). This also emphasizes the need to understand the impact of specimen fabrication technique on the resulting properties measured in the laboratory.

Future work with the data gathered in this study could include additional testing on the PG 52-34 binder to try to identify a cause for the unexpected behavior, and specifically to test for the presence of REOB. Recent research has also been conducted to develop index parameters to identify whether a binder or mixture will be susceptible to cracking in the field. Analysis of the existing data could be conducted to evaluate the mixtures in relation to those parameters. Pavement analysis using the measured material properties and actual cross-sections for the field sections would be helpful to more fully understand the differences in how the mixtures perform, along with quantitative measurements of the field performance over time. Finally, all the mixture testing in this project only considered the short term aging condition. Evaluation of long term aged materials may more distinctly separate the mixtures with satisfactory performance from those that are unsatisfactory.

Based on the ongoing results from this study in combination with the TPF 5(230) project, NHDOT has implemented a practical limitation of 1.0% TRB in mixtures (~20-25% RAP by weight of total mix) and is working towards a better understanding of binder versus mixture measurements, the impact of aging, and the impact of various binder additives (such as REOB) that may be used in production of virgin binders supplied to the state.