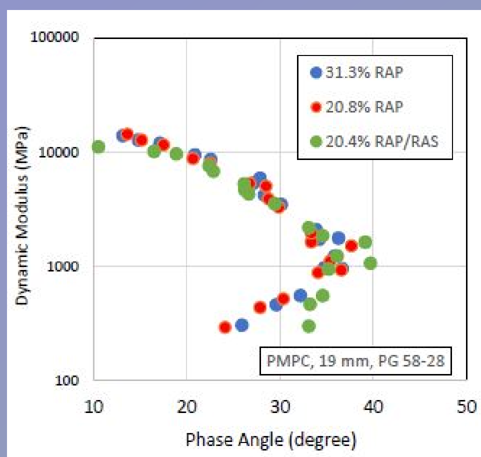

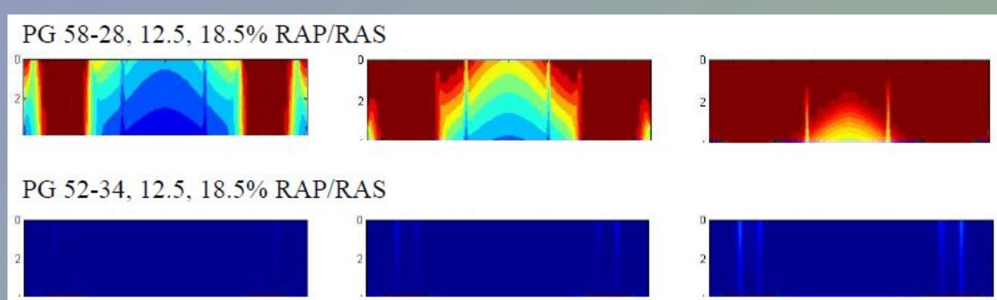

Correlation between Laboratory and Plant Produced High RAP/RAS Mixtures

Final Report

Prepared by the University of New Hampshire Department of Civil Engineering for the New Hampshire Department of Transportation in cooperation with the U.S. Department of Transportation, Federal Highway Administration

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16. Abstract

Cracking is one of the most prevalent types of distresses in asphalt pavements. There are different cracking index parameters that are determined from tests conducted on binders and mixtures to assess cracking potential. The objective of this study is to compare binder and mixture parameters and evaluate the similarities and differences between the rankings and values obtained. This study includes binder and mixture testing on 14 plant produced mixtures including three different binder grades, three binder sources, three aggregate gradations, and mixtures containing a range of RAP and/or RAS contents. Testing included PG grading and 4mm DSR testing on the extracted and recovered binders that were long term aged. Mixture testing included complex modulus, SVECD fatigue, and DCT testing on short term aged mixtures. Parameters evaluated included high and low PG temperatures, ΔT_{cr}, Glover-Rowe parameter (binder and mix-based), R value, dynamic modulus, phase angle, number of cycle to failure from SVECD and LVECD analysis, and fracture energy. The results show that generally the binder parameters correlate well with each other but the mixture parameters do not. Good correlation was observed between binder and mixture stiffness-based parameters, but there was generally low correlation observed between binder and mixture cracking parameters for the mixtures evaluated in this study, possibly a result of differences in aging level. Recommended future work includes non-linear statistical analysis, incorporation of field performance, and testing on long term aged mixtures.

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DISCLAIMER

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NHDOT Project 15680R

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1- Introduction

The use of recycled materials in pavement is an environmentally friendly practice that decreases the use of natural resources, i.e. aggregate and binder, and can also produce a more economical paving mixture. The use of reclaimed asphalt pavement (RAP) in HMA is routine in New Hampshire and the use of Recycled Asphalt Shingles (RAS) has also been explored. At the start of this project, NHDOT specifications limited the amount of total recycled asphalt binder in a mixture to 1.0% without extensive additional testing. This typically corresponds to approximately 18-25% RAP by total weight. The amount of RAS binder was limited to 0.6% (2.5-3% RAS by total weight). NHDOT and local contractors were interested in pursuing the use of higher percentages of RAP and potentially also using RAS in state projects, but were concerned about introducing cracking issues. Recycled materials contain aged binder, so using higher amounts of these materials can produce stiffer mixtures that are less workable and may be more prone to cracking. The same issue occurs when the virgin mixtures age. Generally, the existence of aged binder in hot mix asphalt (HMA) increases the stiffness and decreases the ductility and relaxation capability, ultimately resulting in less cracking resistance.

Annually, a lot of money is spent on maintenance and repair of pavements in the US. Cracking is the most common issue in flexible pavement structures which affects ride quality. Also, water penetration increases from the surface to underlying soil layers with the increase of cracking. Although the two most prevalent types of cracks, fatigue and thermal cracking, have different mechanisms, they are influenced by similar factors. The mixture combination and volumetric design, environmental conditions, aging and recycled materials content, traffic loading volume, and pavement structure affect both kinds of cracking.

The asphalt industry has been moving towards performance based design, reinforced by federal legislation under the Moving Ahead Progress for the 21st Century Act. Many different methods and approaches have been developed over the last several decades to evaluate the performance of asphalt mixtures in the laboratory. Originally, most laboratory testing was performed on laboratory fabricated specimens; more recently, the differences between laboratory and plant production methods have been recognized. Different handling, mixing, and compaction methods in the lab can make a difference between the measured properties of lab produced mixtures and those properties in the mixtures produced at plants. An understanding of differences between the properties and performance measured on specimens fabricated in different ways is important for implementation of performance based approaches. To develop a performance based approach, this study includes testing on both binder and asphalt mixtures with a wide range of variables. The fabrication method (lab versus plant), aggregate size and gradation, binder PG grade and source, and recycled materials' type and content are different in the mixtures.

Objectives

The objectives of this project were to:

- evaluate the effect of mixture variables (binder grade, Nominal Maximum Aggregate Size (NMAS), binder source, and RAP content) on HMA cracking performance in short term aged condition
- compare the measured properties of plant produced and lab produced mixtures and investigate which parameters make more difference in plant versus lab produced mixtures
- compare properties measured from extracted and recovered binders with those measured from mixtures and determine if binder and mixture testing produce similar results
- provide recommendations to the existing specification with regards to evaluating mixtures with high recycled material content

2- Materials and Methods

2.1. Mixture Information

This study included testing on 14 plant produced (PMPC) and 11 lab produced (LMLC) mixtures. The PMPC specimens were fabricated at two drum plants in Lebanon, NH, and Hooksett, NH, by Pike Industries, Inc. The raw materials were collected and brought to NHDOT for fabrication of the LMLC specimens. The mixtures produced at Lebanon were placed in the field along New Hampshire (NH) State Route 12 near Westmoreland during the 2013 construction season. The Hooksett mixtures were produced during the 2014 construction season; these were not placed on state jobs and therefore the field location was not tracked. The mixtures are varied in binder PG grade (PG 52-34, PG 58-28), binder source, NMAS (12.5 and 19 mm), recycled material type, and binder replacement amount. Table 1 shows the combinations evaluated, mix design volumetric information, and actual binder replacement values. Table 2 and Figure 1 show the aggregate gradations for different mixtures. The RAP binder had a continuous grade of 81.3-19.3° C (determined by Pike Industries, Inc. using Abson recovery and trichloroethylene solvent). The RAS material was primarily tear-off shingles obtained from P.J. Keating located in Lunenburg, Massachusetts and could not be graded in the laboratory.

Table 1- Mixtures Properties and Information

Virgin Binder PG Grade	Binder Source	NMAS (mm)	%Total Asphalt (P_{be})	VMA (%)	(VFA) (%)	%Total Binder Replacement (% RAP/ % RAS)	Average % air PMPC Specimens	Average % air LMLC Specimens
58-28 (2013)	McAsphalt	12.5	5.3 (4.7)	15.5	74.9	18.9 (18.9/0)	7.7	6.4
	McAsphalt	12.5	5.3 (4.7)	15.1	76.6	18.5 (7.4/ 11.1)	6.8	-[a]
	McAsphalt	12.5	5.3 (5.0)	16.2	75.8	28.3 (28.3/ 0)	7.4	6.5
	McAsphalt	19	4.7 (4.2)	14.1	74.4	20.8 (20.8/0)	6.1	-
	AveryLane	19	4.8 (4.4)	15.0	71.3	20.4 (8.2/ 12.2)	6.3	5.7
	AveryLane	19	4.7 (4.4)	14.1	75.9	31.3 (31.3/ 0)	6.0	5.6
52-34 (2013)	McAsphalt	12.5	5.3 (4.7)	15.5	74.9	18.9 (18.9/0)	6.3	6.8
	McAsphalt	12.5	5.3 (4.7)	15.1	76.6	18.5 (7.4/ 11.1)	6.8	-
	McAsphalt	12.5	5.3 (5.0)	16.2	75.8	28.3 (28.3/ 0)	6.9	6.4
	Suncor	19	4.8 (4.4)	15.0	71.3	20.4 (8.2/ 12.2)	5.7	5.6
	Suncor	19	4.7 (4.4)	14.1	75.9	31.3 (31.3/ 0)	6.1	5.7
58-28 (2014)	Avery Lane	9.5	6.1 (5.7)	16.5	78.9	21.3 (21.3/0)	5.7	6.0
	Avery Lane	12.5	5.8 (5.5)	15.9	79.5	22.4 (22.4/0)	5.3	5.6
64-28 (2014)	Avery Lane	9.5	6.1 (5.7)	16.5	78.9	16.4 (16.4/0)	5.9	6.0

Table 2- Aggregate Gradation

	Lebanon						Hooksett	
Sieve Size (mm)	12.5 mm 20% RAP RAS	12.5 mm 30% RAP	12.5 mm 20% RAP	19 mm, 20% RAP RAS	19 mm 30% RAP	19 mm 20% RAP	12.5 mm	9.5 mm
	% Passing							
37.5	100	100	100	100	100	100	100	100
25	100	100	100	100	100	100	100	100
19	100	100	100	99	99	99	100	100
12.5	98.6	98.6	98.6	83.4	83.4	82.6	98.9	100
9.5	86.4	86.9	86.3	70.3	70	69.2	86.5	98
4.75	59.9	60	59.2	46.3	47.2	46.7	57.9	78
2.36	41.7	41.7	41.5	32	32.4	32.4	44.0	62
1.18	29.5	30.7	30.7	23.3	23.5	23.8	34.3	49
0.6	19.8	21.1	21.3	16	16.2	16.5	25.2	35
0.3	11.1	11.4	11.4	9	9.3	9.3	15.9	22
0.15	5.8	6.1	5.9	4.7	5.2	5	8.0	12
0.075	3.7	3.9	3.9	3.1	3.3	3.1	4.68	8.5

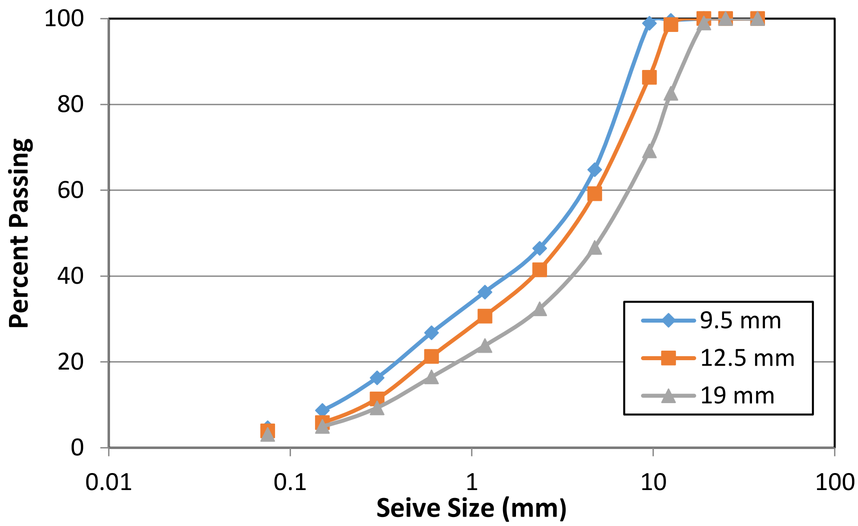


Figure 1- Aggregate Gradations

2.2. Specimen Fabrication

Plant Mixed Plant Compacted: For all of the mixtures, loose mix was sampled in the plant and then compacted immediately to produce plant mixed plant compacted (PMPC) specimens. Specimens 150 mm in diameter and approximately 180 mm tall specimens were compacted using a Superpave Gyratory Compactor (SGC). The PMPC specimens were fabricated and compacted by Pike Industries Inc. The gyratory specimens were transferred to the UNH laboratory and stored for future coring, cutting, and testing. Final test specimens were 100 mm in diameter and 130-150 mm tall with a target air void content of 6 ± 0.5%.

Laboratory Mixed Laboratory Compacted: The raw materials (aggregate, virgin binder, and RAP) were transferred from the plants to the NHDOT laboratory. The materials were batched using the mixture design proportions, mixed at the recommended temperatures, and short term oven aged at 135ºC for 4 hours before being compacted using an SGC. The air void content for each mix was targeted to match the PMPC specimen air void content. These specimens were also transferred to UNH laboratory for further preparation and testing.

2.3. Binder Testing

The asphalt binder from each of the mixtures (both plant and laboratory mixed) was extracted and recovered. The recovered binders were fully characterized for PG grade and critical cracking temperature at the NHDOT laboratory. The asphalt binder cracking device (ABCD) testing was also performed by NHDOT to evaluate cracking temperature. Also, 4 mm DSR testing was conducted on some materials by Gerry Reinke at Mathy Construction to develop binder shear modulus mastercurves. The binder testing procedures and details are described in the following sections.

2.3.1. Binder Extraction and Recovery

The binder extraction was performed by NHDOT in accordance with AASHTO T 164, procedure 12, using a centrifuge extractor and toluene solvent in order to determine the asphalt binder content. The asphalt binder was recovered based on ASTMD7906-14 using a rotary evaporator. The extracted and recovered binder was then subjected to PAV aging for PG grading tests; it was assumed that short term aging (normally done using RTFO) was completed through the plant production or short term oven aging on the mixtures in the laboratory.

2.3.2. PG Grading

PG grading was conducted on virgin and extracted and recovered binders following AASHTO M320and included the following tests:

- Dynamic shear rheometer (DSR), (AASHTO T315) on original binder, short term aged (either through production or RTFO, AASHTO T240) and long term aged (PAV, AASHTO R28) samples. By measuring complex shear modulus (G*) and phase angle (δ), the stiffness and viscous behavior of binder are determined at intermediate and high temperatures.
- Bending beam rheometer (BBR, AASHTO T313) to evaluate the performance of binder against low temperature cracking. Two parameters of creep stiffness (S(t)) and the rate of change of creep stiffness (m) are obtained to show the binder resistance to creep and rate of relaxation, respectively.

2.3.3. Asphalt Binder Cracking Device (ABCD)

Determination of the cracking temperature of asphalt binder using the asphalt binder cracking device, ABCD, (AASHTO TP 92-14) is a relatively new test to predict the thermal cracking temperature of binder under stress-strain conditions similar to what is encountered in the field. The AASHTO method was followed by NHDOT.

2.3.4. Dynamic Shear Rheometer (DSR) using 4mm plates

Western Research Institute (WRI) has recently developed the 4 mm dynamic shear rheometer (DSR) and made it possible to reliably measure properties at low temperatures using instrument compliance corrections for the DSR measurements. Figure 2 shows the 4 mm binder samples in the mold and also in the DSR instrument. 4 mm DSR testing was done on a smaller specimen (4 mm diameter) to compare with the regular DSR testing, and over a range of temperatures to construct shear modulus mastercurves and perform rheological analysis. To perform the analysis, Abatech Rhea software was used.

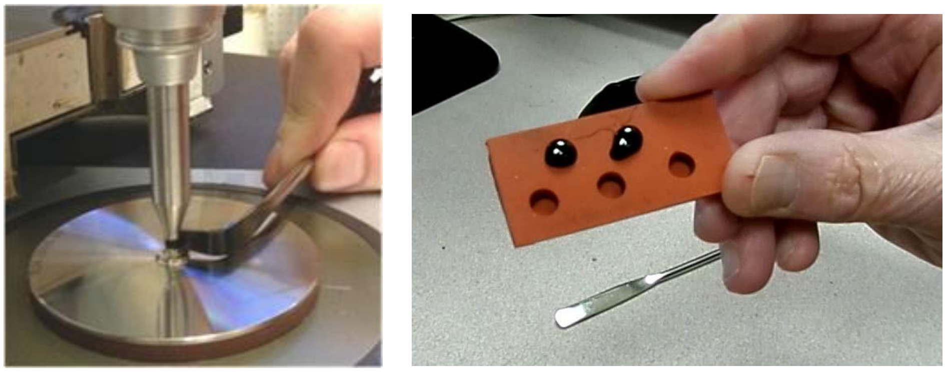


Figure 2- 4mm DSR binder sample (Western Research Institute)

2.4. Mixture Testing

The performance of mixtures was evaluated using complex modulus, uniaxial fatigue testing, and disc-shaped compact tension (DCT) testing conducted on both plant and lab produced mixtures. Gyratory specimens were compacted at the plant without reheating and stored in the laboratory. Prior to testing, the gyratory specimens were cored and cut to the appropriate test specimen dimensions. The air void content of each specimen was measured and the average values of three replicates for each mixture are shown in Table 3. To accurately compare the results of lab and plant produced mixture, the lab mixtures were compacted to match the density of the plant mix specimens.

Table 3- Average Air Void Content of Specimens for Different Mixtures

No.	Binder PG Grade	NMSA	%Total Binder Replacement (% RAP/ % RAS)	Average Air Void (%)		
				Dynamic modulus (Plant/Lab)	Fatigue (Plant/ Lab)	DCT (Plant/Lab)
1	58-28	12.5	18.9 (18.9/0)	7.7/6.6	7.6/6.6	-
2		12.5	18.5 (7.4/11.1)	6.8/-	6.6/-	-
3		12.5	28.3 (28.3/ 0)	7.4/6.5	7.1/6.4	8.4/-
4		19	20.8 (20.8/0)	6.2/-	6.4/-	-
5		19	20.4 (8.2/12.2)	6.3/5.7	5.8/5.3	7.0/-
6		19	31.3 (31.3/ 0)	6.3/5.6	6.1/5.4	7.1/-
7	52-34	12.5	18.9 (18.9/0)	6.2/6.8	6.3/6.8	7.6/-
8		12.5	18.5 (7.4/ 11.1)	6.8/-	6.9/-	-
9		12.5	28.3 (28.3/ 0)	6.9/6.3	6.6/6.6	-
10		19	20.4 (8.2/12.2)	5.7/5.6	5.7/5.4	6.5/-
11		19	31.3 (31.3/ 0)	6.1/5.7	5.7/5.4	6.9/-
12	58-28	12.5	22.4 (22.4/0)	5.5/5.6	5.4/5.6	7.0/7.2
13		9.5	21.3 (21.3/0)	5.8/6.2	5.7/5.8	6.8/7.0
14	64-28	9.5	16.4 (16.4/ 0)	5.9/6.3	5.8/5.8	7.2/7.2

2.4.1. Complex Modulus Testing

Complex modulus testing, following AASHTO TP-79, was performed to determine dynamic modulus and phase angle for each mixture. Testing was performed on three cylindrical specimens of each mix at different temperatures (4.4°, 21.1°, and 37.8° C) and a range of frequencies (0.1, 0.5, 1.0, 5.0, 10, and 25 Hz) to develop master curves. The testing was conducted using the asphalt mixture performance tester (AMPT) equipment in unconfined compression; four LVDTs with a 70 mm gage length were used to measure deformations. Dynamic modulus and phase angle can be calculated from measured stresses and strains as shown in equations 1 and 2, respectively.

$$|E^*| = \frac{\sigma_{amp}}{\varepsilon_{amp}} \tag{1}$$

Where $|E^*|$ = dynamic modulus (psi), σ_{amp}= amplitude of applied stress (psi), and ε_{amp}= amplitude of strain response (in/in).

$$\delta = 2\pi f \Delta t \tag{2}$$

Where δ is phase angle (degrees), f is load frequency (Hz), and Δt is the time lag between stress and strain peak to peak. Dynamic modulus and phase angle were calculated using a Matlab code and the RHEA® software was used to construct the master curves. Figure 3 shows the AMPT equipment at the UNH lab and a complex modulus specimen in the test chamber.

Figure 3- Asphalt Mixture Performance Tester (AMPT) and Complex Modulus Testing Configuration

2.4.2. Uniaxial Fatigue Testing

Uniaxial fatigue testing was conducted on four specimens of each mixture, using UTS 032 "S-VECD Fatigue" software. Testing details are described in AASHTO TP 107 *Determining the Damage Characteristic Curve of Asphalt Concrete from Direct Tension Cyclic Fatigue Tests*. Four LVDTs with a 70 mm gage length were mounted to measure deformation. The specimens were 100 mm in diameter and 130 mm in height and DEVCON® steel putty was used to glue the end plates to the specimens. Testing temperature was determined based on the virgin binder PG grade used in the mixture and was calculated as follows:

$$test\ temp = \left[\frac{high\ PG\ temperature + low\ PG\ temperature}{2} - 3\right]$$

Damage analysis for each mixture was performed and damage characteristic curves (C versus S) were obtained using subroutines within the software and fatigue performance predictions were made using the models available within the Alpha-F software. Also, the fatigue cracking resistance can be assessed using the relationship between the fatigue failure criterion (G^R) versus number of cycles. Figure 4 shows a fatigue testing specimen and its configuration in the AMPT.

Figure 4- Uniaxial Fatigue Testing Specimen and the configuration in AMPT

2.4.3. Disc-Shaped Compact Tension (DCT)

The Disc-shaped compact tension test, specified in ASTM D7313, is an energy-based method to evaluate the fracture resistance and low temperature cracking performance of asphalt mixtures. The specimen gyratory was 152.4 mm in diameter, and 50.8 mm in thickness, with two holes (25.4 mm diameter) and a 62.5 mm notch. Testing was conducted in the displacement control mode using a crack mouth opening rate of 1 mm/min on three replicate specimens of each mixture (Figure 5).

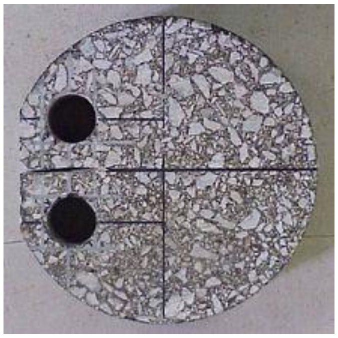
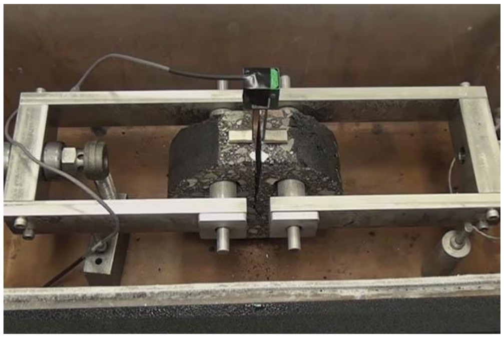
 

Figure 5- Disk-Shaped Compact Tension Testing Specimen and Configuration, (ICT, and Minnesota Transportation Research Blog)

The fracture energy (G_f) was calculated as the area under the load versus crack mouth opening displacement (CMOD) curve (Figure 6). The higher G_f indicates the mixture is more resistant to low temperature fracture.

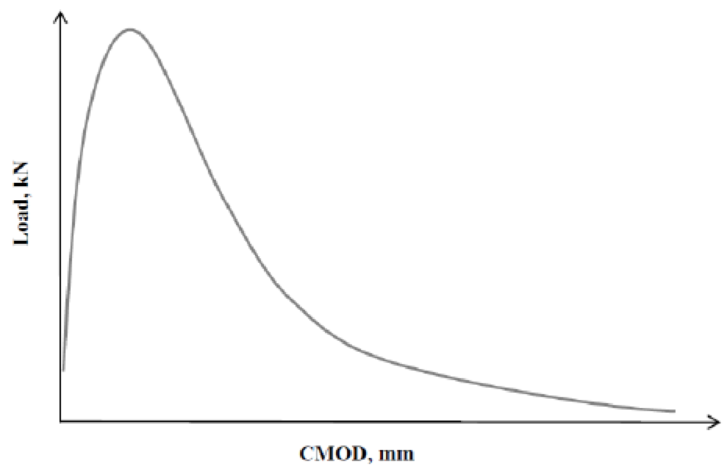


Figure 6- A Typical Load-CMOD Test Curve (Marasteanu et al., 2012)

3- Results and Discussion

3.1. Binder Results

3.1.1. PG Grading

<u>Lebanon Mixtures</u>

The continuous high and low PG temperatures for the different virgin and extracted and recovered binders from the Lebanon plant are shown in Figures 7 and 8, respectively. These results were obtained by NHDOT from DSR and BBR testing on extracted and recovered binders from both lab and plant produced mixtures. The high PG temperatures from the lab produced mixtures were greater than those from the plant produced mixtures and there are slight differences with the different binder sources. The two PG 52-34 virgin binders did not quite meet the required performance grade on the low side. The difference between binders from the PMPC and LMLC mixtures was less pronounced on the low temperature side and all of the low grades were controlled by the m-value. In most cases for both 12.5 and 19 mm extracted binders, PMPC mixtures showed colder temperatures.

The mixtures containing RAS had warmer temperatures than RAP only mixtures and the binders extracted from the 19 mm mixtures had warmer temperatures than those extracted from the 12.5 mm mixtures for the same recycled material content. The different binder sources for 12.5 mm and 19 mm may cause the difference in high and low temperature PG grade of extracted and recovered binders, so that the warmer high temperatures from the Suncor and Avery Lane virgin binders resulted in warmer high temperature of extracted and recovered binders from 19 mm mixtures than 12.5 mm mixtures. The slightly higher actual binder replacement for the 19 mm mixture (20.8% versus 18.9% for 12.5 mm) may contribute to the warmer temperatures, as well. The results of the PG grading analysis indicate that the LMLC materials were more highly aged than the PMPC materials and that the difference between the two depends on the mixture recycled content, effective binder content, virgin binder grade, and possibly binder source.

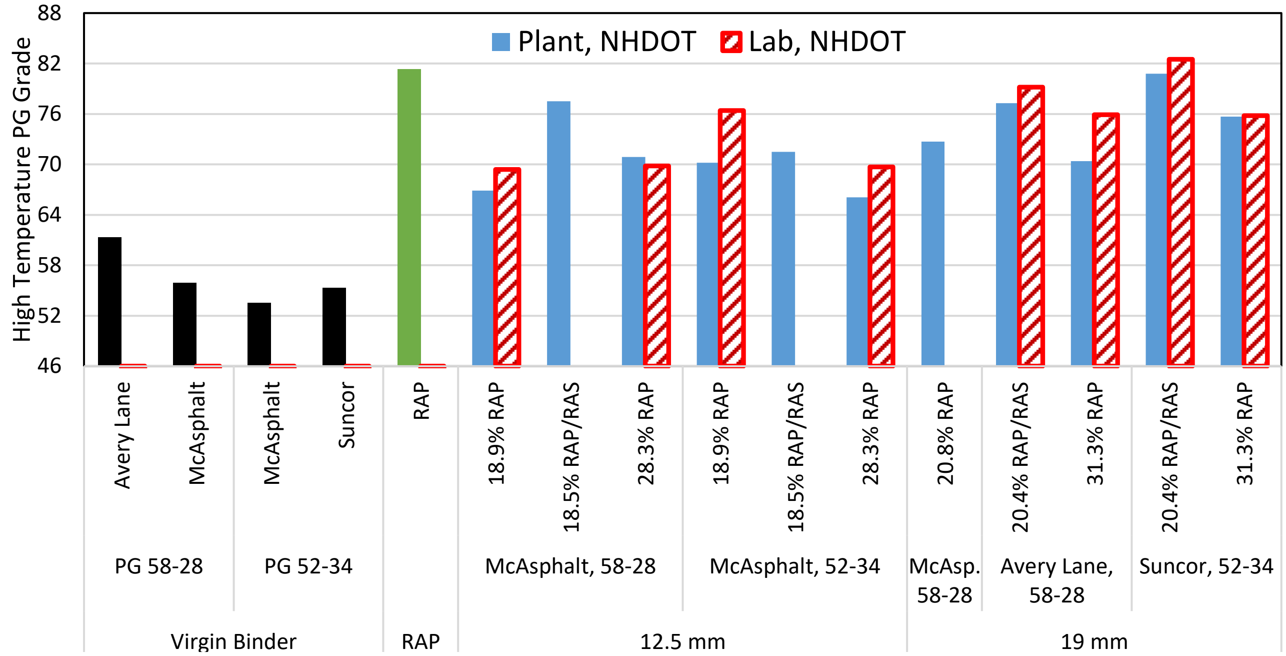


Figure 7- High PG Temperature for Different Lebanon Binders

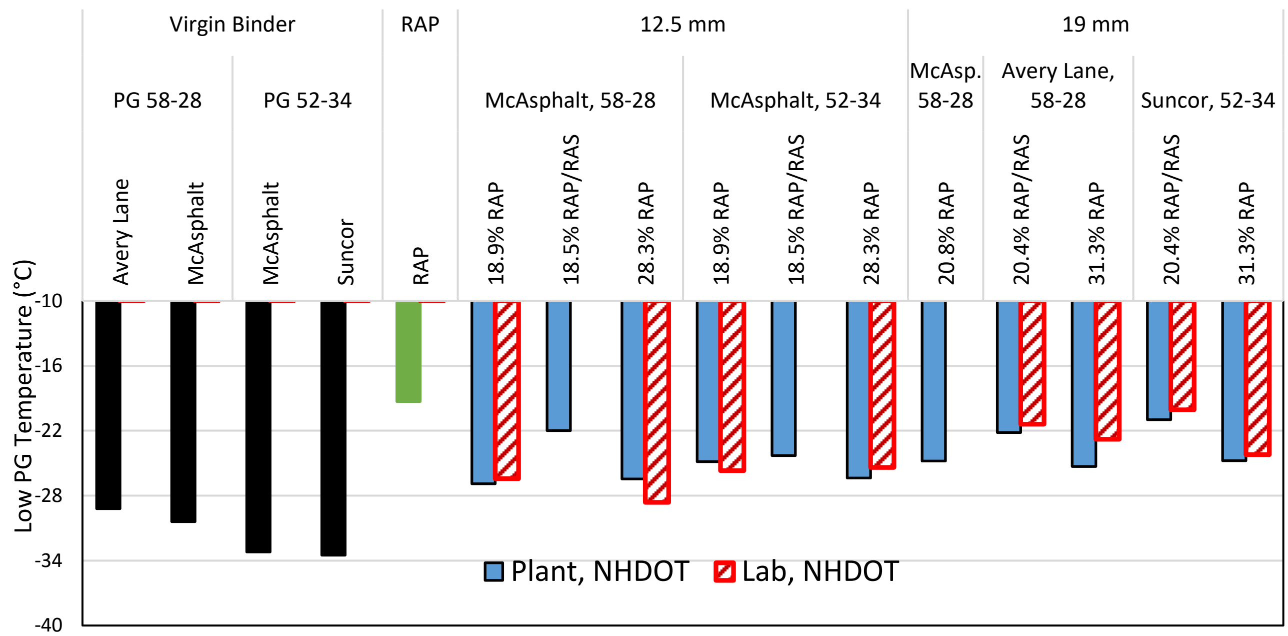


Figure 8- Low PG Temperature for Different Lebanon Binders

Figure 9 presents the temperature at which the material met the BBR creep stiffness value criteria (S = 300 MPa) and Figure 10 presents the ΔT_{cr} of different extracted binders. ΔT_{cr} is the difference between the temperature at which the material meets the creep stiffness criteria and temperature at which the material meets the m-value criteria (m=0.300), (Equation 3).

$$\Delta T_{cr} = T_{cr\ (stiffness)} - T_{cr\ (m-slope)} \quad (3)$$

$T_{cr\ (stiffness)}$ is the critical low temperature where S(60) =300 MPa, and $T_{cr\ (m-slope)}$ is the critical low temperature where m(60) = 0.300.

The S values for most plant produced mixtures were colder than those for lab produced mixtures, with larger differences observed with the 18.9% RAP mixtures. The difference was greater for two McAsphalt and Suncor binder sources, while the S values for the Avery Lane binder source materials were very similar.

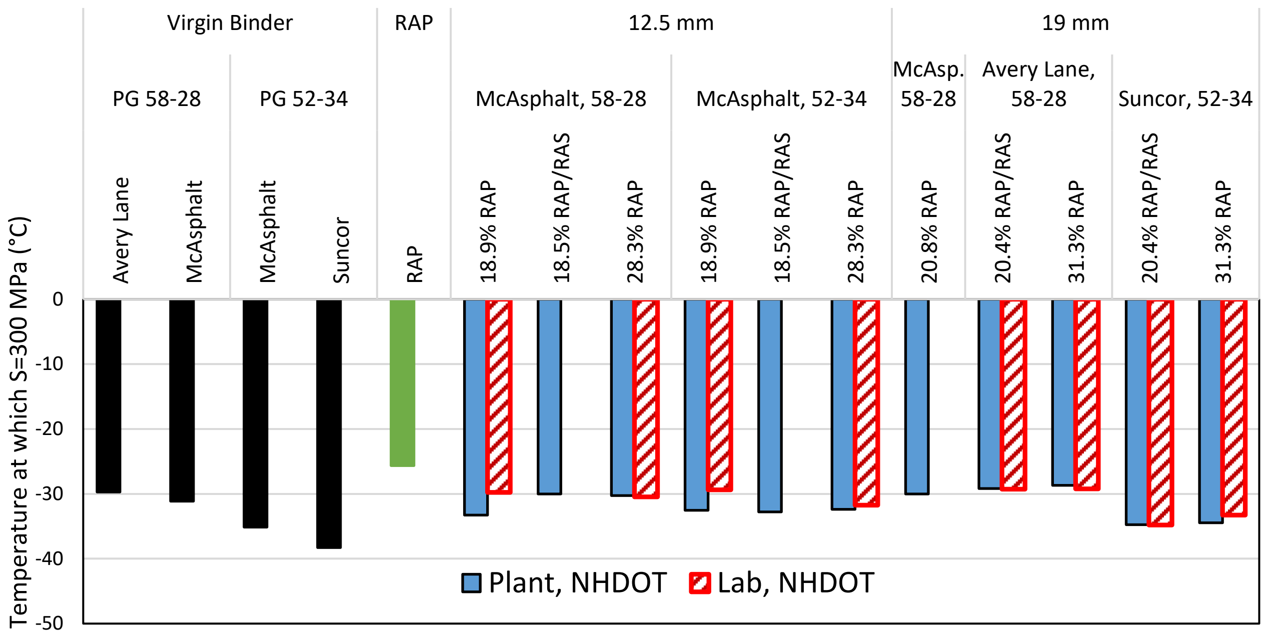


Figure 9- Creep Stiffness for Lebanon Mixtures

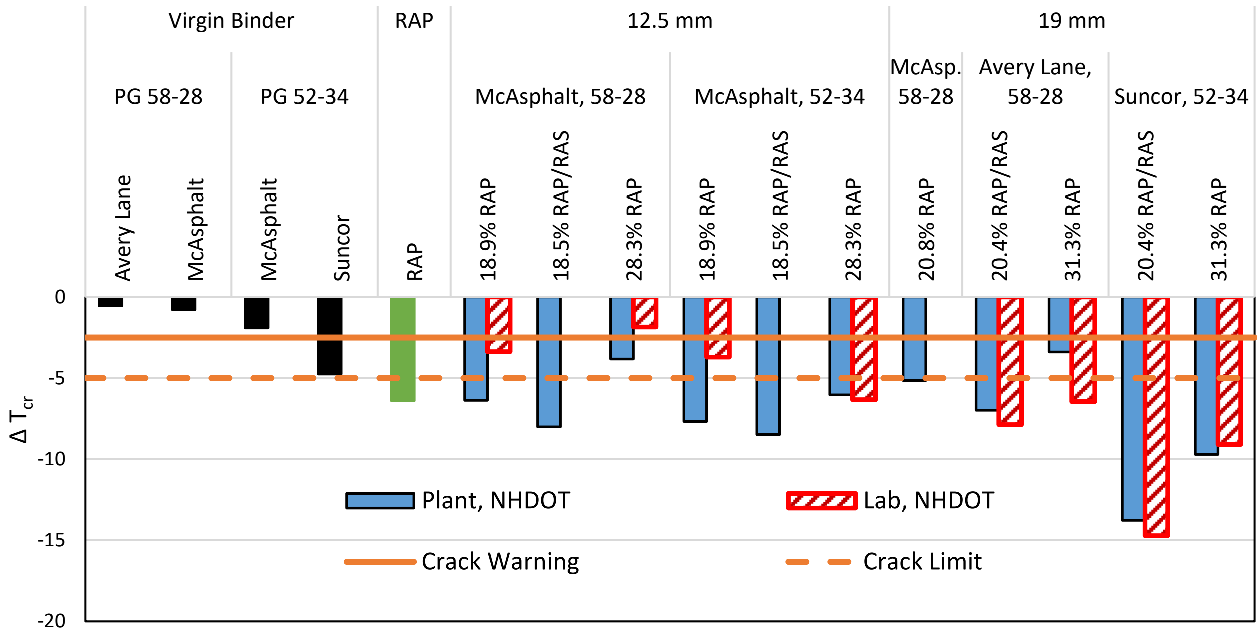


Figure 10- ΔT_{cr} of Different Lebanon Binders

According to Figure 10, the ΔT_{cr} is negative for all binders, indicating they are m-controlled. The cracking warning (Anderson, 2011) and cracking limit (Rowe, 2011) lines are drawn in this figure as well. Most of the binders did not pass those criteria. For the 12.5 mm mixtures, the PMPC recovered binders showed larger ΔT_{cr} values than the LMLC recovered binders in most cases. This indicates that the aging which the asphalt is experiencing in the plant is changing the relaxation capacity (m-value) of the binder more than it is changing the stiffness (S value) as compared to the aging the asphalt is experiencing in the lab. However, the trend is opposite for the 19 mm mixtures with the Avery Lane and Suncor binder sources. The recovered binders from 19mm and PG 52-34 mixtures showed larger negative ΔT_{cr} values than the 12.5 mm and PG 58-28 mixtures, respectively. An interesting observation is that the trend of plant versus lab produced mixtures is opposite for ΔT_{cr} as compared to the low temperature PG grade.

<u>Hooksett Mixtures</u>

Figure 11 shows the high PG temperature from Hooksett mixtures measured by NHDOT. All extracted and recovered binders from lab produced mixtures had higher high temperatures than plant produced mixtures, indicating that binders extracted and recovered from lab produced mixtures are expected to be stiffer than plant produced mixtures. The greatest difference was observed for the PG 58-28, 9.5 mm, 21.3% RAP mixture.

On the low temperature side presented in Figure 12, the difference between lab and plant was much smaller. The plant produced materials using the PG 58-28 binder had warmer low PG temperature than lab produced materials while the trend is the opposite for the one PG 64-28 mixture.

Figures 13 and 14 show the critical temperature at S=300 MPa, and delta Tcr values, respectively. Although the critical temperature at S=300 MPa was very similar for different mixtures, and also for plant and lab produced mixtures, the difference in ΔTcr values is very clear. All of the binders recovered from lab produced mixtures were more m-controlled than binders from plant produced mixtures; this follows the same trend that was observed with the Lebanon materials with the Avery Lane binder source.

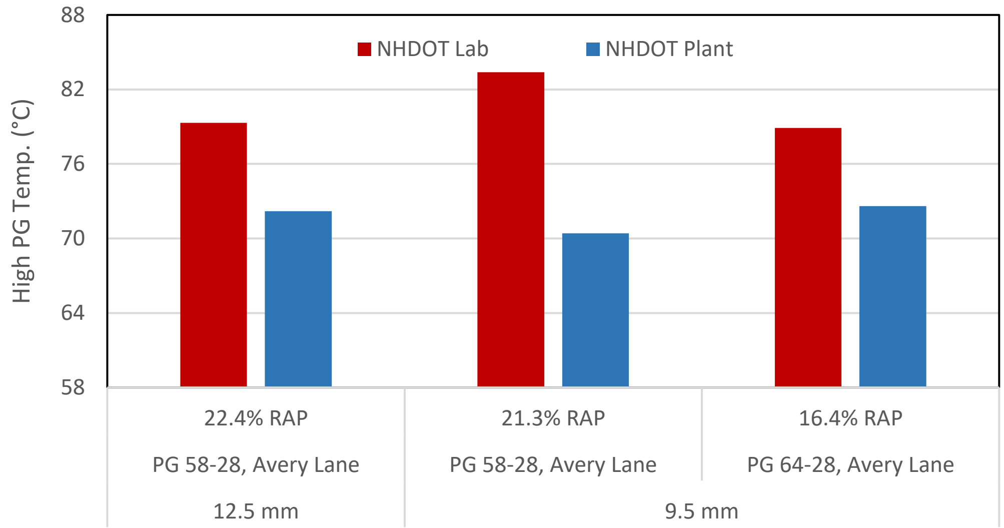


Figure 11- High PG Temperature for Hooksett Mixtures

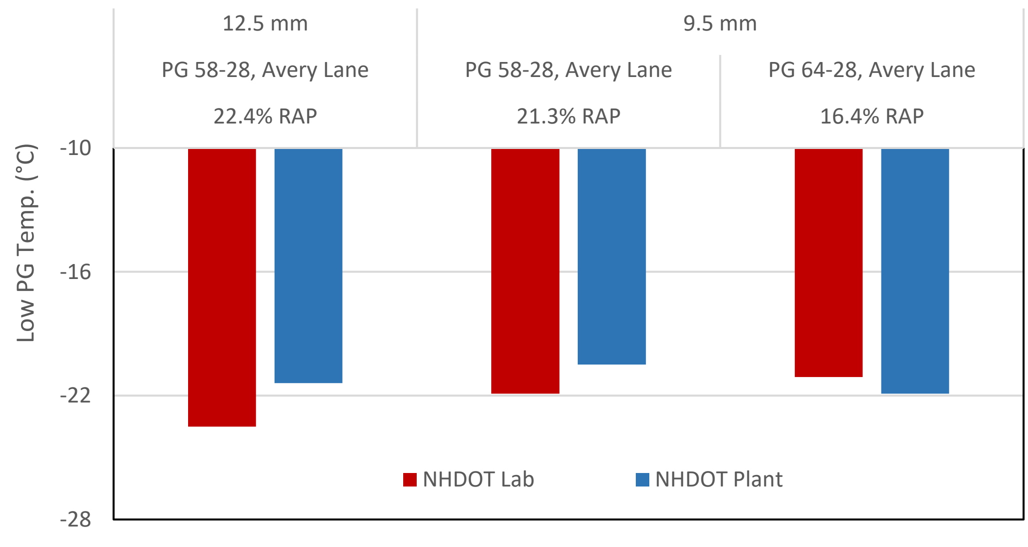


Figure 12- Low PG Temperature for Hooksett Mixtures

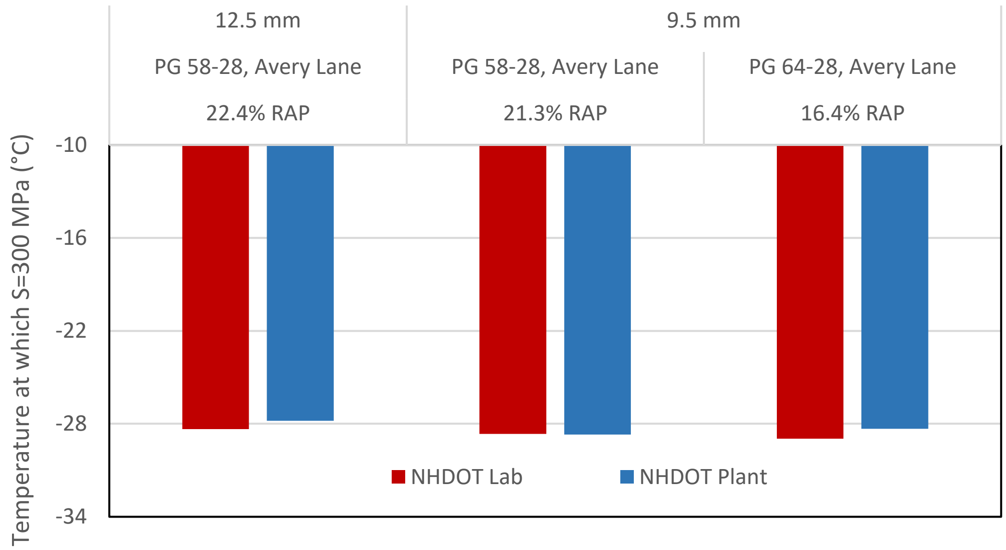


Figure 13- Critical Temperature where S=300 MPa for Hooksett Mixtures

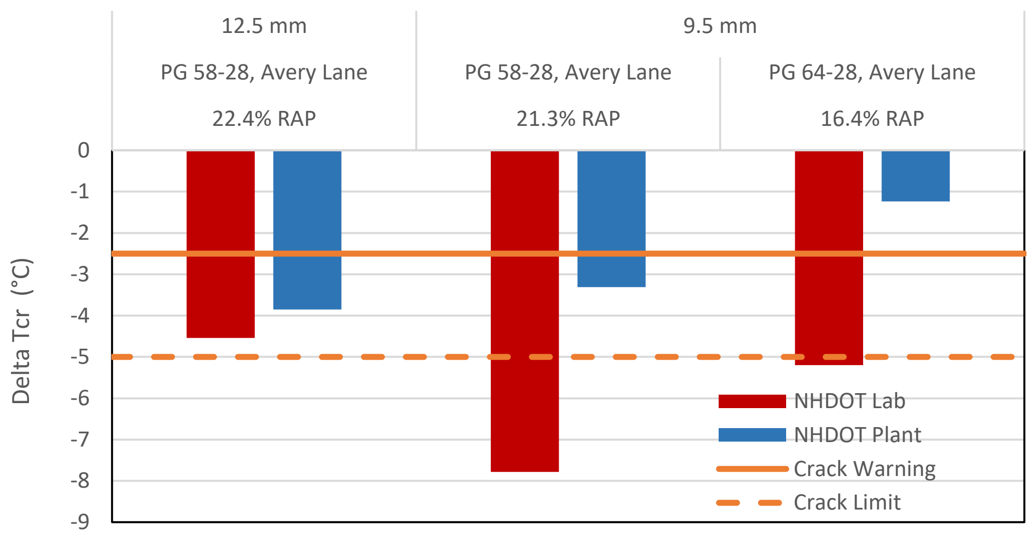


Figure 14- Delta Tcr for Hooksett Mixtures

3.1.2. Asphalt Binder Cracking Device (ABCD) Testing

Figure 15 compares the cracking temperature of extracted and recovered binders from plant and lab produced mixtures determined from the ABCD testing. The cracking temperatures of lab produced binders were warmer than plant produced mixtures. Generally, PG 52-34 binders had colder temperatures than the PG 58-28 binders, indicating better low temperature cracking resistance. The only exception was the McAsphalt binder, 12.5 mm, 18.9% RAP mixture where the PG 52-34 showed slightly warmer temperature than PG 58-28. The biggest difference between lab and plant produced mixtures was observed with this mixture as well.

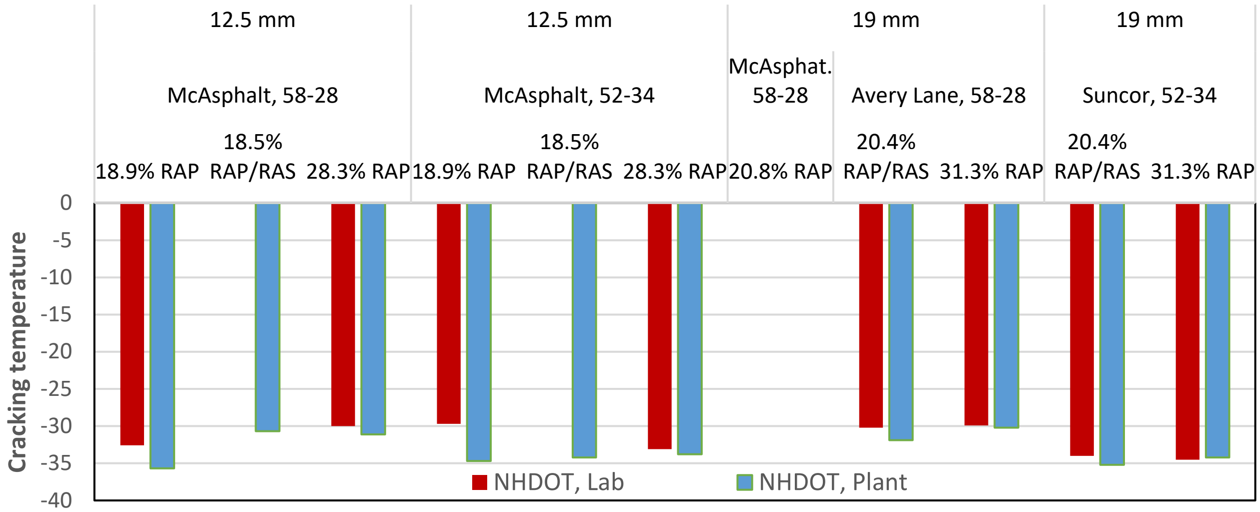


Figure 15- Cracking Temperature for Extracted and Recovered Lebanon Binders

Figure 16 shows the critical cracking temperature determined from ABCD testing plotted against the low temperature PG grade for all extracted and recovered binders. The results show that the critical temperature measured from ABCD was lower than the low temperature PG grade for all of these binders.

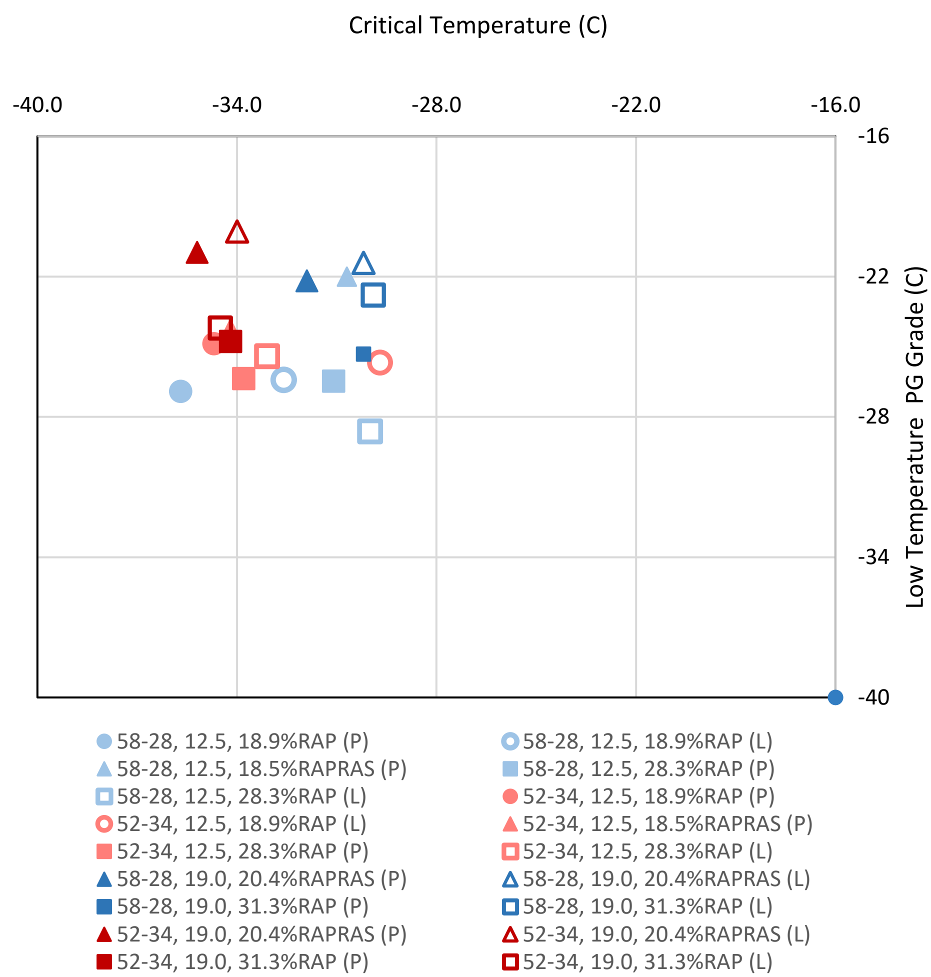


Figure 16- Critical Temperature versus Low Temperature PG Grade

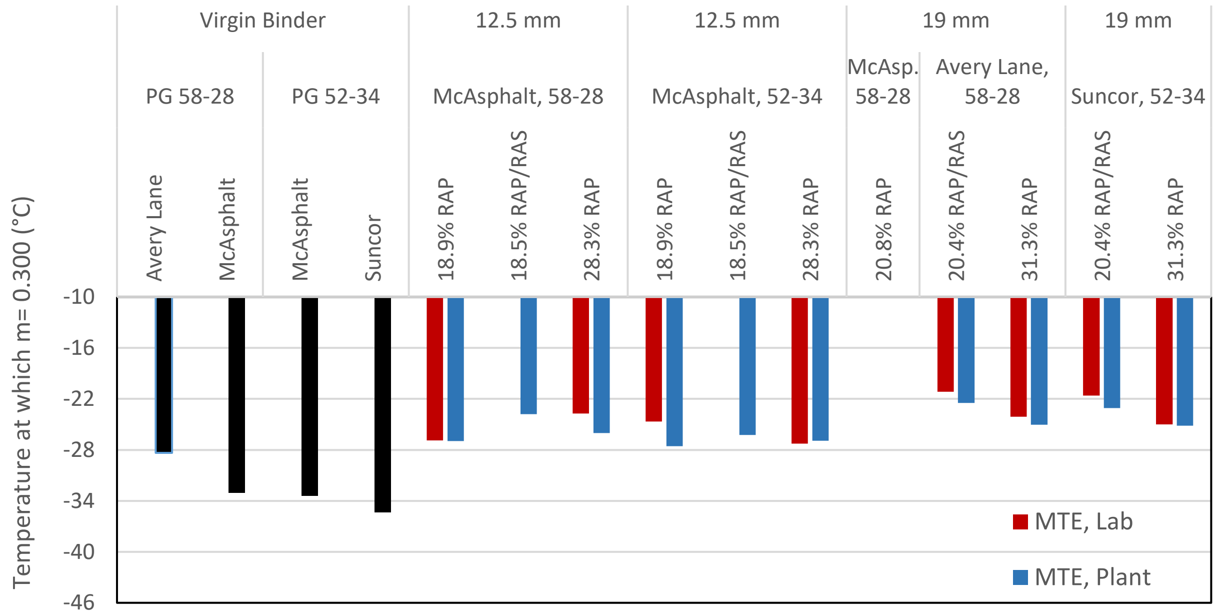
3.1.3. Lebanon 4mm DSR Testing

Extracted and recovered binders for most of the mixtures were sent to Mathy Construction (MTE) for testing using the 4mm DSR protocol. The materials and aging conditions evaluated are summarized in Table 4. The two McAsphalt binders (PG 58-28 and PG 52-34) were aged only through one 20 hr. PAV aging cycle due to lack of sufficient material on which to perform a second 20 hr. PAV aging. The Avery Lane PG 58-28 and Suncor PG 52-34 were aged and tested for two 20 hr. PAV aging cycles with 4 mm DSR evaluation after each PAV cycle. The testing results show there were elevated zinc levels in the Suncor PG 52-34 samples, indicating that Re-refined Engine Oil Bottoms (REOB) was likely used as a component in the manufacture of those binders.

Table 4- Properties of Different MTE Samples

Virgin Binder PG Grade	Binder Source	NMAS (mm)	%Total Asphalt (P_{be})	Plant	Lab	%Total Binder Replacement (% RAP/ % RAS)	20 hr PAV	40 hr PAV
58-28 (2013)	McAsphalt	12.5	5.3 (4.7)	✓	✓	18.9 (18.9/0)	✓	-
	McAsphalt	12.5	5.3 (4.7)	✓	-	18.5 (7.4/ 11.1)	✓	-
	McAsphalt	12.5	5.3 (5.0)	✓	✓	28.3 (28.3/ 0)	✓	-
	McAsphalt	19	4.7 (4.2)	-	-	20.8 (20.8/0)	✓	-
	AveryLane	19	4.8 (4.4)	✓	✓	20.4 (8.2/ 12.2)	✓	✓
	AveryLane	19	4.7 (4.4)	✓	✓	31.3 (31.3/ 0)	✓	✓
52-34 (2013)	McAsphalt	12.5	5.3 (4.7)	✓	✓	18.9 (18.9/0)	✓	-
	McAsphalt	12.5	5.3 (4.7)	✓	-	18.5 (7.4/ 11.1)	✓	-
	McAsphalt	12.5	5.3 (5.0)	✓	✓	28.3 (28.3/ 0)	✓	-
	Suncor	19	4.8 (4.4)	✓	✓	20.4 (8.2/ 12.2)	✓	✓
	Suncor	19	4.7 (4.4)	✓	✓	31.3 (31.3/ 0)	✓	✓

Figure 17 shows the critical temperatures at creep stiffness= 300 MPa and m value=0.300 obtained from 4 mm DSR testing for extracted and recovered binders at 20 hr PAV aging level. The results were very similar to the values obtained from BBR testing by NHDOT. The binders extracted and recovered from lab produced specimens had warmer low temperature (m-value). There is the same trend for RAP/RAS and 19 mm mixtures as compared to only RAP and 12.5 mm mixtures.



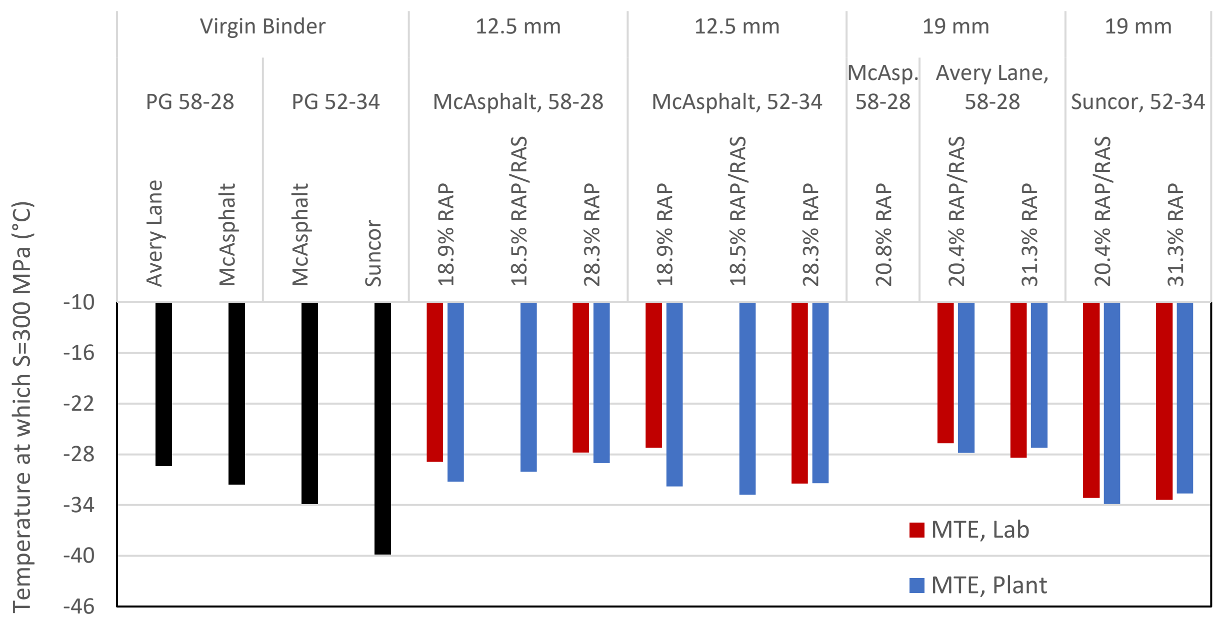


Figure 17- m and S values from 4 mm DSR testing (MTE) at 20 hr PAV

ΔTcr values at 20 hr PAV for different binders from MTE are shown in Figure 18. Generally, ΔTcr obtained from 4 mm DSR testing were larger than those measured by NHDOT using BBR testing (Figure 10), but the trend is similar. RAP/RAS mixtures had significantly higher ΔTcr than only RAP mixtures. Also, Suncor binder showed a higher ΔTcr than the other sources.

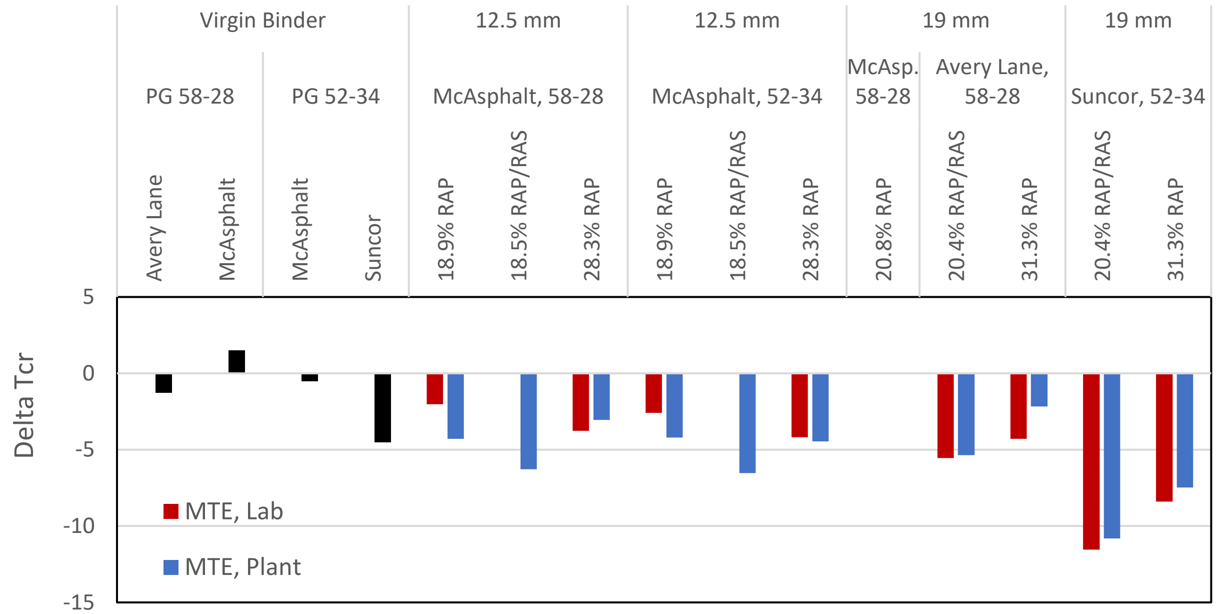


Figure 18- ΔTcr from 4 mm DSR testing (MTE), 20 hr. PAV

The complex modulus mastercurves for the virgin binders after 20 hr. and 40 hr. of PAV aging are shown in Figure 19. The two PG 58-28 binders were very similar and had higher G* than the two PG 52-34 binders, with the Suncor binder showing the softest mastercurve. The Avery Lane and Suncor binders were also subject to 40 hr. PAV aging. The complex modulus mastercurves for both of the binders after 40 hr. PAV were greater than 20 hr. PAV, indicating more stiffness after longer aging time.

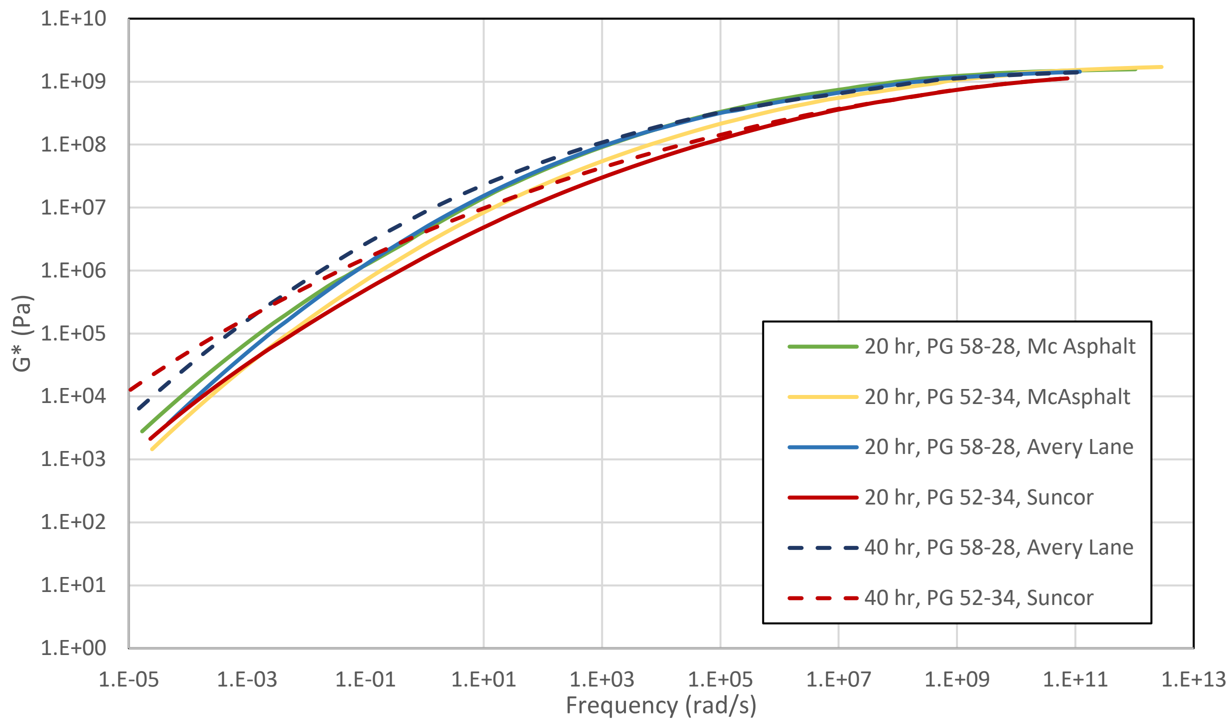


Figure 19- G* mastercurves of virgin binders (15° C reference temperature)

Figures 20 and 21 compare the G* mastercurves of binders extracted and recovered from 12.5 and 19 mm plant and lab produced mixtures, respectively. Direct comparison of G* mastercurves showed that the plant and lab produced mixtures had very close mastercurves. Generally, slightly higher G* values were observed for lab produced mixtures. Statistical analysis indicates that the only statistically significant difference was for the PG 58-28, 12.5 mm, 28.3% RAP mixture.

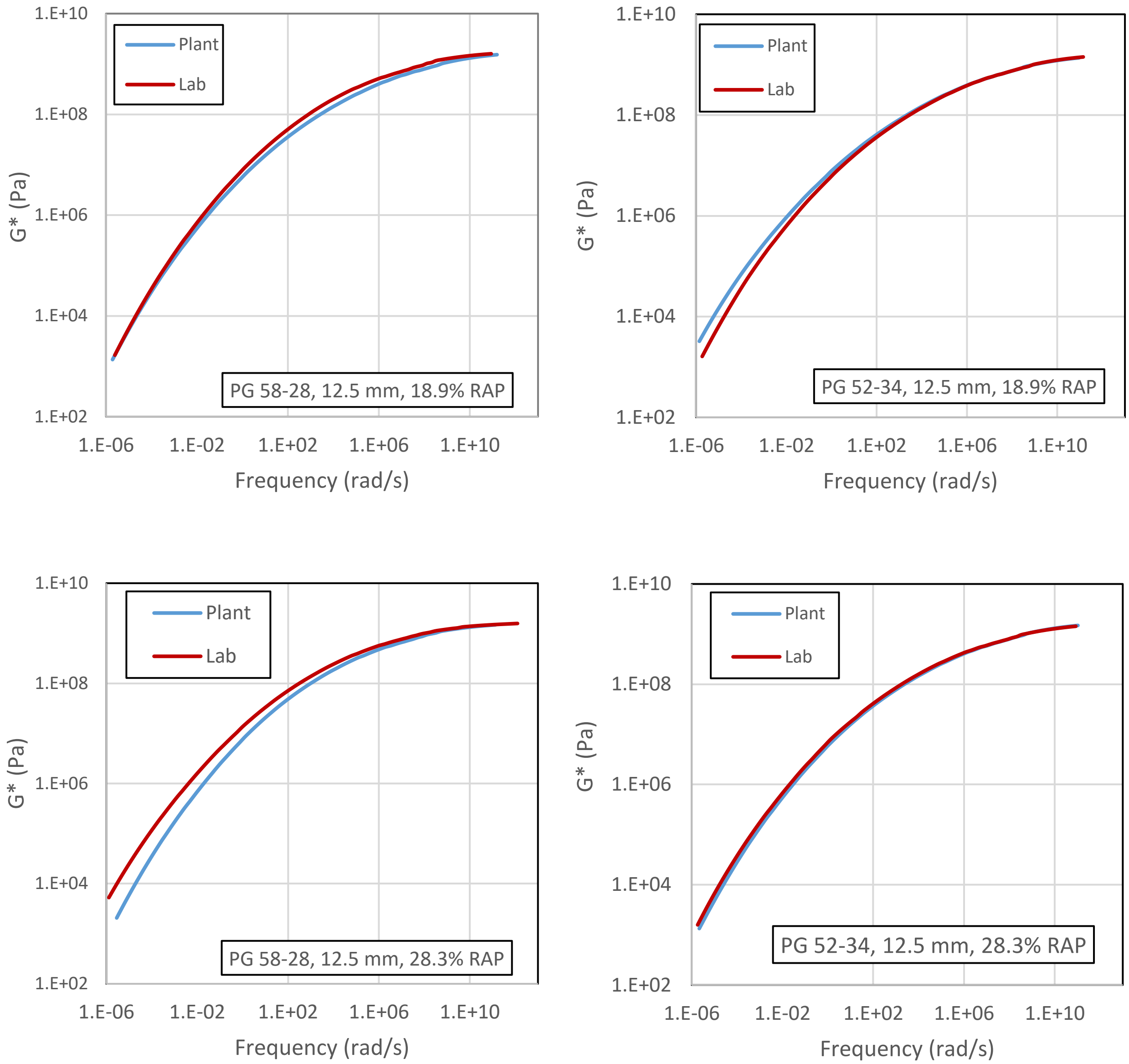


Figure 20- G* mastercurves of extracted and recovered binders from 12.5 mm mixtures (20hr PAV, 15° C reference temperature)

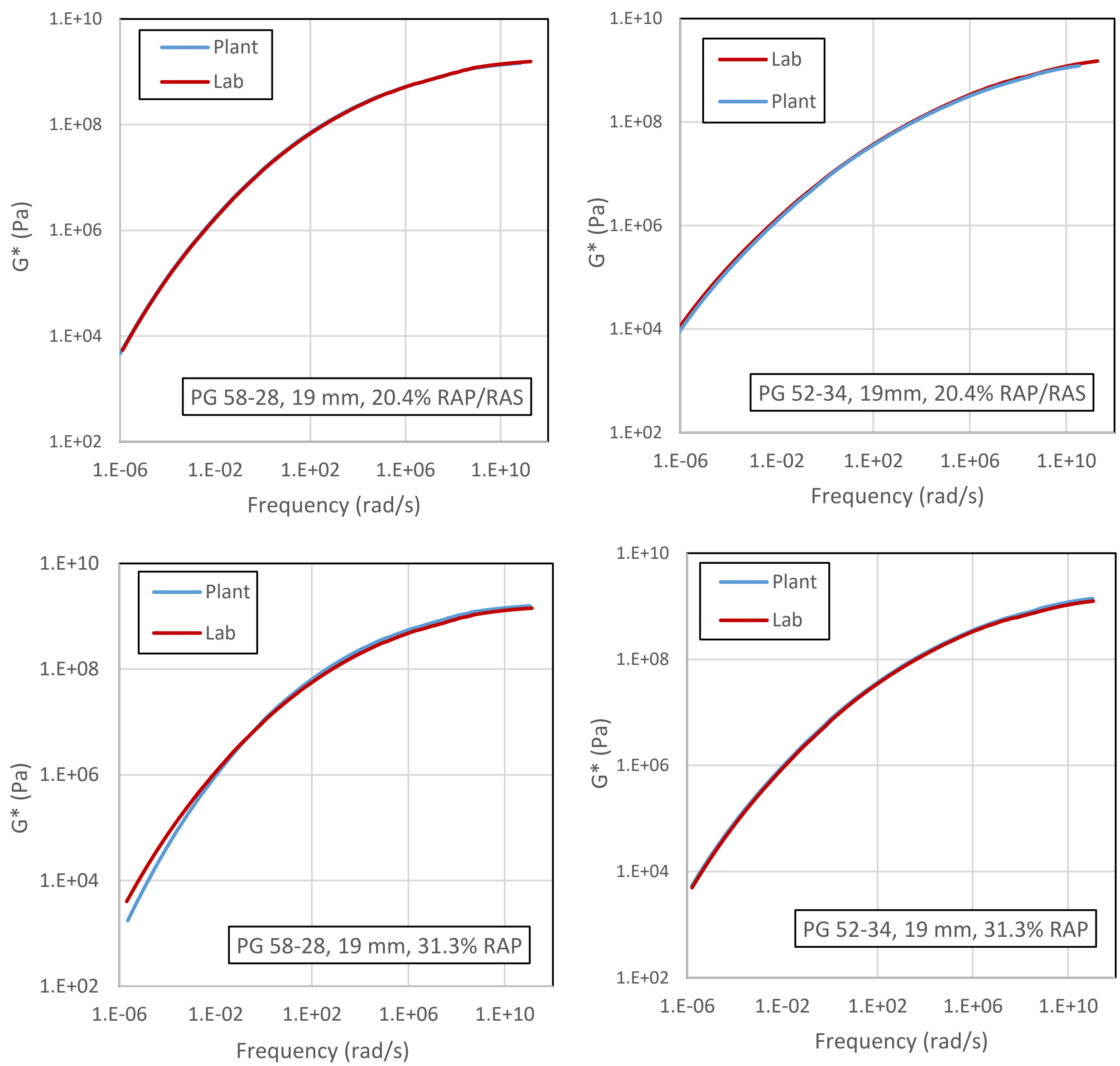
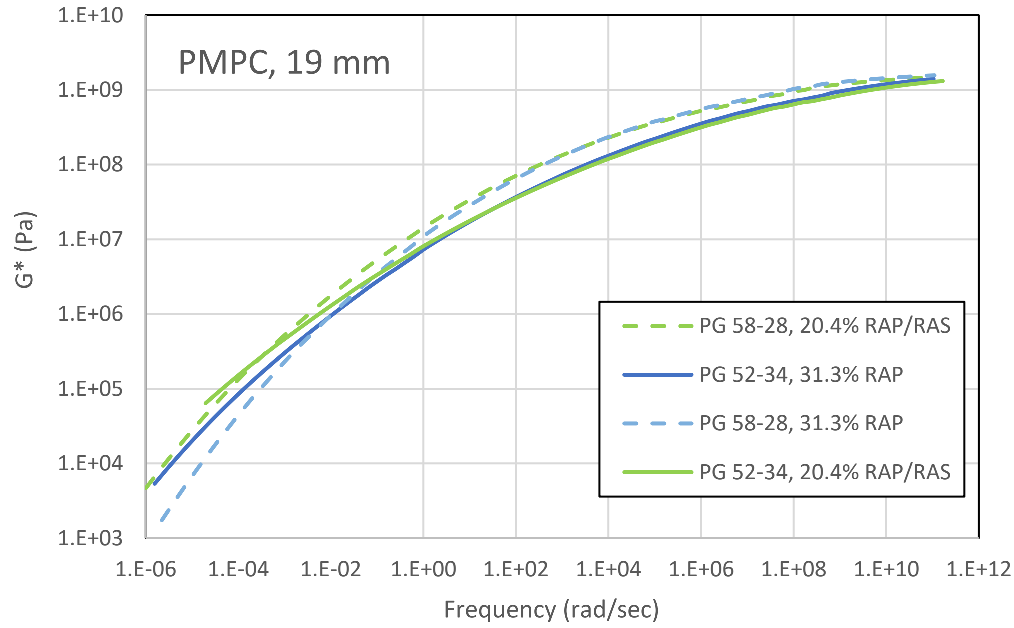


Figure 21- G* mastercurves of extracted and recovered binders from 19.0 mm mixtures (20hr PAV, 15° C reference temperature)

Figures 22 and 23 show the complex modulus mastercurves of binders extracted and recovered from plant produced and lab produced mixtures, respectively. The trend of 19 mm mixtures is the same for both plant and lab produced mixtures; PG 58-28 mixtures had higher complex modulus for higher frequencies, while PG 52-34 mixtures showed greater G* for the frequencies lower than 0.1 rad/sec. Also, 19 mm, 31.3% RAP and RAP/RAS mixtures had very similar G* in high frequencies, while in low frequencies RAP/RAS mixtures showed higher complex modulus.

For 12.5 mm mixtures, RAP/RAS plant produced mixtures were stiffer than the other mixtures. The 18.9% and 28.3% RAP mixtures did not follow a consistent trend for both plant and lab produced mixtures.



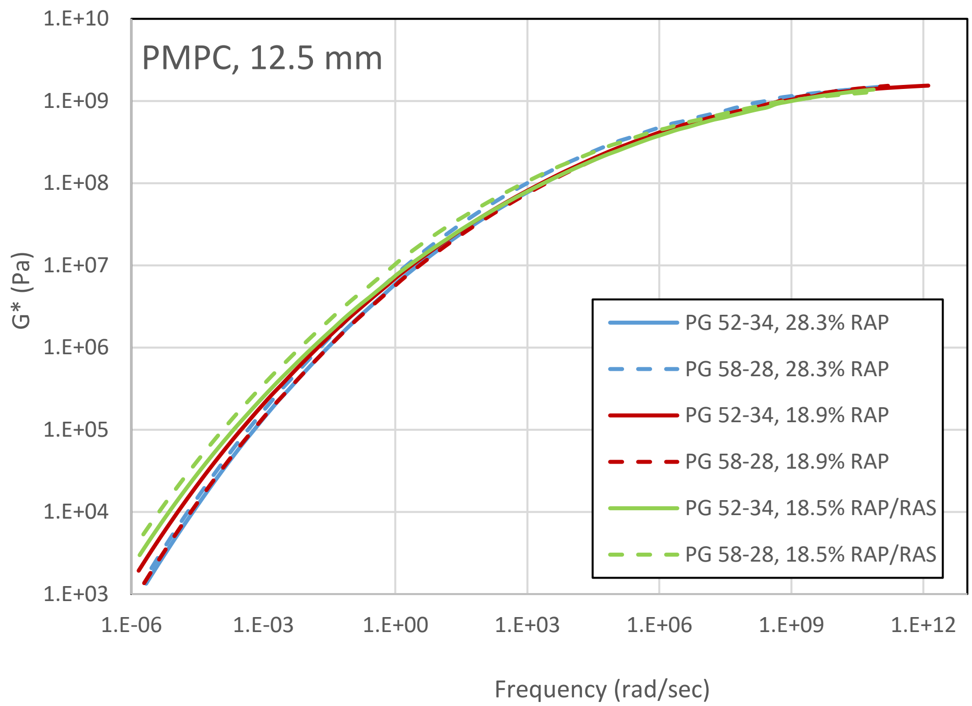


Figure 22- G* mastercurves of extracted and recovered binders from PMPC mixtures (20hr PAV, 15° C reference temperature)

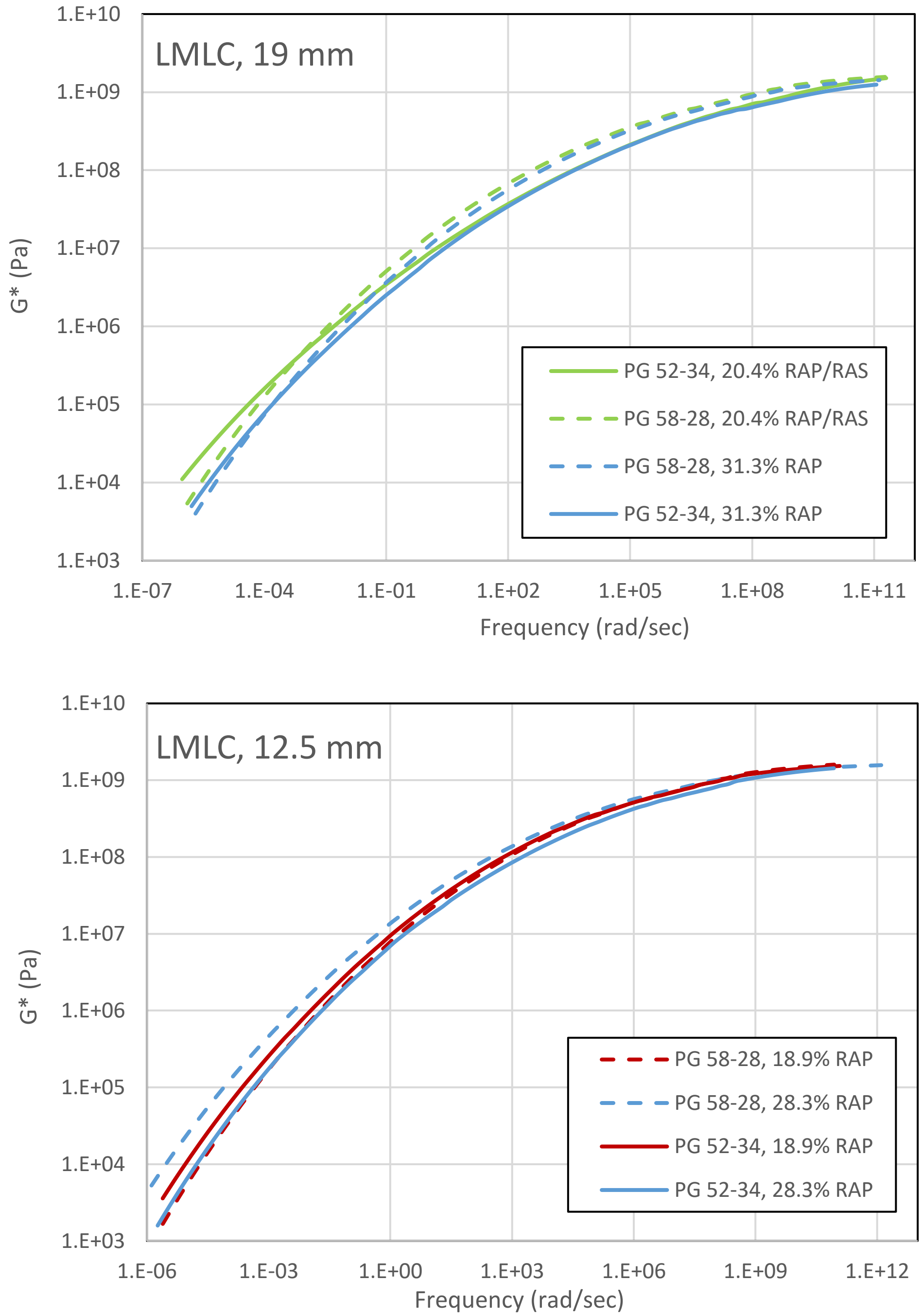


Figure 23- G* mastercurves of extracted and recovered binders from lab produced mixtures (20hr PAV, 15° C reference temperature)

Figure 24 shows the rheological index (R value) for different binders. R value is defined as the difference between the log of the glassy modulus and the log of the dynamic modulus at the crossover frequency. Generally, as the asphalt materials age, the R value increases. Among virgin binders, PG 52-34 binders had higher R value than PG 58-28 binders. Suncor binder showed the highest R value which translates to extracted and recovered binders from the mixtures produced with the Suncor binder. RAP/RAS mixtures had higher R value than the other mixtures. Figure 25 compares the R value of virgin binders after 20 and 40 hour PAV aging. In all of the cases, the R value increased as PAV aging increased from 20 to 40 hours.

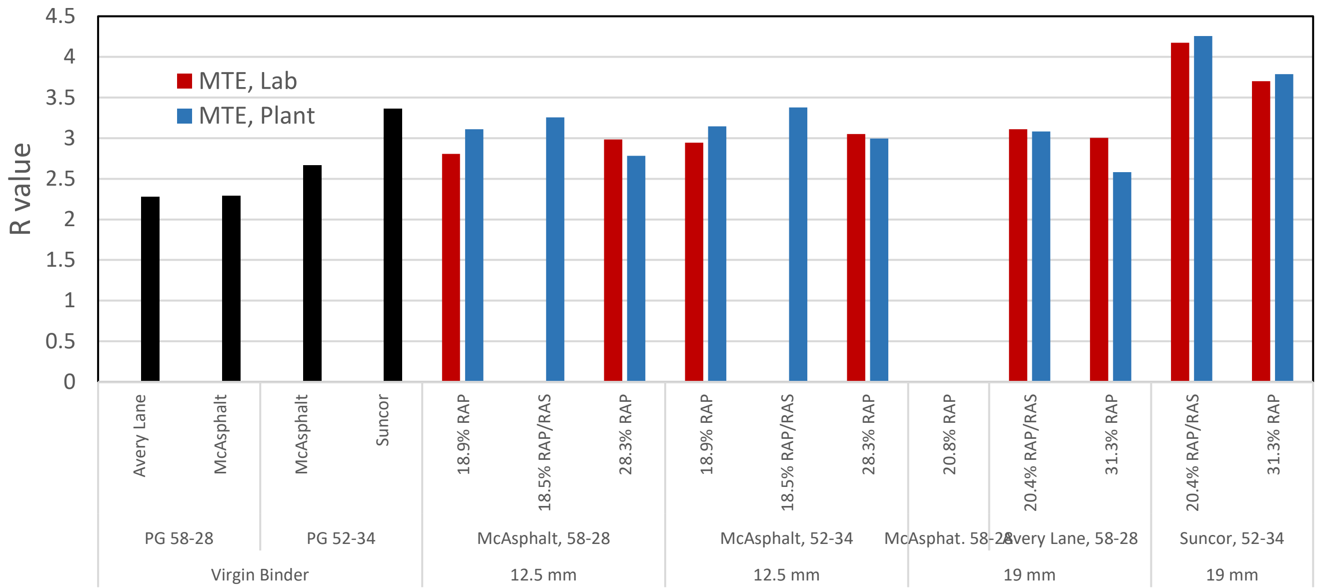


Figure 24- Rheological parameter (R-value) for different extracted and recovered binders

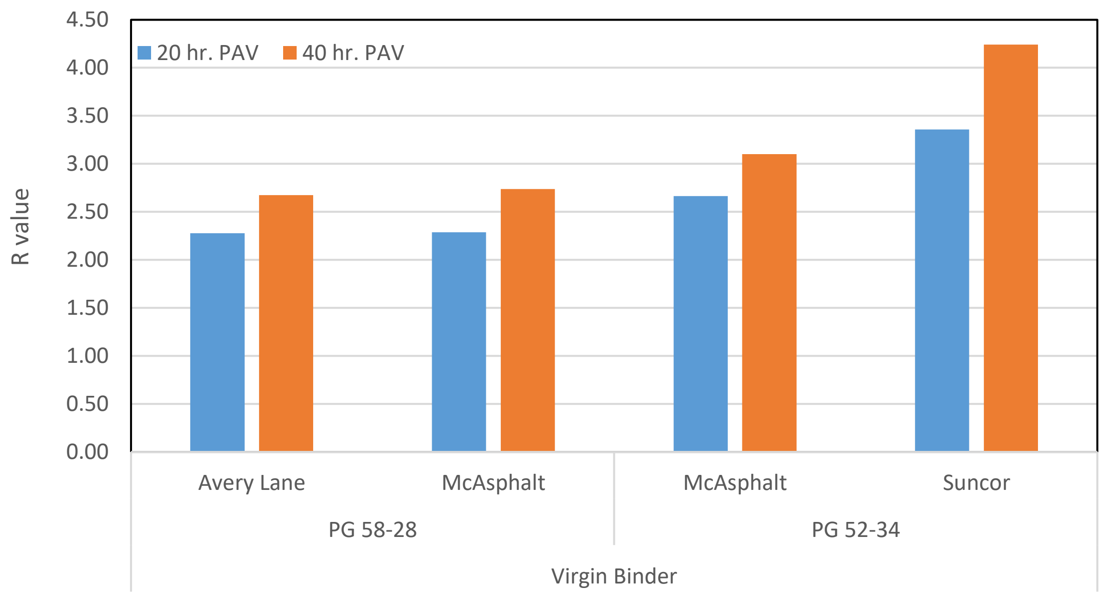


Figure 25- Rheological parameter (R-value) for virgin binders

Figure 26 shows the crossover frequency versus R value for different mixtures. Generally, materials that are further towards the lower right corner of the graph would be more likely to have cracking issues and the materials evaluated move that direction with aging, as expected.

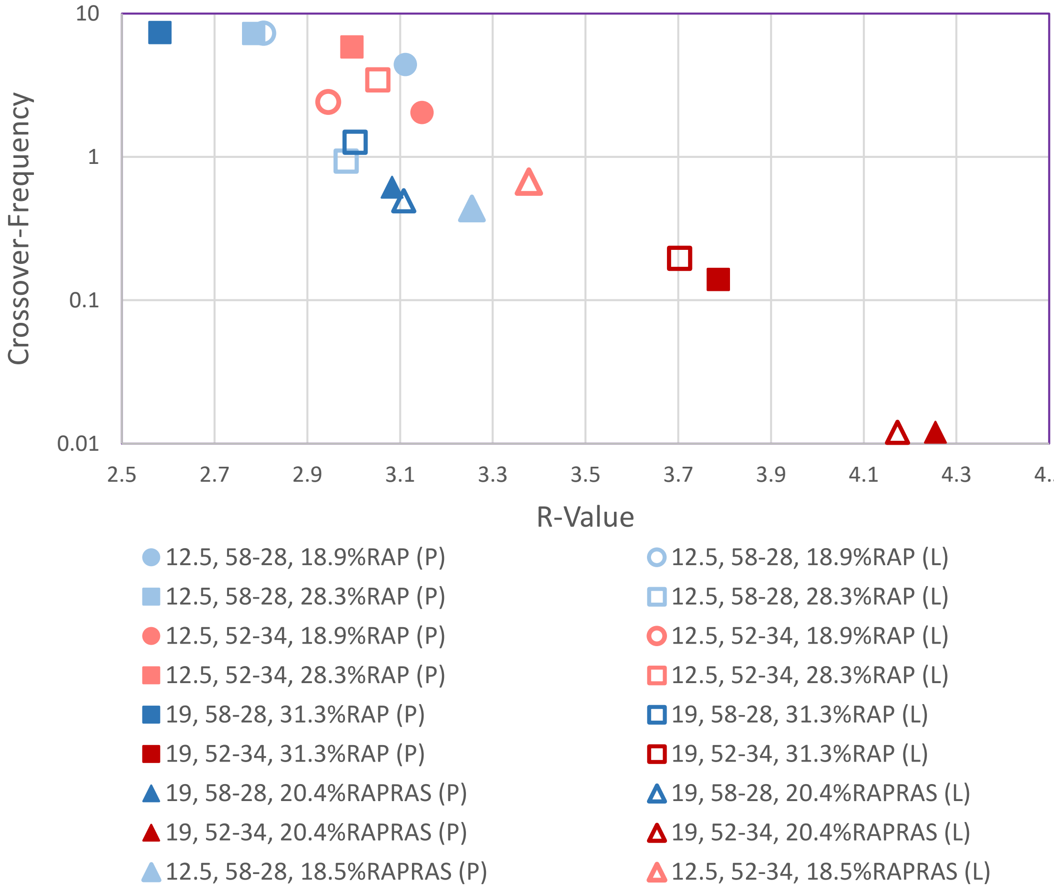


Figure 26- Crossover Frequency versus R-value for different mixtures

3.2. Mixture Results

3.2.1. Lebanon Mixtures

<u>Complex Modulus</u>

Direct comparisons of dynamic modulus mastercurves for plant and lab produced mixtures are shown in Figures 27 and 28. The results show that the lab produced mixtures generally had higher dynamic modulus curves than plant produced mixtures. The difference between LMLC and PMPC dynamic modulus mastercurves was greater for 19 mm mixtures and the PG 58-28 base binder mixtures. Larger differences with a PG 58-28 base binder mixture were also observed in the previous NHDOT High RAP project. However, the results of statistical analysis (T-test) for dynamic modulus and phase angle presented in Tables 5 and 6 show that there was not a significant difference between dynamic modulus and phase angle of plant and lab produced mixtures, except for the PG 58-28, 12.5 mm, 18.9% RAP mixture.

Figures 29 and 30 show the direct comparison of Black space diagrams for the PMPC and LMLC mixtures. The lab produced mixtures were generally stiffer and had lower phase angles than the plant produced mixtures. The combination of higher stiffness and lower phase angle indicates that these mixtures may be more susceptible to cracking.

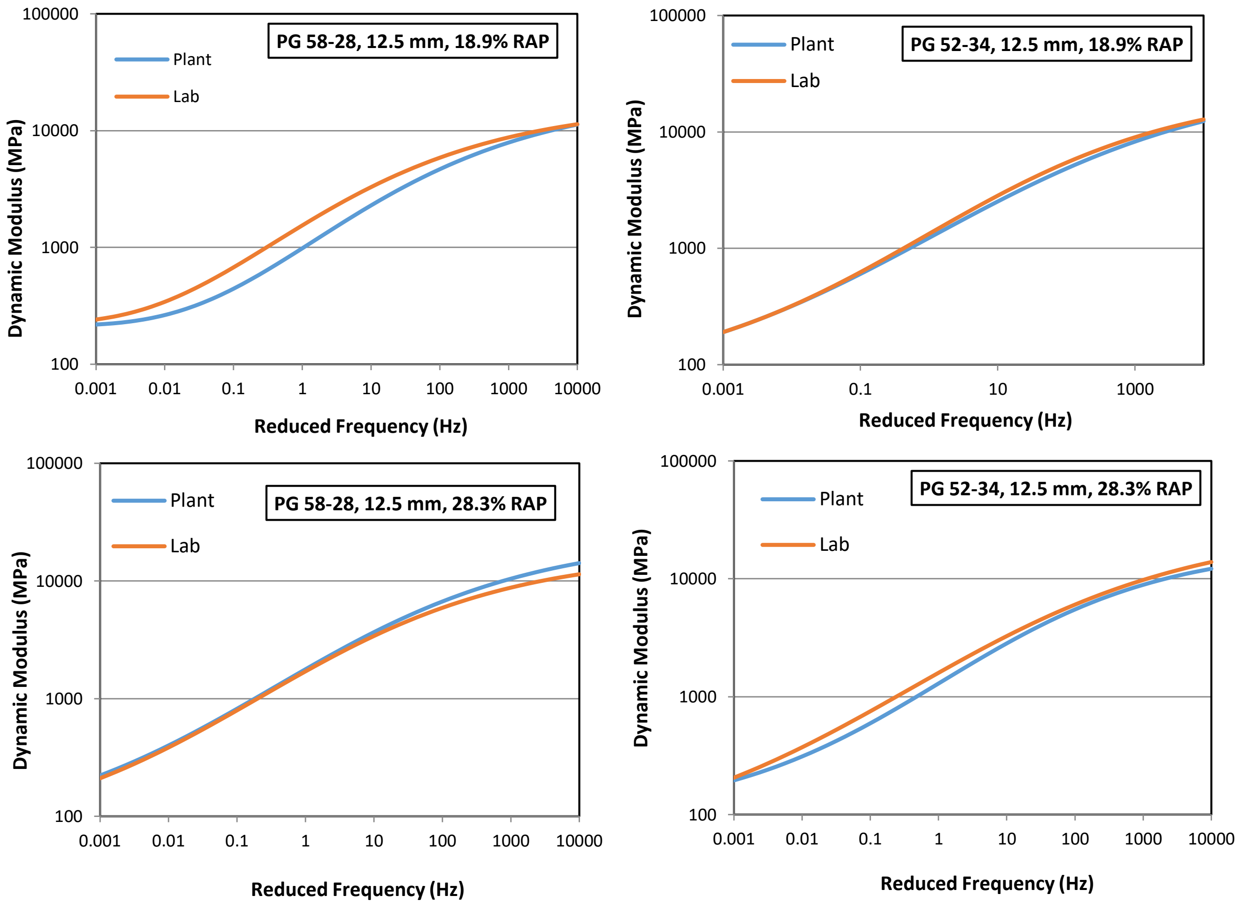


Figure 27- Dynamic Modulus Mastercurves for 12.5 mm, LMLC and PMPC Mixtures

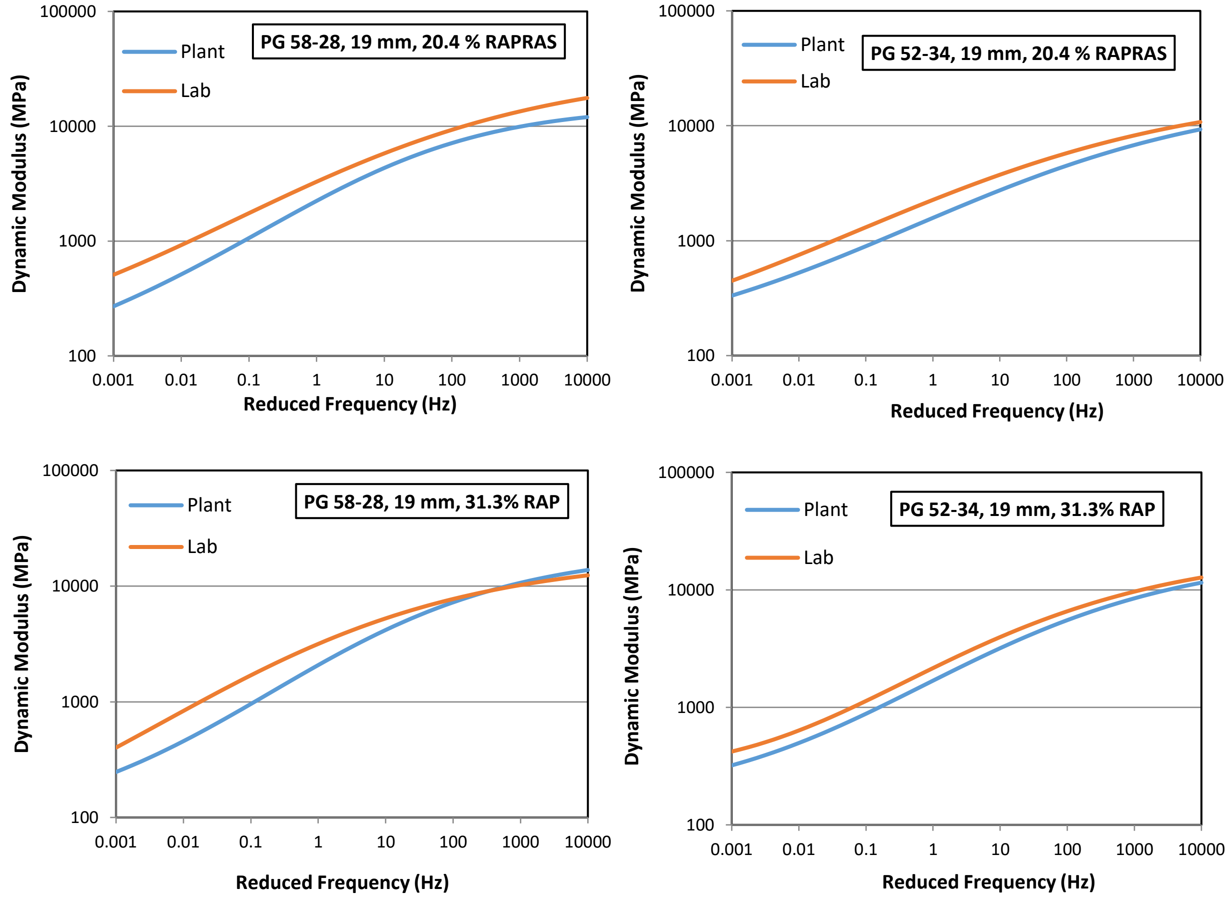


Figure 28- Dynamic Modulus Mastercurves for 19 mm, LMLC and PMPC Mixtures

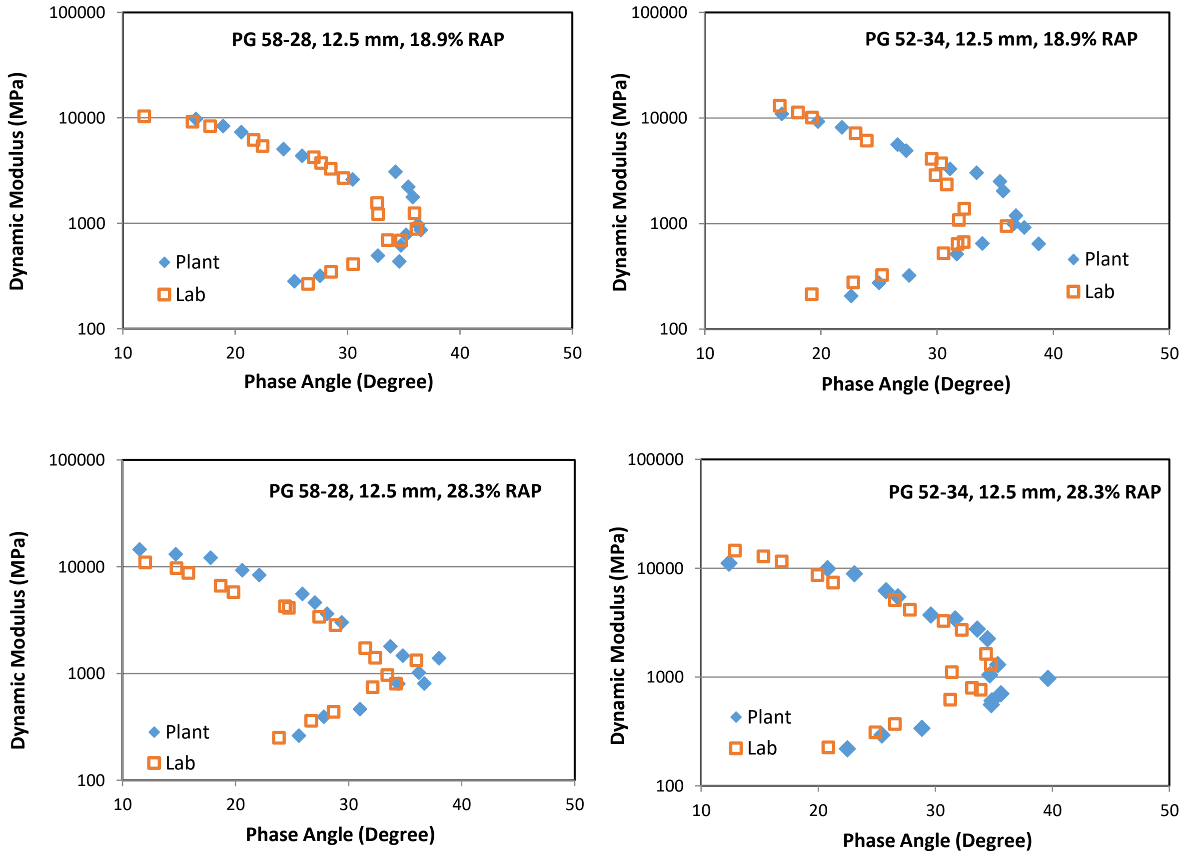


Figure 29- Black Space Diagrams of Different Plant and Lab Produced (12.5 mm) Mixture

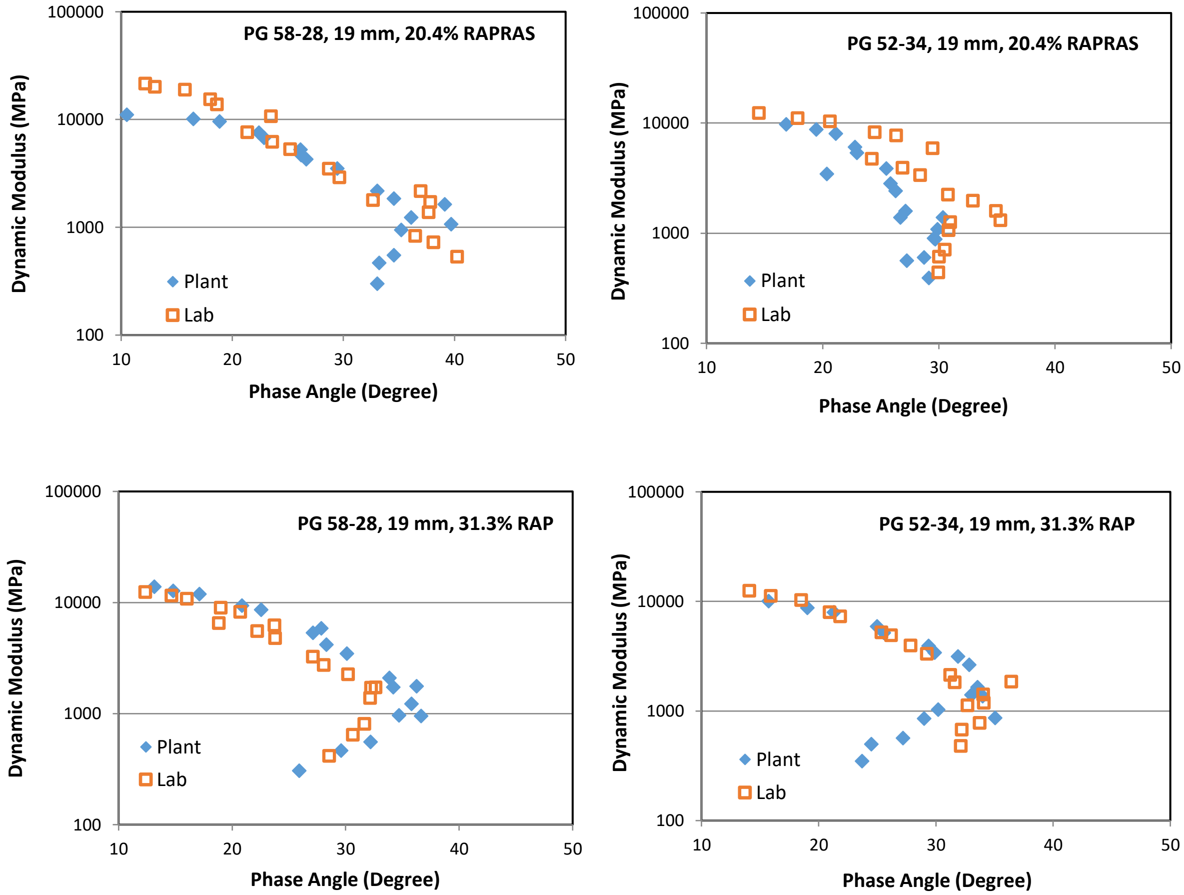


Figure 30- Black Space Diagrams of Different Plant and Lab Produced (19 mm) Mixture

Table 5- Statistical Analysis (T-Test) for Dynamic Modulus of Different Mixtures

	25 Hz	10 Hz	5 Hz	1 Hz	0.5 Hz	0.1 Hz
	PG 58-28, 12.5 mm, 18.9% RAP (Plant versus Lab)					
4.4° C	0.1140	0.0744	0.0542	0.0360	0.0336	0.0219
21.1° C	0.0788	0.0427	0.0434	0.0306	0.0341	0.0332
37.8° C	0.0506	0.0633	0.0780	0.1077	0.0934	0.2569
	PG 58-28, 12.5 mm, 28.3% RAP (Plant versus Lab)					
4.4° C	0.1686	0.1781	0.2019	0.1838	0.1476	0.1956
21.1° C	0.1314	0.2057	0.2971	0.5876	0.5904	0.9266
37.8° C	0.7699	0.7492	0.6946	0.7559	0.6824	0.8385
	PG 52-34, 12.5 mm, 18.9% RAP (Plant versus Lab)					
4.4° C	0.2701	0.1811	0.1745	0.1067	0.1092	0.0767
21.1° C	0.1523	0.1625	0.1603	0.1776	0.2505	0.9140
37.8° C	0.8205	0.7302	0.8375	0.9070	0.9186	0.7177
	PG 52-34, 12.5 mm, 28.3% RAP (Plant versus Lab)					
4.4° C	0.1048	0.1254	0.1274	0.1008	0.1023	0.0790
21.1° C	0.6370	0.3885	0.3514	0.2916	0.2766	0.2452
37.8° C	0.4255	0.4489	0.5556	0.6035	0.9775	0.7712
	PG 58-28, 19.0 mm, 20.4% RAP/RAS (Plant versus Lab)					
4.4° C	0.1784	0.1745	0.1788	0.1711	0.1681	0.1446
21.1° C	0.1843	0.1834	0.1683	0.1570	0.1733	0.1545
37.8° C	0.0339	0.0884	0.0566	0.0470	0.0716	0.1140
	PG 58-28, 19.0 mm, 31.3% RAP (Plant versus Lab)					
4.4° C	0.1395	0.1693	0.2314	0.1327	0.1187	0.0331
21.1° C	0.2080	0.1731	0.1380	0.1012	0.1001	0.0770
37.8° C	0.1513	0.1331	0.1103	0.0927	0.0907	0.0603
	PG 52-34, 19.0 mm, 20.4% RAP/RAS (Plant versus Lab)					
4.4° C	0.5835	0.5911	0.5759	0.4893	0.4589	0.4115
21.1° C	0.4146	0.4011	0.4041	0.4058	0.4174	0.4001
37.8° C	0.5603	0.5066	0.5111	0.5492	0.7238	0.6472
	PG 52-34, 19.0 mm, 31.3% RAP (Plant versus Lab)					
4.4° C	0.1375	0.1423	0.1256	0.0773	0.0598	0.0400
21.1° C	0.0613	0.0760	0.1453	0.1468	0.1397	0.1459
37.8° C	0.0754	0.1131	0.1382	0.1899	0.2334	0.2781

Table 6- Statistical Analysis (T-Test) for Phase Angle of Different Mixtures

	25 Hz	10 Hz	5 Hz	1 Hz	0.5 Hz	0.1 Hz
	PG 58-28, 12.5 mm, 18.9% RAP (Plant versus Lab)					
4.4° C	0.2879	0.0494	0.0866	0.0624	0.0151	0.1295
21.1° C	0.0219	0.0276	0.0542	0.0882	0.0913	0.0377
37.8° C	0.4226	0.1236	0.0575	0.0299	0.1235	0.1961
	PG 58-28, 12.5 mm, 28.3% RAP (Plant versus Lab)					
4.4° C	0.8845	0.8995	0.5700	0.5448	0.4685	0.7360
21.1° C	0.4226	0.5897	0.7842	0.3568	0.2361	0.1954
37.8° C	0.4226	0.0351	0.2667	0.0491	0.1946	0.0696
	PG 52-34, 12.5 mm, 18.9% RAP (Plant versus Lab)					
4.4° C	0.9656	0.4554	0.2932	0.1312	0.1877	0.1268
21.1° C	0.9038	0.2662	0.2750	0.2707	0.3178	0.4105
37.8° C	0.3206	0.0039	0.0927	0.1374	0.2347	0.0153
	PG 52-34, 12.5 mm, 28.3% RAP (Plant versus Lab)					
4.4° C	0.9714	0.1067	0.1069	0.1063	0.1114	0.1383
21.1° C	0.7324	0.3518	0.5361	0.7823	0.8853	0.6943
37.8° C	0.0586	0.1474	0.0760	0.2495	0.6321	0.3218
	PG 58-28, 19.0 mm, 20.4% RAP/RAS (Plant versus Lab)					
4.4° C	0.5026	0.1150	0.4223	0.4504	0.4712	0.5101
21.1° C	0.1837	0.3806	0.3455	0.3351	0.2627	0.2299
37.8° C	0.8020	0.8499	0.7790	0.8650	0.7234	0.7518
	PG 58-28, 19.0 mm, 31.3% RAP (Plant versus Lab)					
4.4° C	0.4738	0.3591	0.4522	0.4848	0.6812	0.5594
21.1° C	0.0020	0.1188	0.0448	0.0545	0.0805	0.0636
37.8° C	0.3024	0.0968	0.2922	0.4337	0.4548	0.4529
	PG 52-34, 19.0 mm, 20.4% RAP/RAS (Plant versus Lab)					
4.4° C	0.5905	0.3945	0.5661	0.7936	0.5887	0.5427
21.1° C	0.1407	0.3049	0.1967	0.0575	0.0632	0.0873
37.8° C	0.2804	0.6634	0.7221	0.6550	0.5019	0.8779
	PG 52-34, 19.0 mm, 31.3% RAP (Plant versus Lab)					
4.4° C	0.4283	0.3869	0.4009	0.2470	0.2412	0.2802
21.1° C	0.4073	0.1970	0.3672	0.4884	0.6821	0.6192
37.8° C	0.1994	0.3275	0.2453	0.2295	0.1857	0.1917

In this section, the average dynamic modulus curves for various mixtures are compared to evaluate the impact of recycled material content, PG grade, and NMSA. Generally, the results were as expected with higher dynamic modulus curves for stiffer binders, coarser aggregate structure, and higher recycled content. The average dynamic modulus mastercurves for the plant produced mixtures at different recycled contents are shown in Figure 31. Figure 32 shows the laboratory produced mixtures. Figures 33 and 34 compare directly the dynamic modulus mastercurves for the

12.5mm and 19mm plant produced mixtures with different binder PG grades. As expected, stiffness of the plant produced mixtures generally increased with increasing RAP content; the RAP/RAS mixtures did not show a consistent trend with respect to the RAP only mixtures. The 19 mm mixtures were generally stiffer than the 12.5 mm mixtures and the PG 58-28 base binder mixtures had higher dynamic modulus values than the mixtures with the PG 52-34 base binder, with greater differences observed for the 19 mm mixtures. Similar trends were observed for the lab produced mixtures in Figure 32.

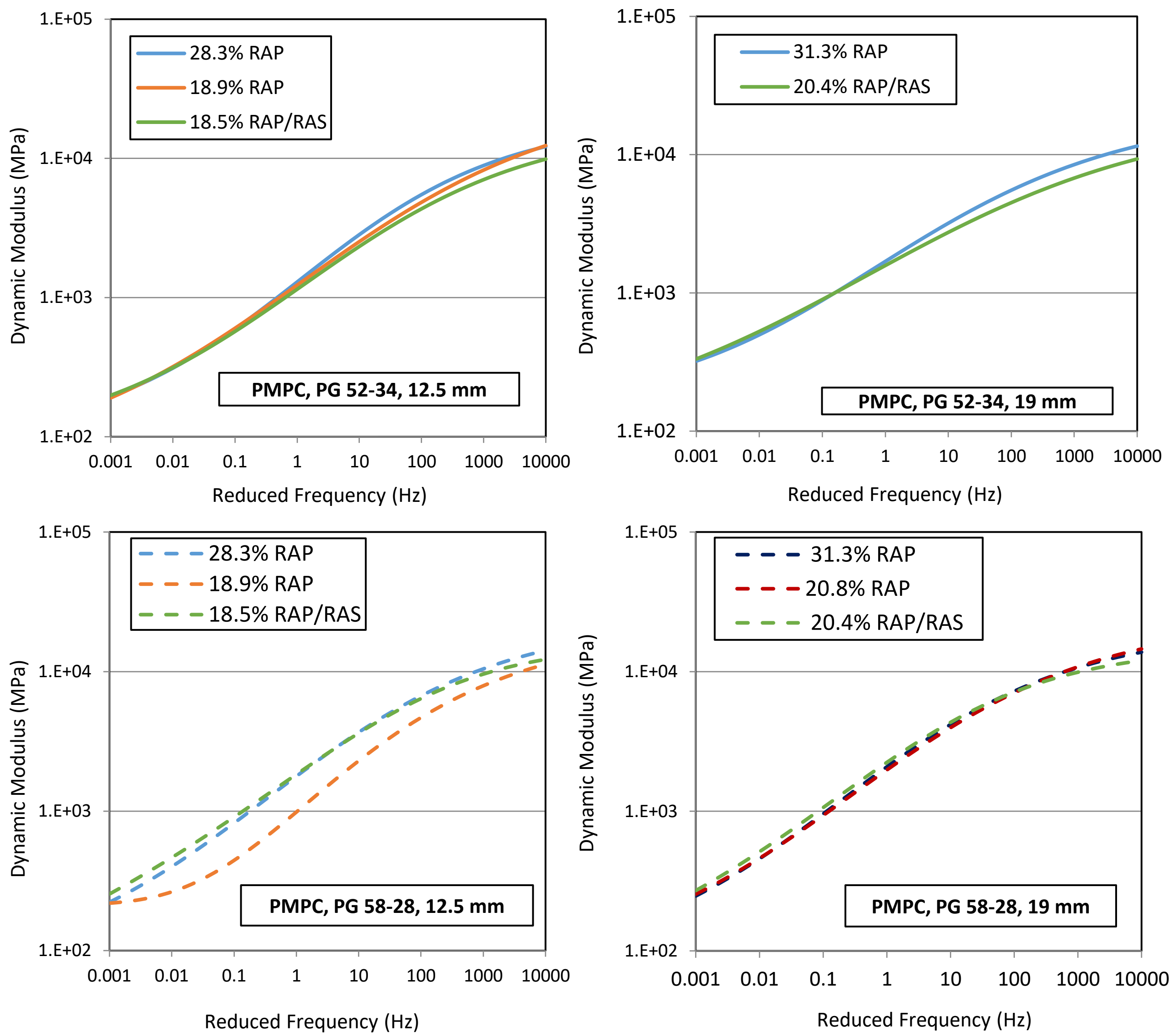


Figure 31- Dynamic Modulus Mastercurves of PMPC mixtures

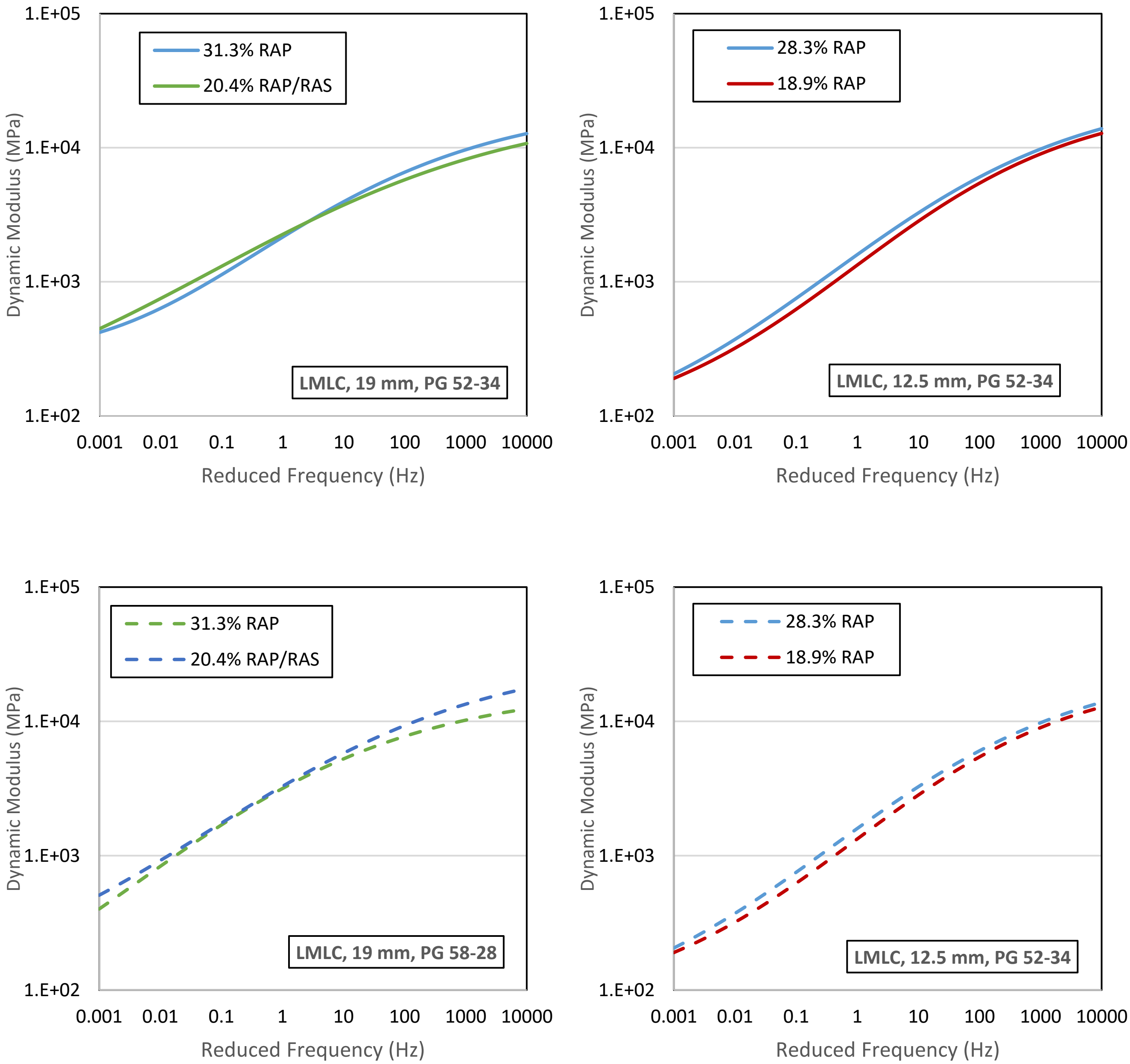
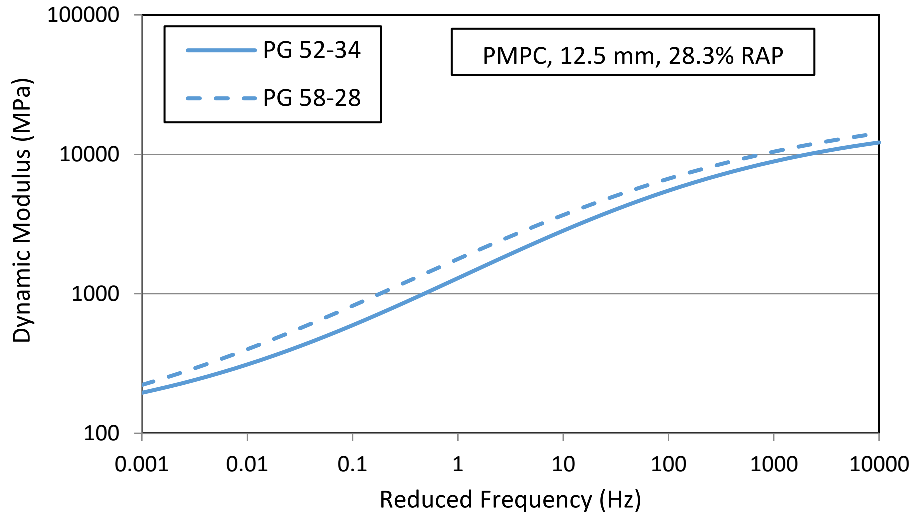
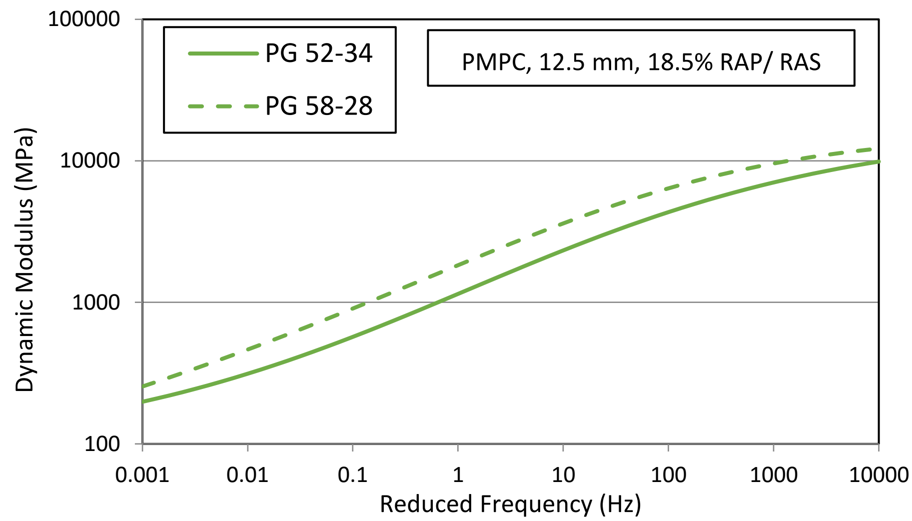


Figure 32- Dynamic Modulus Mastercurves of LMLC mixtures





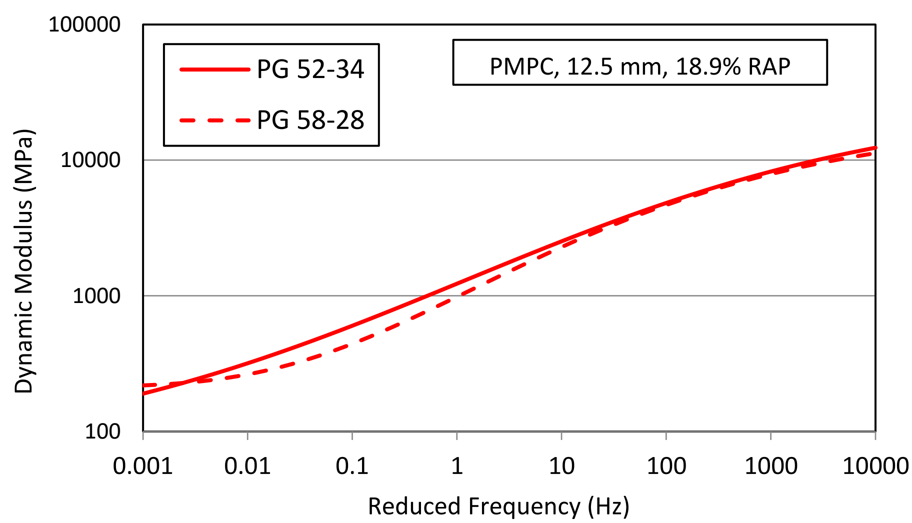
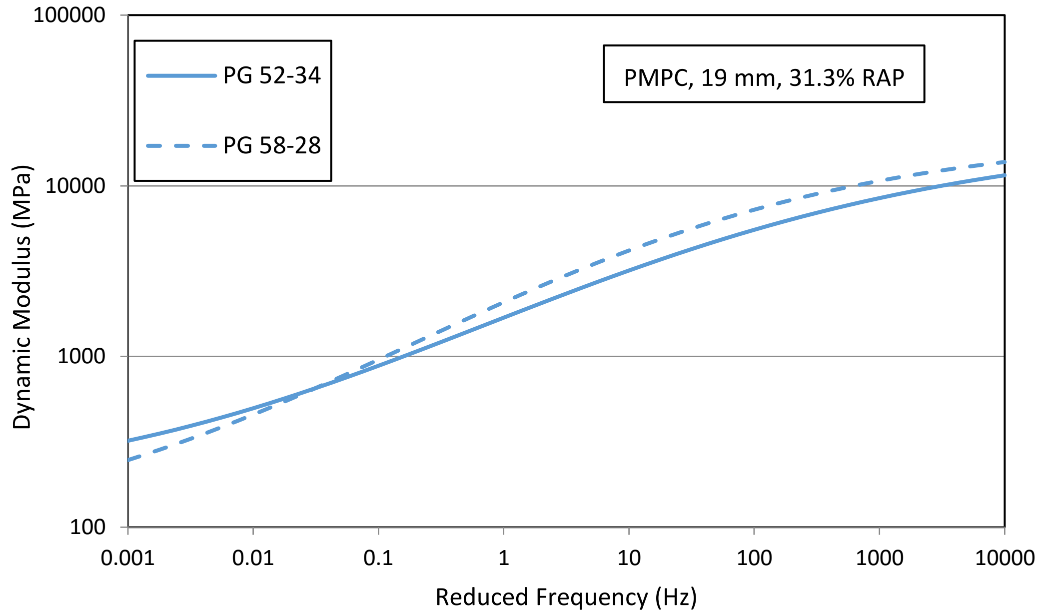


Figure 33- Comparison of Dynamic Modulus Mastercurves (12.5 mm Mixtures)



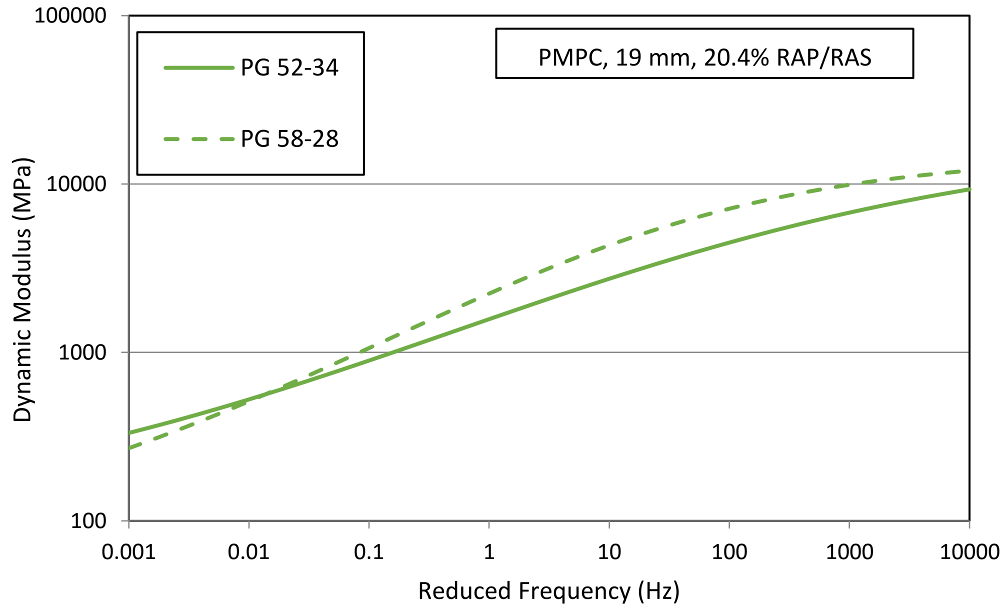


Figure 34- Comparison of Dynamic Modulus Mastercurves (19.0 mm Mixtures)

To capture the stiffness and relaxation capability of mixtures in one plot, the Black space diagrams are shown in Figures 35 and 36 for 12.5 and 19 mm mixtures, respectively. Generally, the PG 52-34 base binder mixtures had similar or lower phase angles than the PG 58-28 base binder mixtures, which was not expected but has been observed with other NH mixtures (NHDOT 15680B Phase

II Final Report). The phase angles generally decreased with increasing RAP content, and the RAP/RAS mixtures had the lowest phase angles. The phase angles were similar across the different gradations.

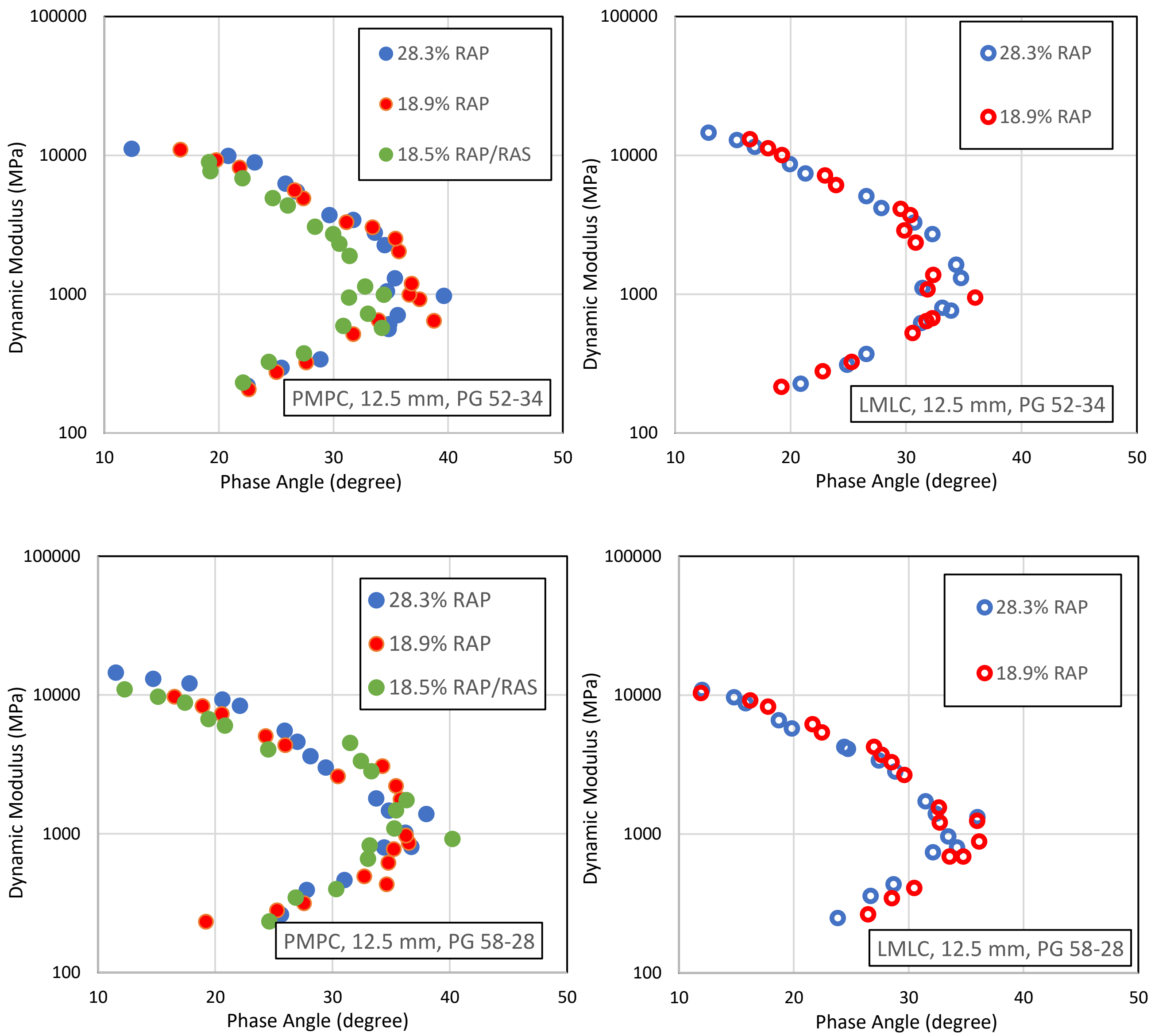


Figure 35- Black Space Diagrams of 12.5 mm Mixtures

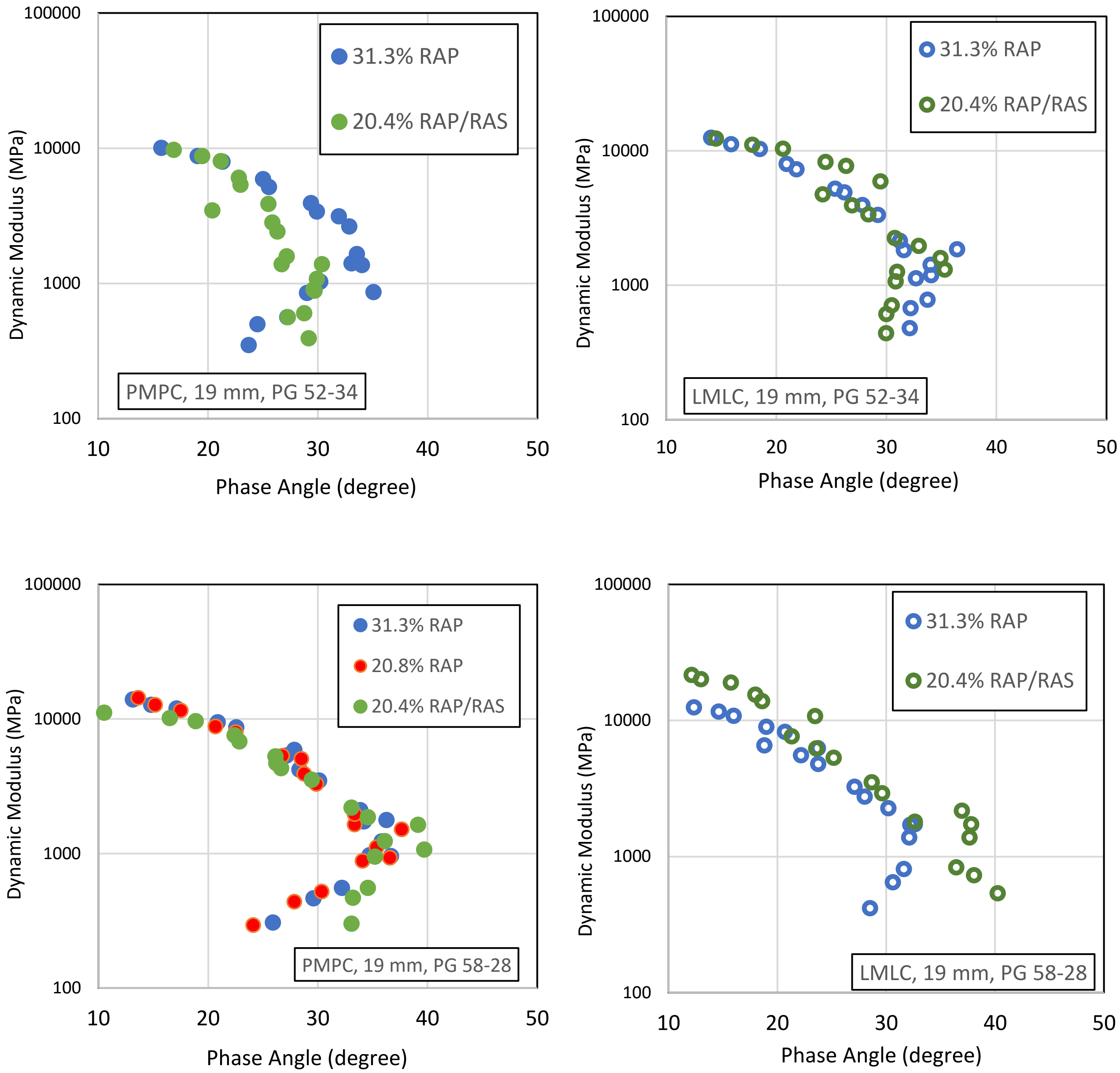


Figure 36- Black Space Diagrams of 19 mm Mixtures

<u>SVECD Fatigue Testing</u>

The results of uniaxial fatigue testing are presented in this section. Figures 37 and 38 compare the damage characteristic curves (C vs S) for the different plant and lab produced mixtures for 12.5 and 19.0 mm NMSA, respectively. Generally, this curve shows how the material integrity decreases as damage is growing. The mixtures that have damage characteristic curves further up and to the right would be expected to perform better, since they are able to maintain their integrity better during fatigue loading (higher pseudo stiffness, C, with same amount of damage, S). However, the cracking performance of a mixture in the field depends on pavement structure as well and it is the combination of the rheological properties (modulus and phase angle) and damage characteristics that will determine how a mixture will perform in a particular pavement structure.

The damage characteristic curves of lab produced mixtures were very close to, or higher than the plant produced mixtures for all 12.5 mm mixtures, while most of the 19 mm lab produced mixtures showed slightly lower fatigue curves than plant produced mixtures.

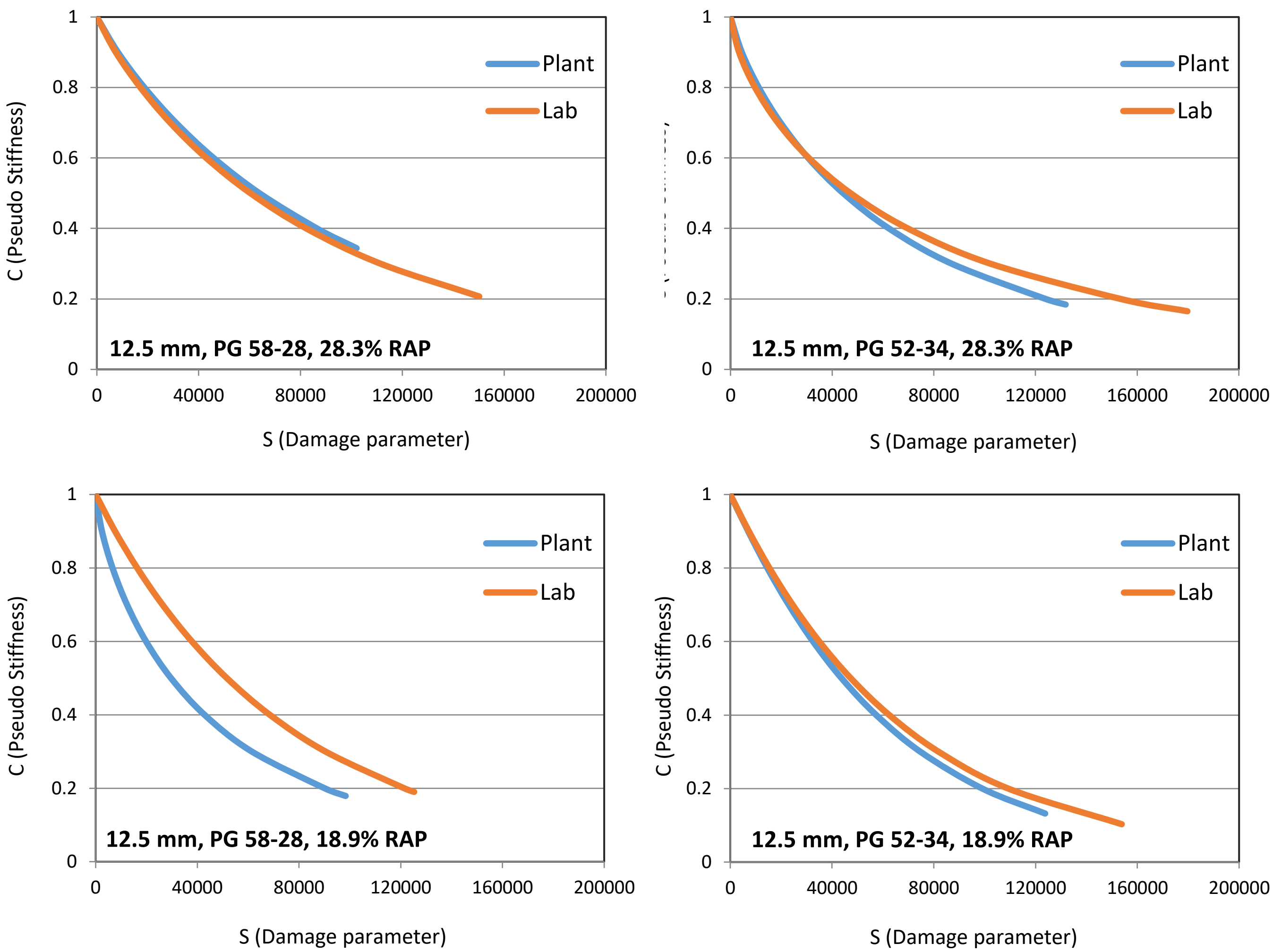


Figure 37- Damage Characteristic Curves for 12.5 mm, LMLC and PMPC Mixtures

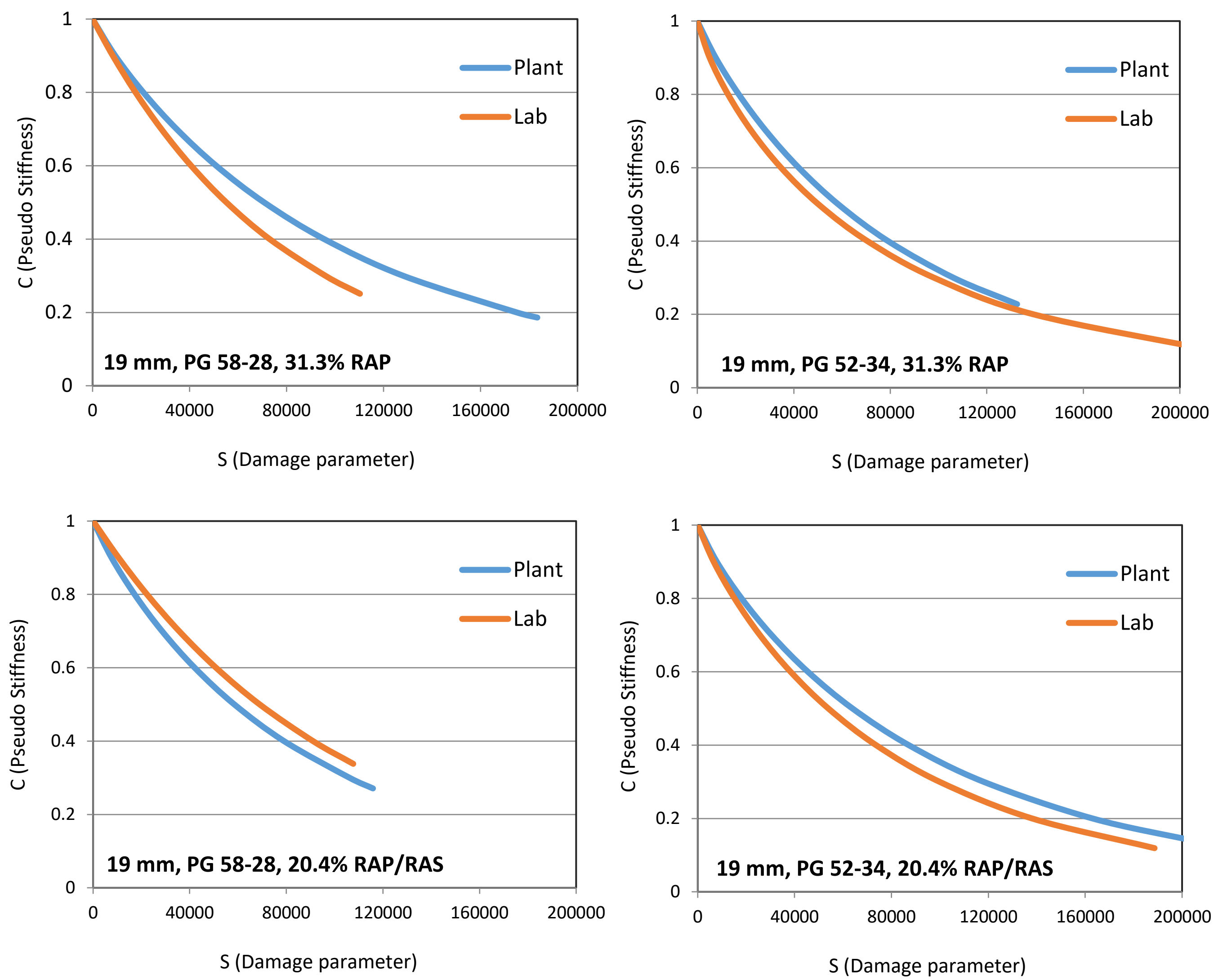


Figure 38- Damage Characteristic Curves for 19 mm, LMLC and PMPC Mixtures

Figures 39 and 40 show the damage characteristics curves of different PMPC and LMLC mixtures, respectively. One interesting point is that there is not much difference between the damage characteristic curves of 19 mm mixtures, while 12.5 mm mixtures show a larger distinction between mixtures. The 18.9% RAP mixtures showed a rapid decrease in material integrity compared to 28.3% RAP and 18.5% RAP/RAS mixtures. The rank order of 18.5% RAP/RAS, 28.3% RAP, and 18.9% RAP was the same for most 12.5 mm mixtures, but it is not always true for 19 mm mixtures. The 31.3% and 20.4% RAP/RAS curves of 19 mm mixtures were too close to each other to be distinguished.

In all of the cases, mixtures with stiffer binder of PG 58-28 showed higher C-S curves than the mixtures with PG 52-34 binder, except for the PMPC, 12.5 mm, 18.9% RAP mixture. The much lower dynamic modulus mastercurve for the PG 58-28 mixture might have affected this mixture. In most cases, the last point of the C-S curve (indicates pseudo stiffness value at failure (C_F)) increased with higher percentage of RAP. This point has been suggested by Hou, et al. (2010) as an indicator value and similar trends with respect to RAP content were observed in another study conducted at North Carolina State University (Norouzi et al. 2014). In this study, the C_F values of 31.3% (28.3%) RAP mixes were higher than those of 20.8% (18.9%) RAP and shows that the more brittle mixtures fail at a higher integrity. C_F values of RAP/RAS mixtures were very close to 31.3% (28.3%) RAP mixtures.

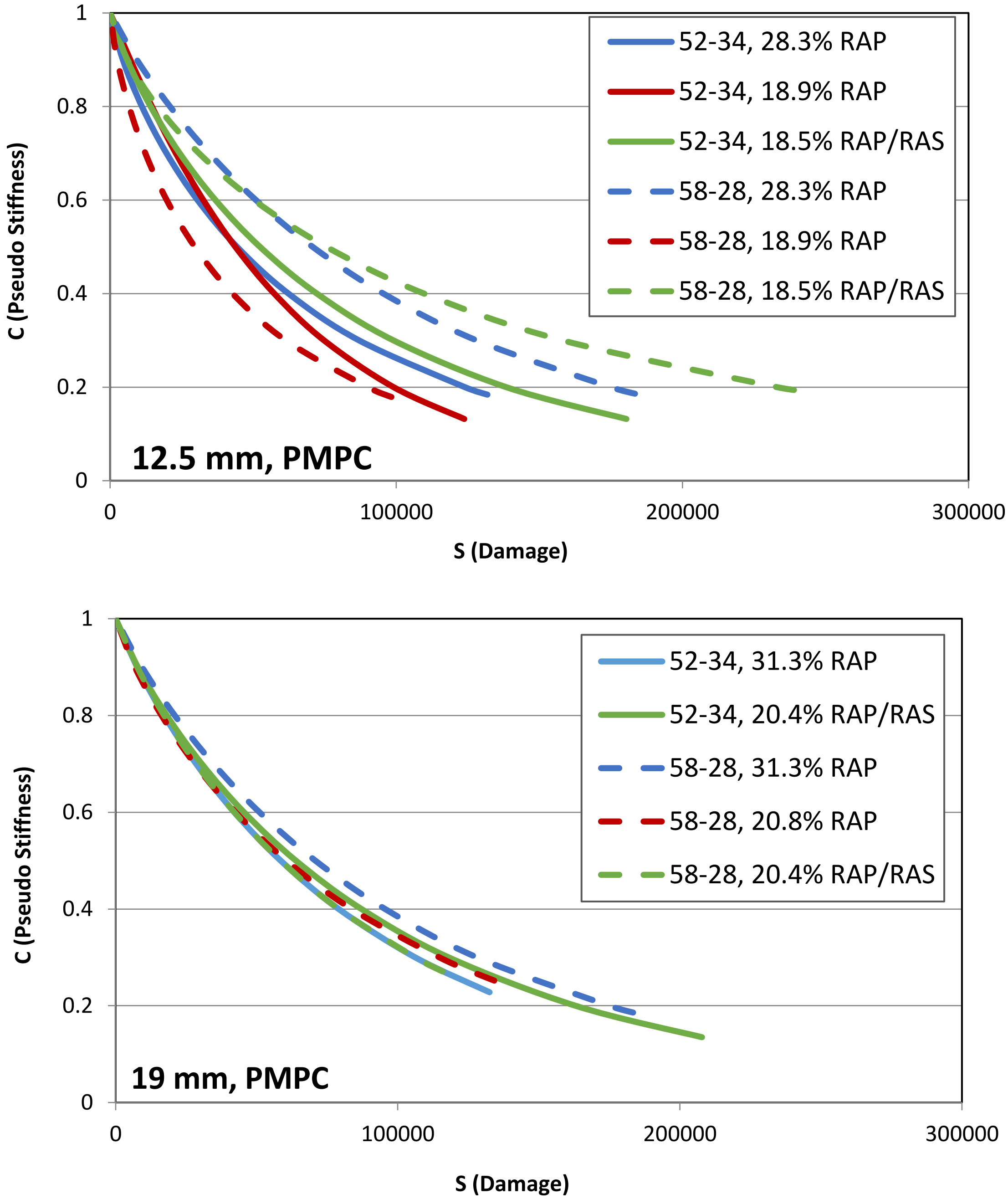
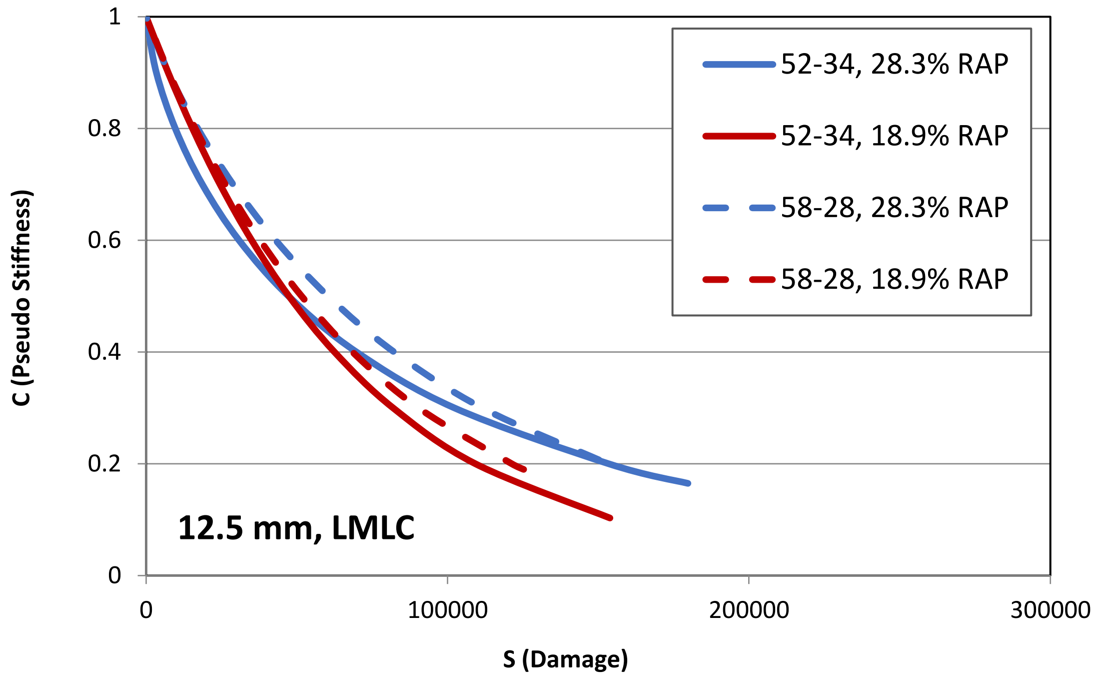


Figure 39- Damage Characteristics Curve for PMPC Mixtures



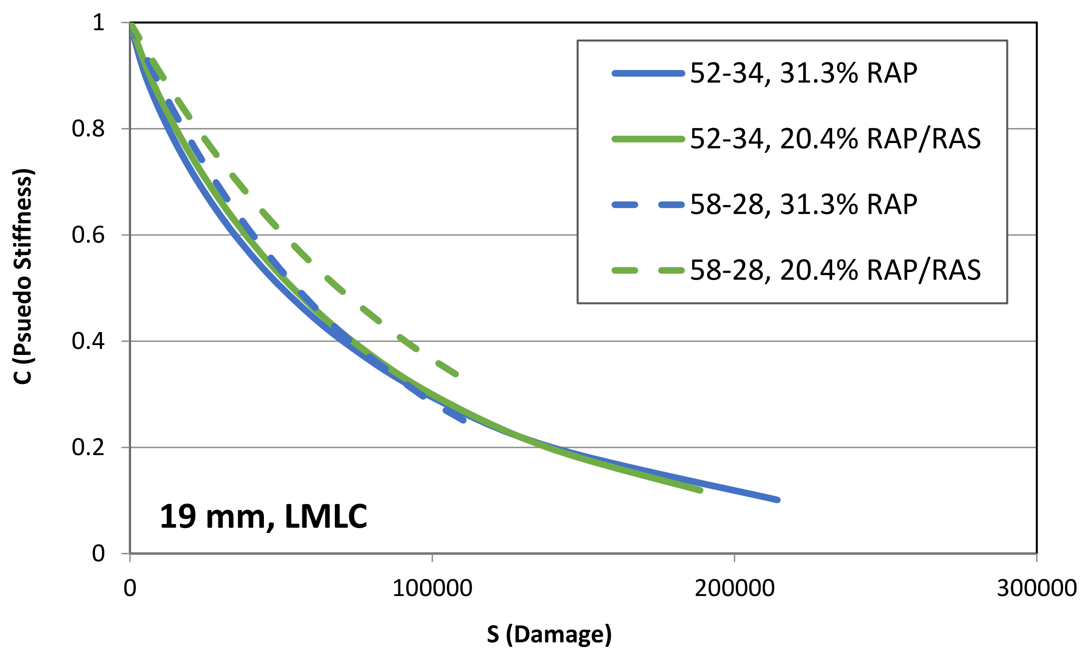


Figure 40- Damage Characteristics Curve for LMLC Mixtures

Figures 41 and 42 compare directly the G^R- N_f diagrams from plant and lab produced mixtures. Generally, lines that are further up and to the right would indicate better fatigue performance, but again, actual field performance will be determined by the combination of rheological and fatigue properties of the mixture and location of the material in the pavement structure in the field. The general trends indicate that the difference between plant and lab produced PG 52-34 mixtures was negligible, while a larger distinction was observed for the PG 58-28 mixtures. Also, in most cases (except 19 mm RAP/RAS mixes), plant produced mixtures showed slightly better fatigue behavior than lab produced mixes, but it may not be a significant difference because of scatter in fatigue data.

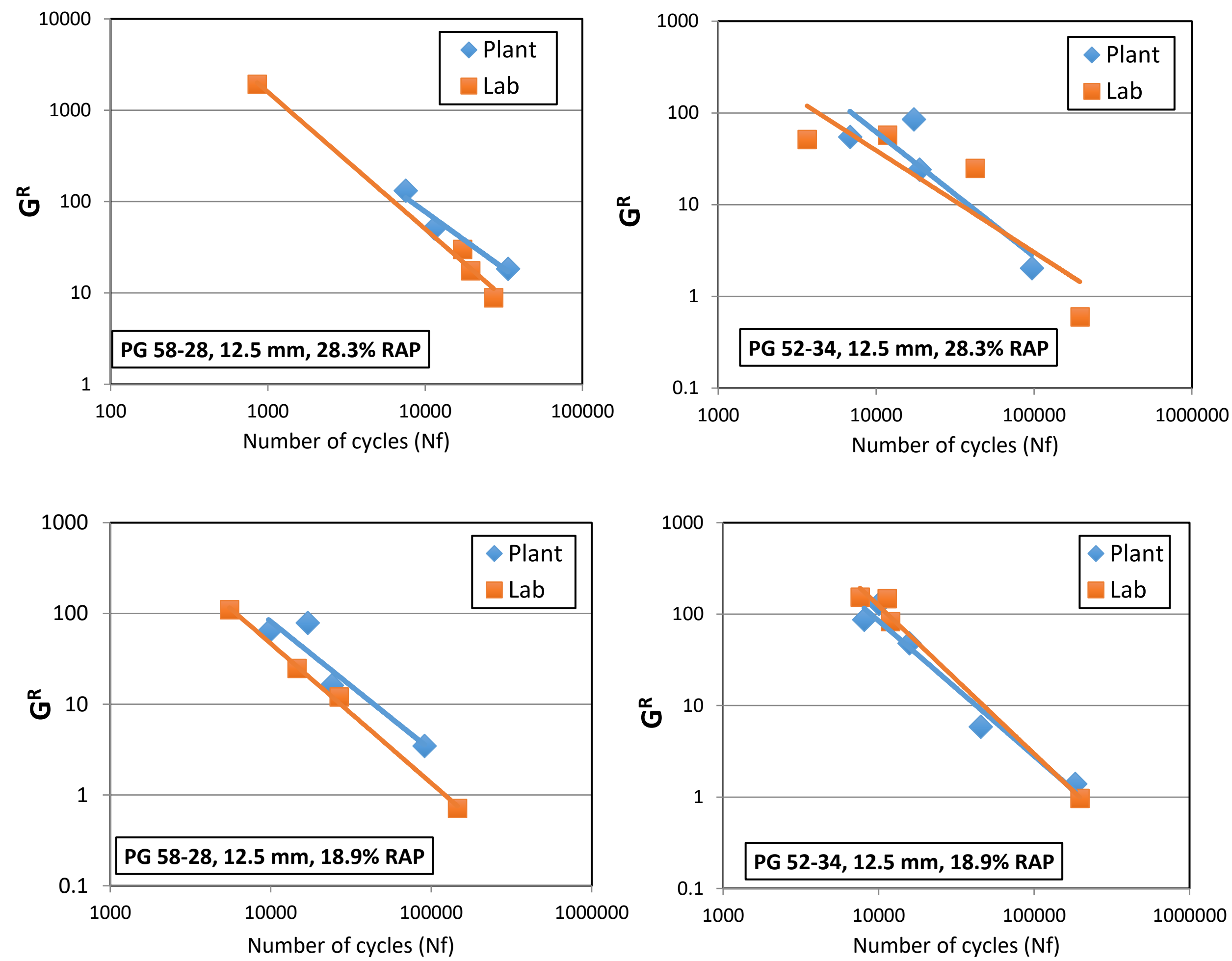


Figure 41- Fatigue Failure Diagrams of Plant versus Lab Produced Mixtures (12.5 mm)

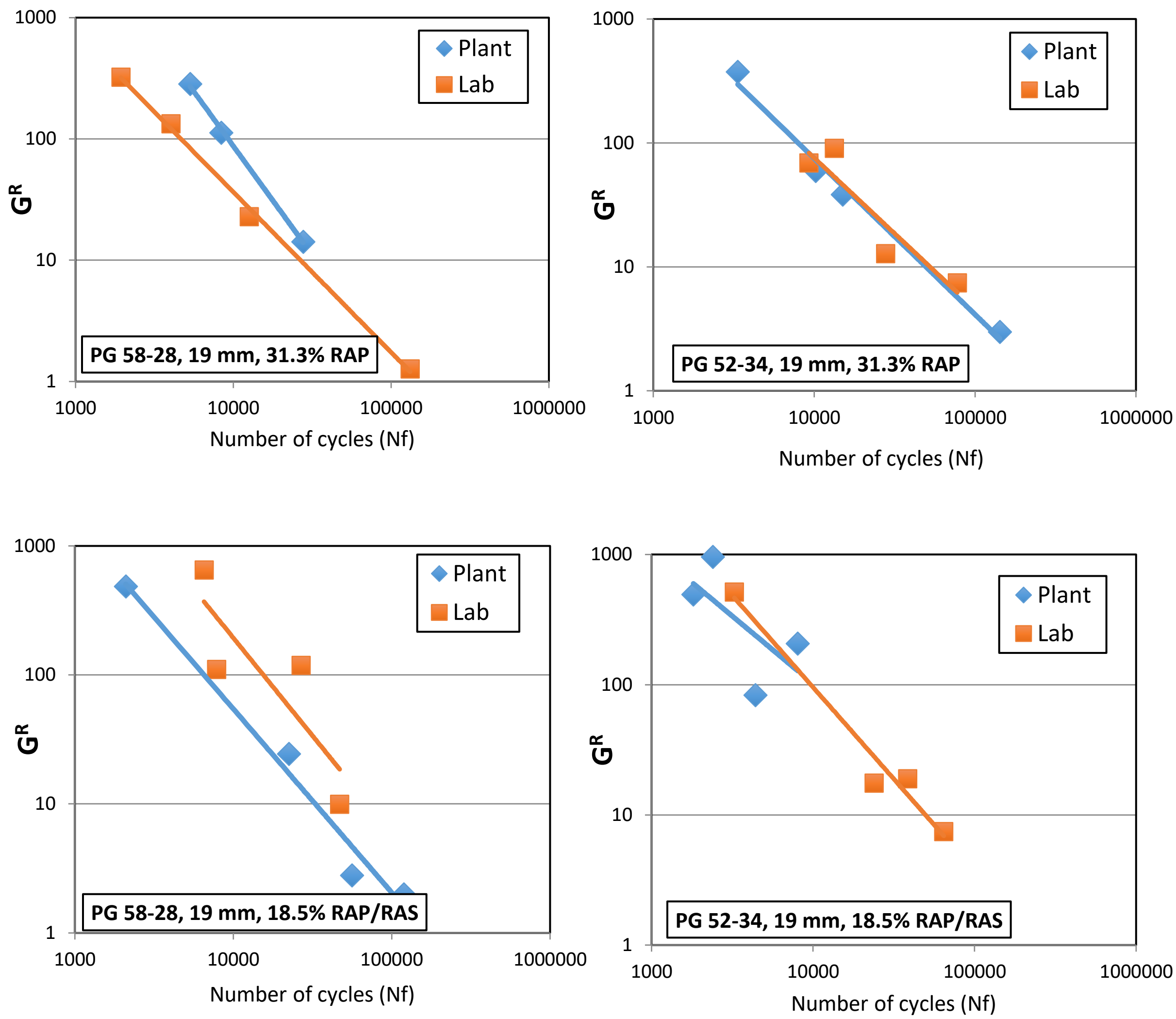


Figure 42- Fatigue Failure Diagrams of Plant versus Lab Produced Mixtures (19.0 mm)

Figure 43 shows the ratio of number of cycles to failure for lab produced mixtures to number of cycles for plant produced mixtures at G^R=100. The bars greater than 1.0 indicate higher number of cycles to failure for lab produced mixtures. The results show that for both RAP/RAS mixtures, lab produced mixtures had better fatigue performance than plant produced mixtures, while for all high RAP mixtures (28.3% and 31.3% RAP), plant produced mixtures had better behavior.

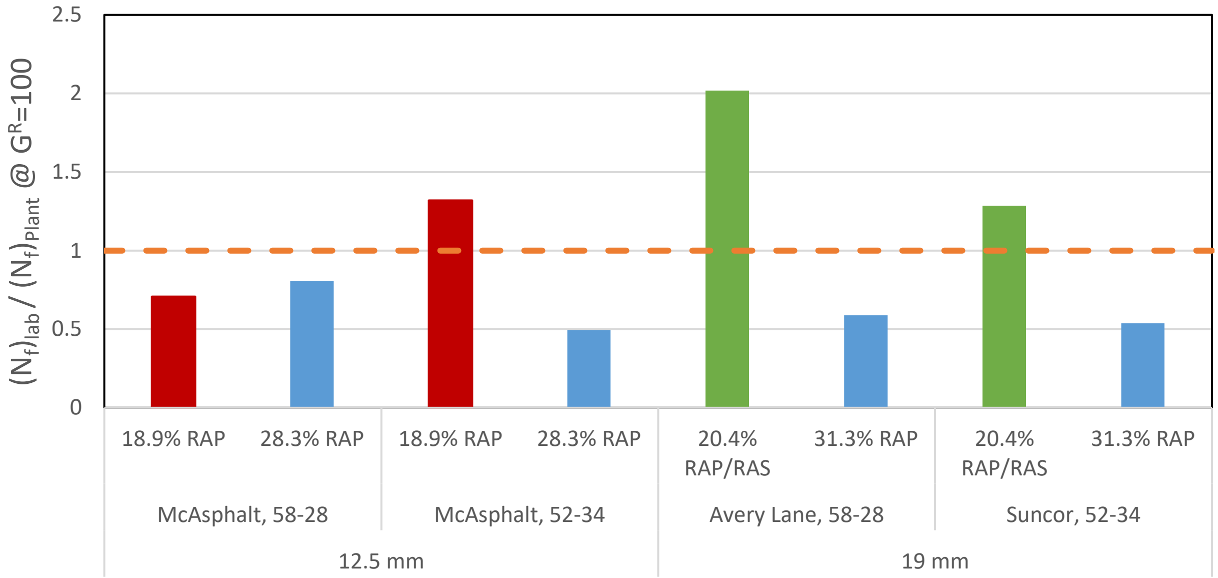
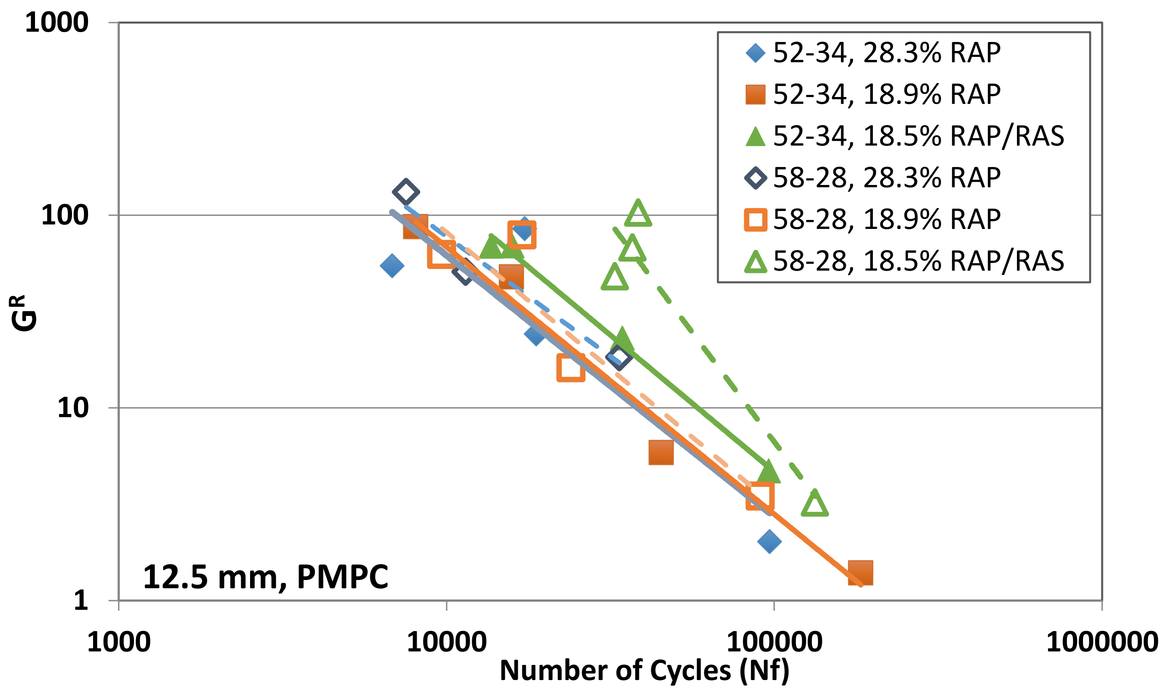


Figure 43- The ratio of $(N_f)_{lab}/(N_f)_{Plant}$ @ G^R=100

Figure 44 shows the fatigue failure criterion (G^R) versus the number of cycles (N_f) for plant produced mixtures. The G^R- N_f diagrams for lab produced mixtures are shown in Figure 45. The 20% and 30% RAP mixtures with both 12.5 and 19 mm NMSA showed similar behavior for both plant and lab produced mixtures, while in most cases, incorporating RAS appeared to improve the location of the G^R-N_f curve.



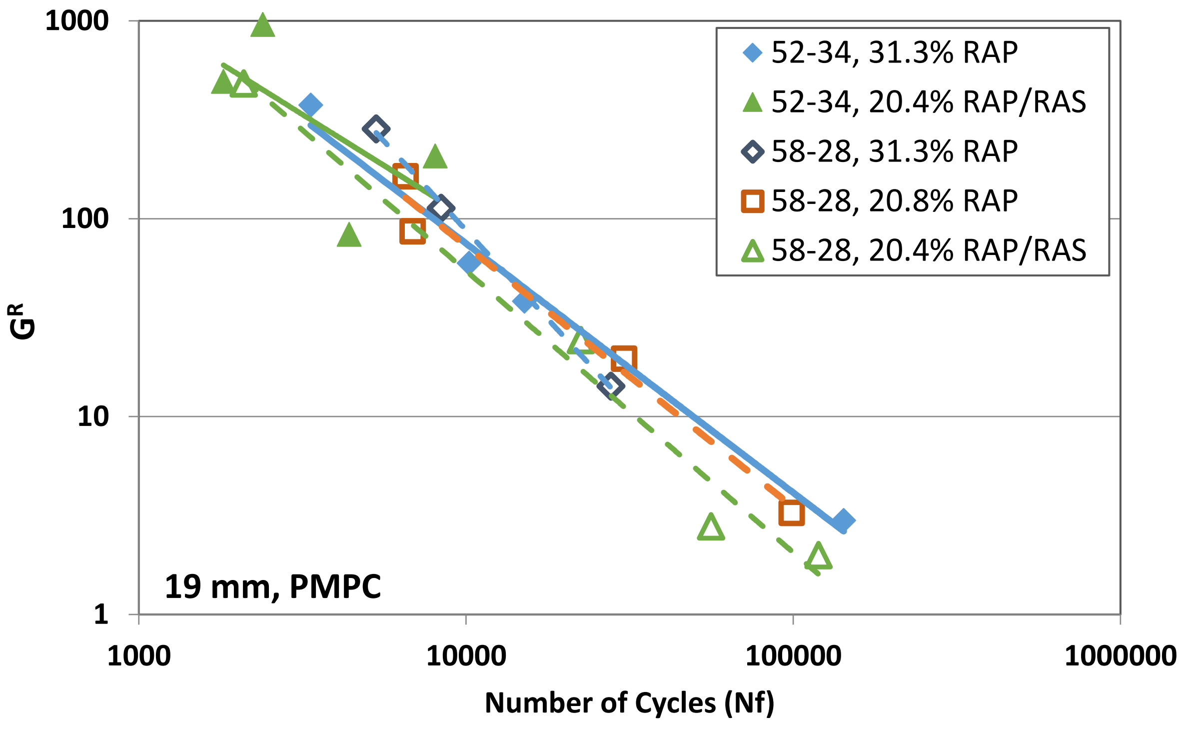
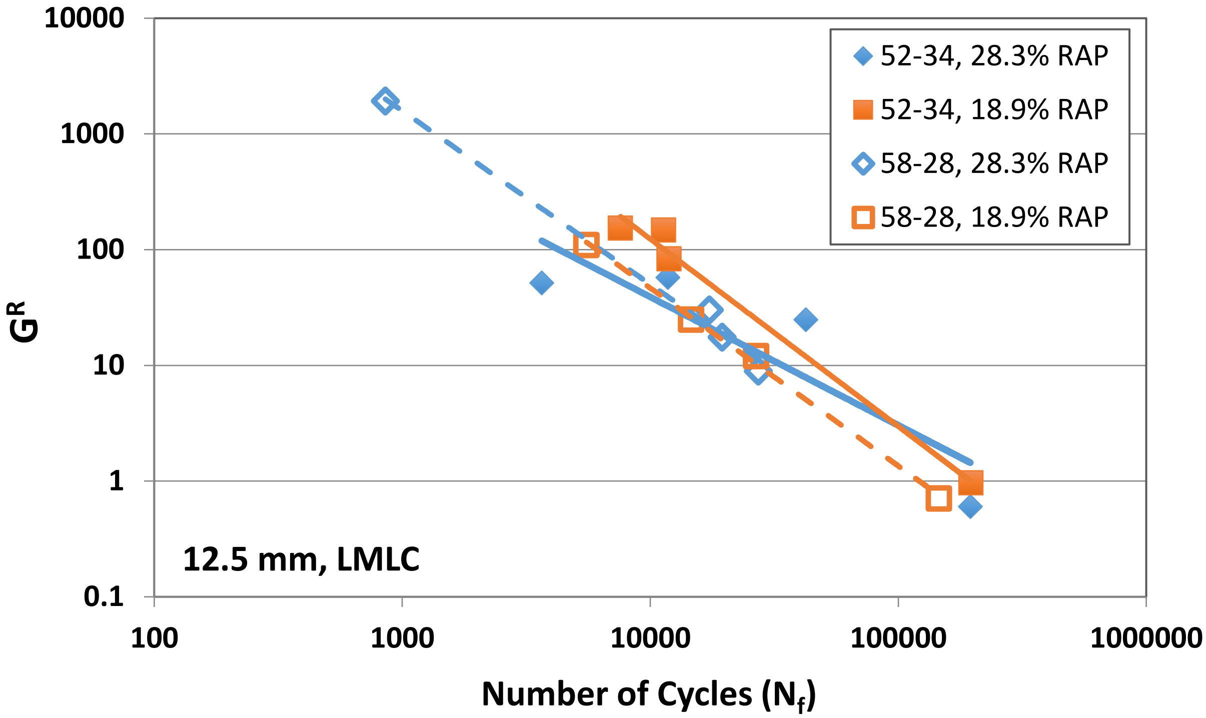


Figure 44- Fatigue Failure Diagrams of PMPC Mixtures



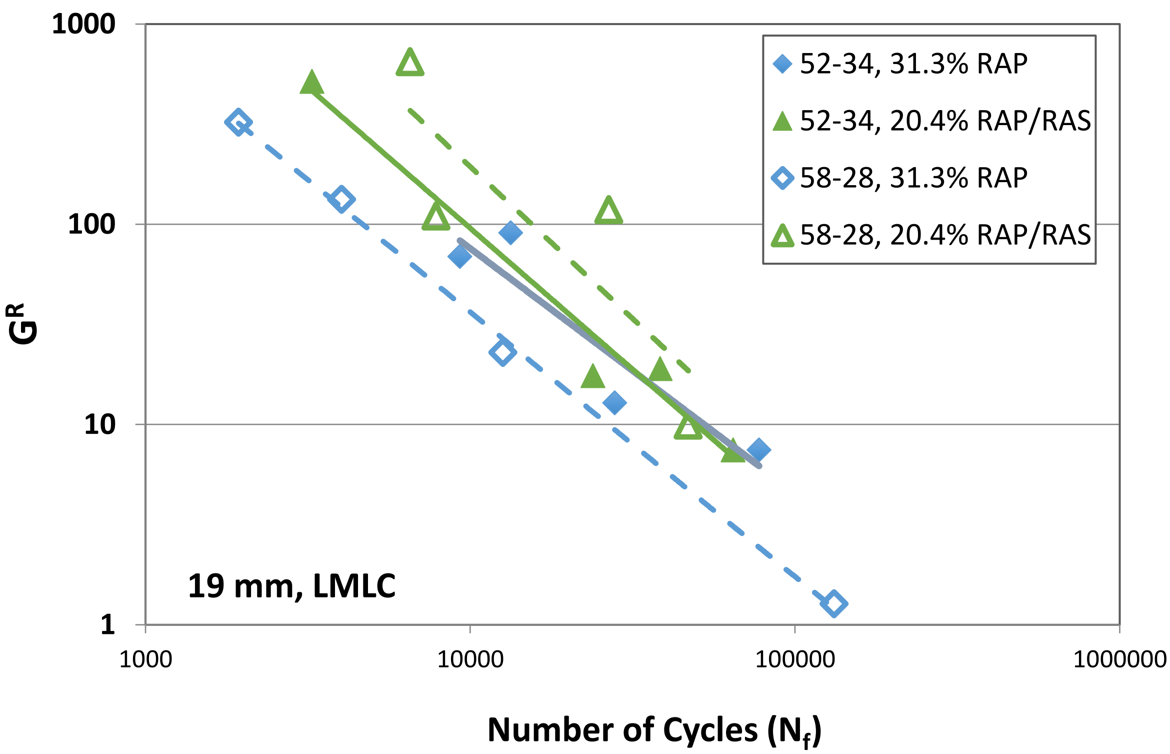


Figure 45- Fatigue Failure Diagrams of LMLC Mixtures

Disc-Shaped Compact Tension (DCT) Testing

The appropriate low temperature PG grade for Westmoreland was determined to be -28° C using the LTPPBind software. DCT testing was performed at -18° C (10 degrees warmer than low temperature PG grade requirement for the pavement location) for all the mixtures. Due to limited material availability, DCT testing could only be conducted on 6 PMPC Lebanon mixtures. The results presented in Figures 46 and 47 show the average fracture energy (area under load-CMOD curve up to failure) and the average G_f/m values, respectively.

The error bars in Figure 46 indicate the standard deviation, which was less than 10% for all mixtures except for the PG 58-28, 19 mm, 20.4% RAP/RAS mixture. The mixtures with finer aggregate showed higher fracture energy before failure, indicating that they would be more resistant to thermal cracking. However, there was not a significant difference between the fracture energy of the mixtures with different aggregate, or binder. This is likely due to the higher binder content in the finer mixtures which make them more ductile. The impact of softer binder on fracture energy was not identical for all mixtures; using PG 52-34 instead of PG 58-28 in 12.5 mm mixtures increased the fracture energy about 16%, while it decreased the 19 mm mixtures about 3% for RAP/RAS and 6% for higher RAP mixtures, although they are statistically similar. For 19 mm mixtures, the energy taken by both RAP/RAS and 31.3% RAP mixtures was similar for both binder PG grades.

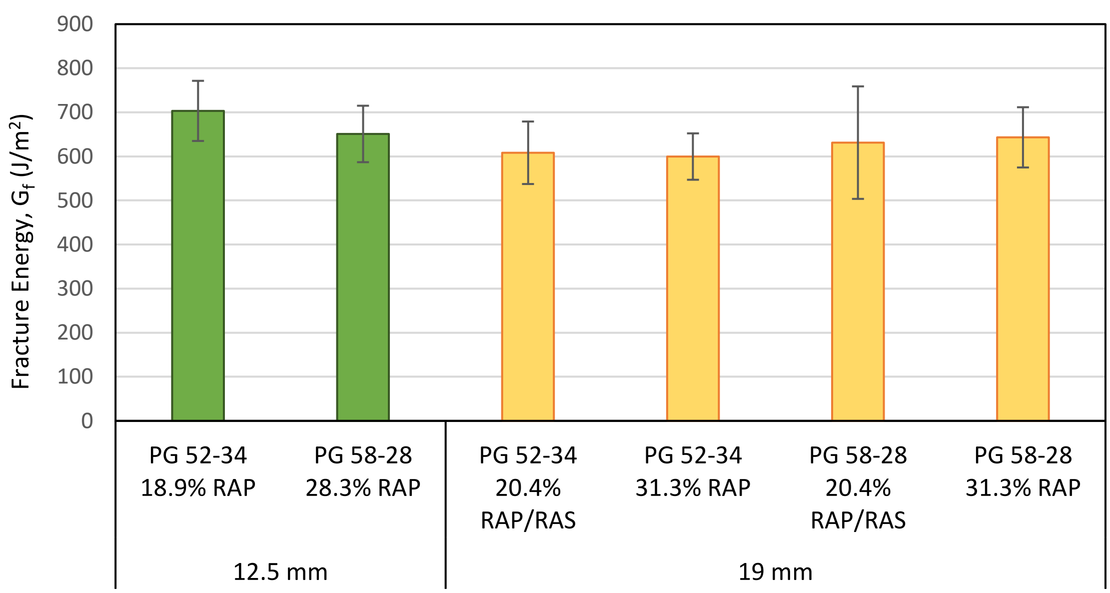


Figure 46- Average Fracture Energy of Different Mixtures

Fracture energy may not capture the ductility of mixture in the post peak region if the mix exhibits a very high peak load. For better understanding of an asphalt mixture's behavior at low temperature, the G_f/m parameter was calculated and results are shown in Figure 47. This parameter is defined as the measured fracture energy divided by the post peak slope (m) of load-CMOD curve. A higher G_f/m indicates the mixture would be expected to have better performance with respect to low temperature cracking. The general trend is in accordance with fracture energy values (Figure 46), but the difference between G_f/m values for different mixtures was higher. The RAP/RAS mixtures were lower than the 31.3% RAP mixtures, and the PG 52-34 binder did not appear to help the low temperature performance as compared to the PG 58-28 binder for the 19mm mixtures although the differences were not all statistically significant.

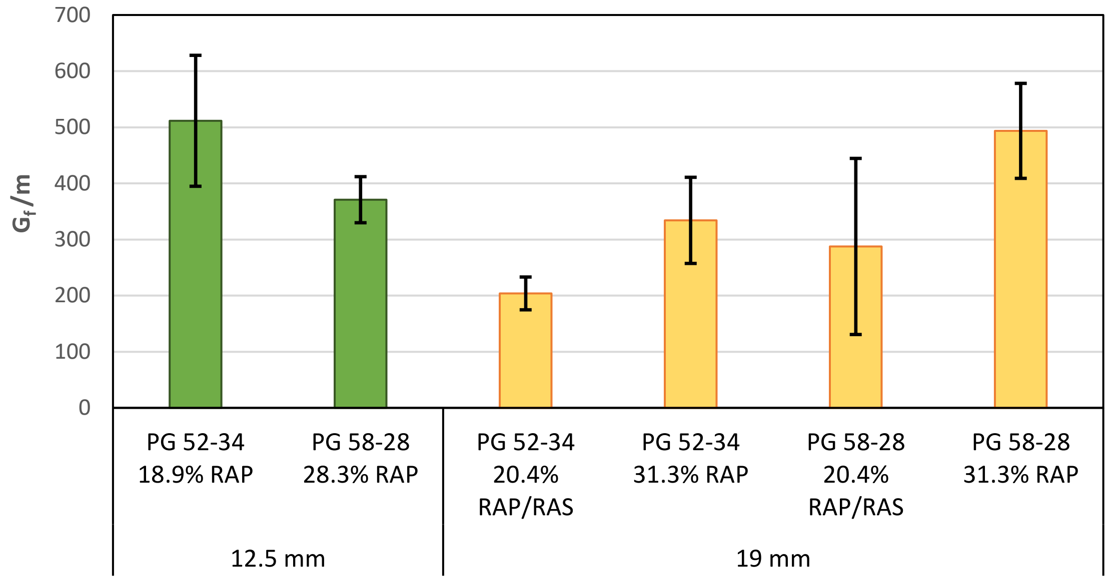


Figure 47- The Parameter of G_f/m for Different Mixtures

3.2.2. Hooksett Mixtures

<u>Complex Modulus</u>

The results presented in Figure 48 show dynamic modulus mastercurves for the Hooksett mixtures. Although the dynamic modulus of plant and lab produced materials for PG 64-28, 9.5 mm, 16.4% RAP mixture were very close, the plant produced mixtures for the two other mixtures with PG 58-28 binder had higher dynamic modulus values than the lab produced mixtures. This trend is not the same as was observed for the Lebanon mixtures. Figure 49 shows the phase angle mastercurves for the Hooksett mixtures. Like dynamic modulus, the phase angle mastercurves for plant and lab produced mixtures for the PG 64-28, 9.5 mm, 16.4% RAP were very similar. The phase angle of the lab produced mixtures with PG 58-28 was slightly higher than plant produced mixtures, especially in intermediate temperatures.

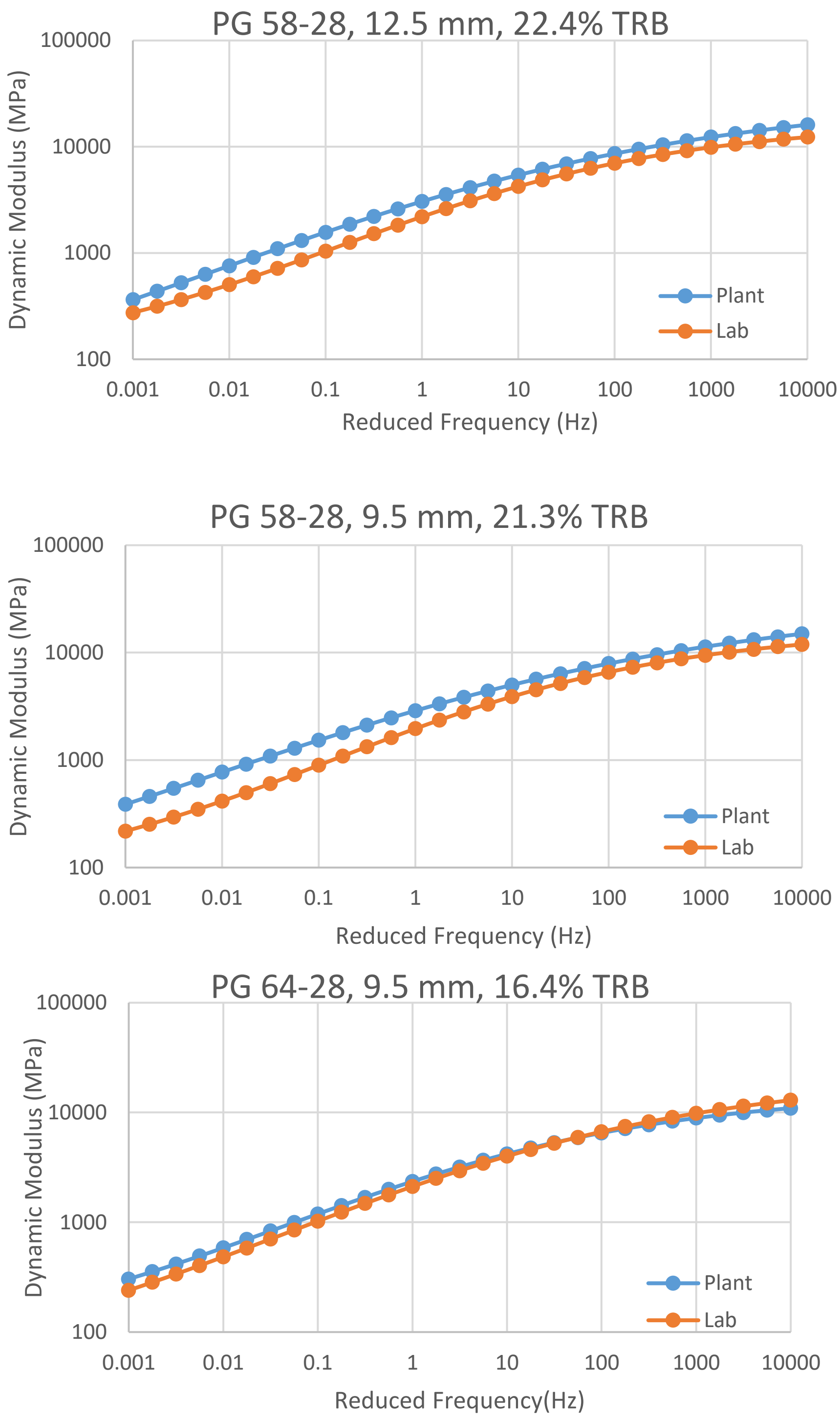
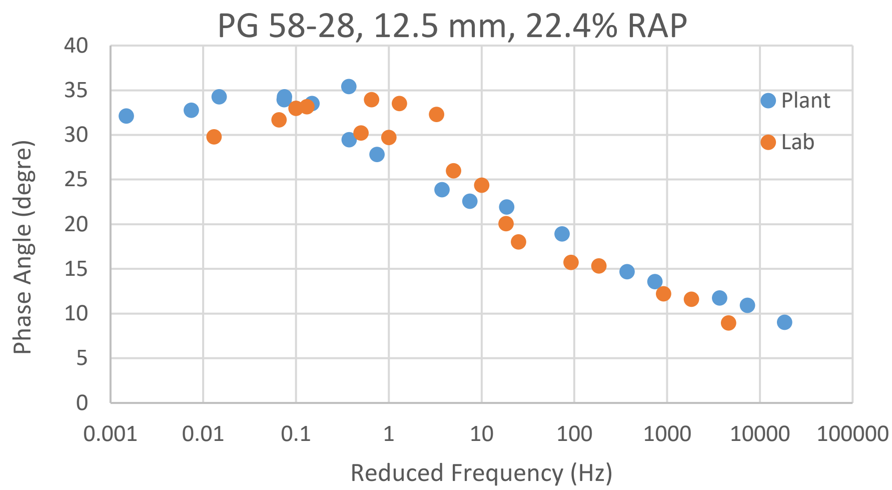
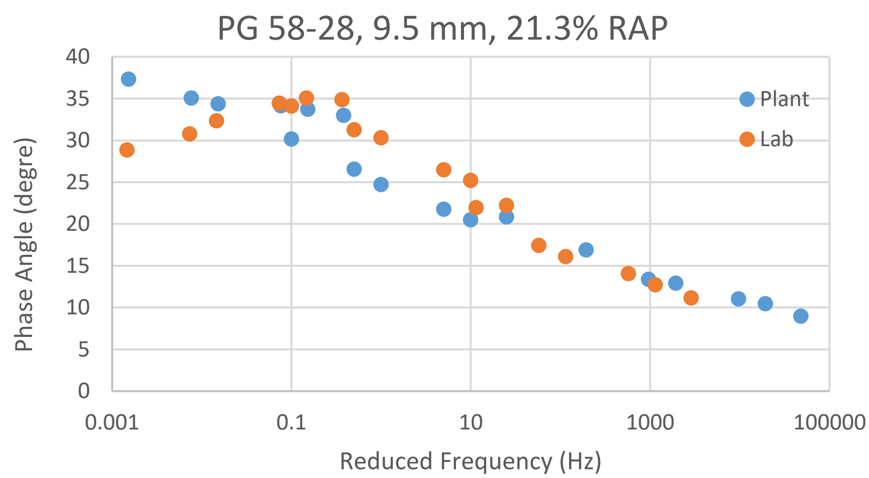


Figure 48- Dynamic Modulus Mastercurves of Hooksett Mixtures





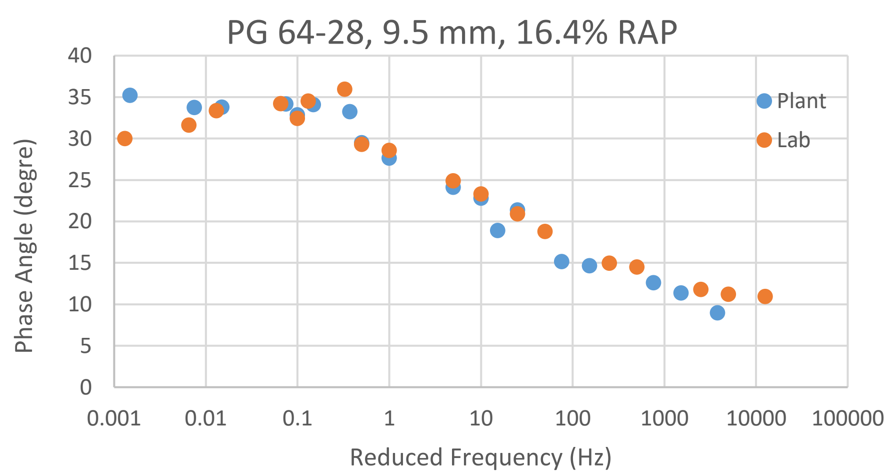


Figure 49- Phase Angle Mastercurves of Hooksett Mixtures

SVECD Fatigue Testing

The damage characteristics curves and fatigue failure criterion for lab and plant produced mixtures are compared in Figures 50 and 51, respectively. There is a good agreement in the trends between dynamic modulus and fatigue results. The plant produced mixtures showed higher integrity than lab produced mixtures for PG 58-28, 22.4% and 21.3% RAP mixtures, and also had higher G^R values, while for the third mixture (PG 64-28, 9.5 mm, 16.4% RAP), the behavior of plant and lab produced mixtures was very close.

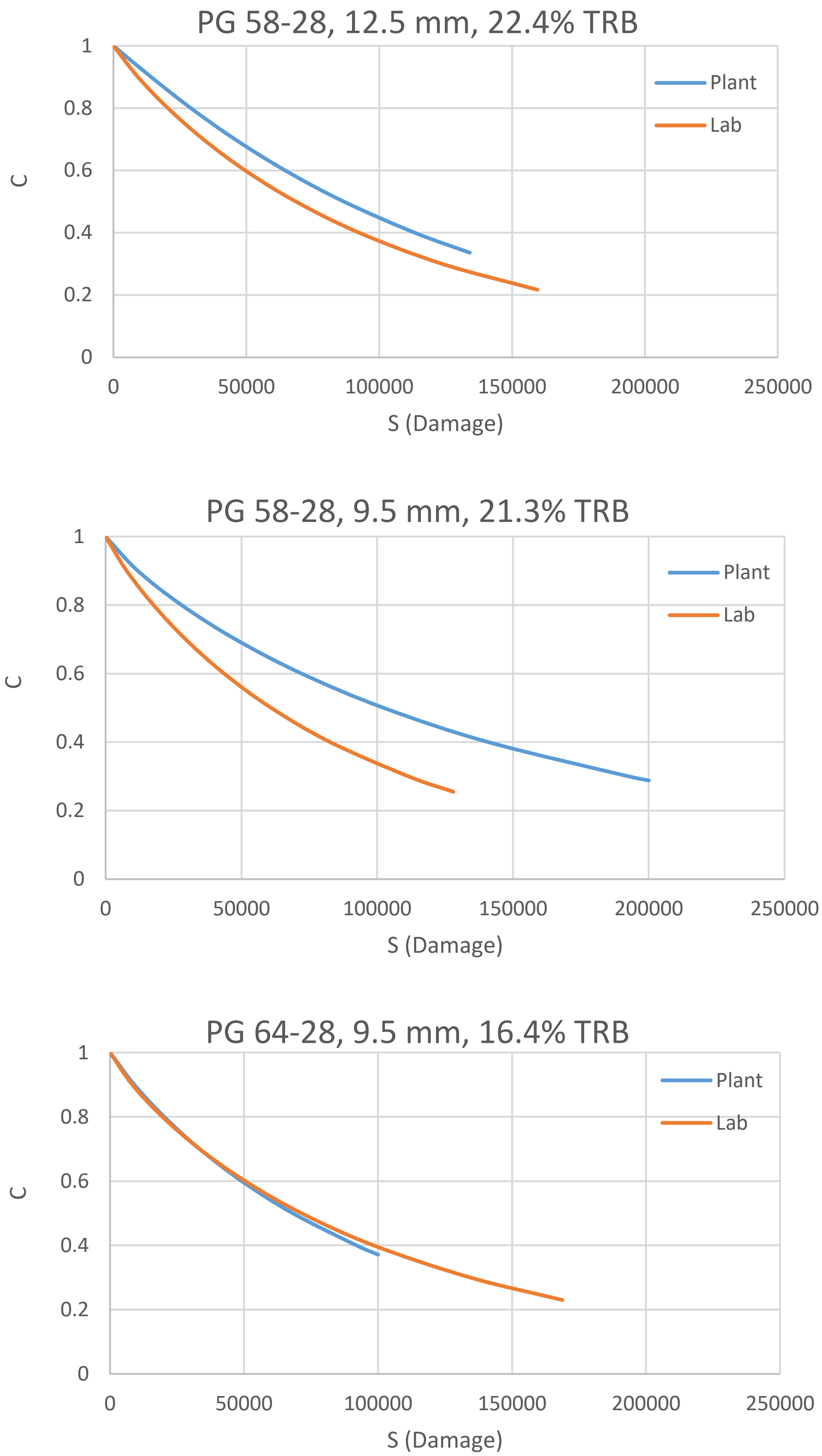


Figure 50- Damage Characteristics Curves of Hooksett Mixtures

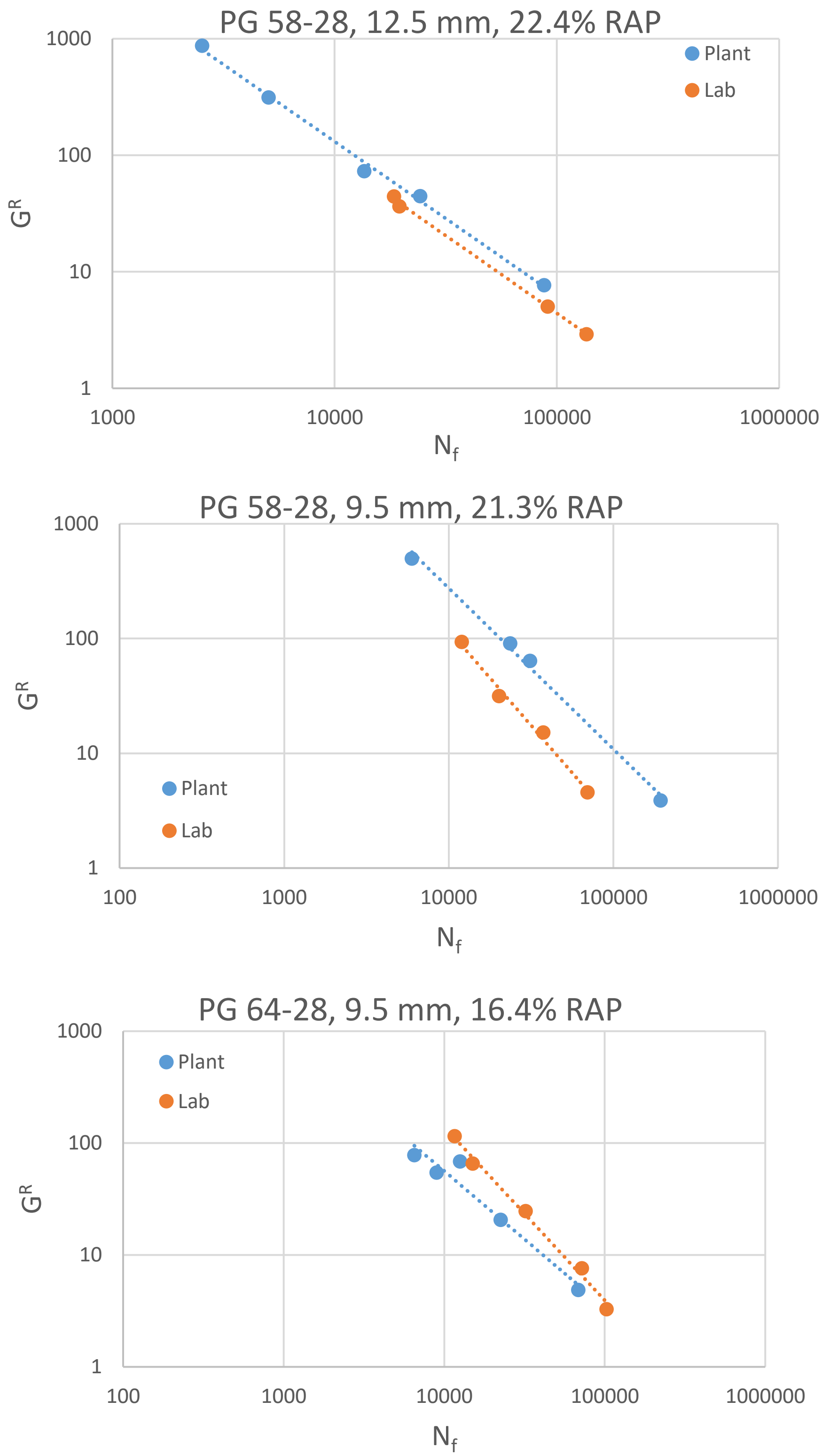
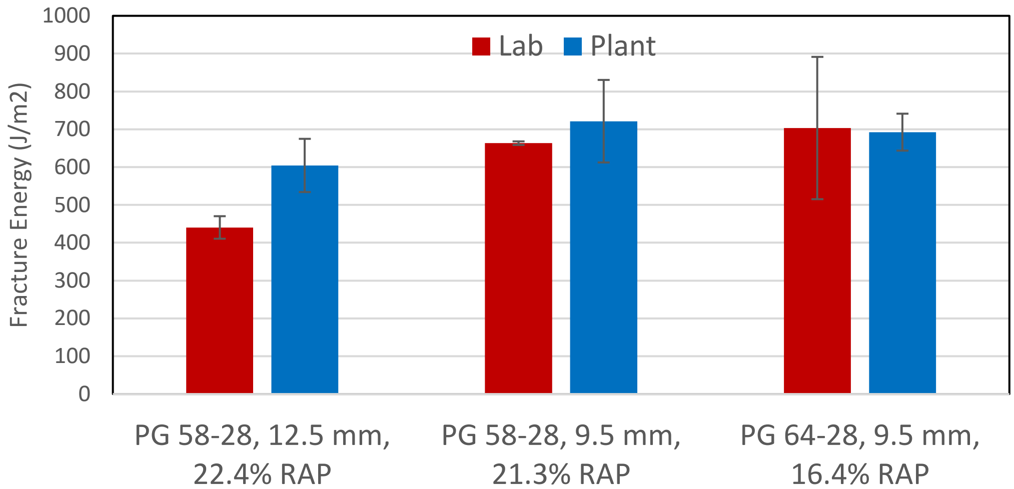


Figure 51- Fatigue Failure Criterion of Hooksett Mixtures

Disk-Shaped Compact Tension (DCT) Testing

The DCT testing was conducted at -18ºC for the Hooksett mixtures. Figure 52 shows the fracture energy and G_f/m values measured from tests on plant and lab produced mixtures. The bars represent one standard deviation. The fracture energy measured from the lab and plant mixtures are statistically the same for the two 9.5 mm mixtures, and the plant material has higher fracture energy for the 12.5 mm mixture. The G_f/m values are statistically similar between plant and lab materials for the 12.5 mm mixture, but the plant values are larger for the two 9.5 mm mixtures.



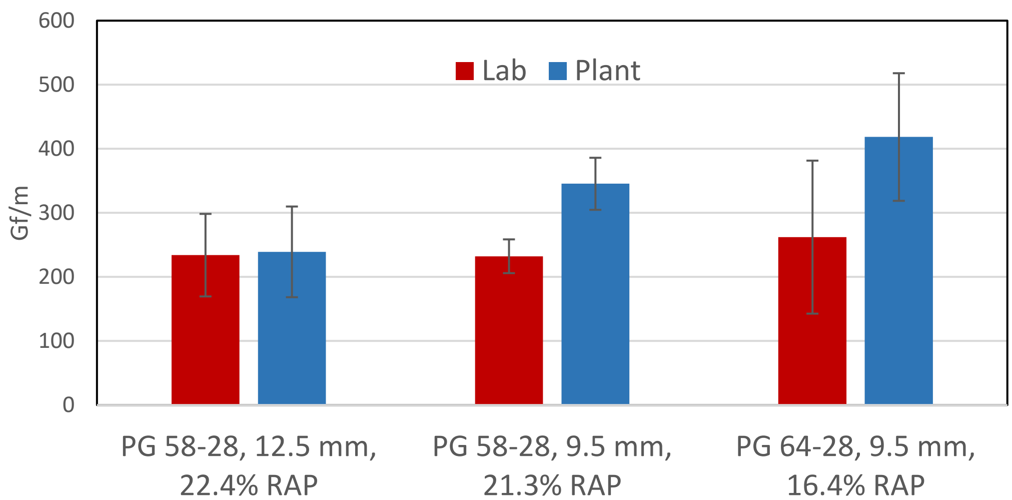


Figure 52- Fracture Energy and Gf/m for Different Hooksett Mixtures

3.3. Pavement Evaluation

To evaluate performance of the mixtures in a pavement structure over time, the LVECD software program was used. The software includes a structural response model (linear elastic or linear viscoelastic) that can calculate stresses and strains using a finite element mesh framework. The rheological and fatigue characteristics of the mixture measured from S-VECD testing are used as inputs in the program to predict cracking over time. This analysis was performed to directly compare the different surface and binder mixtures produced in the laboratory and the plant and also to evaluate the actual combinations of binder and surface layers in the field. The pavement cross-section in which the Lebanon mixtures were placed is shown in Figure 53.

The individual mixture comparisons for the surface mixtures were done using the same binder layer material and the relative amount of damage that occurred in the surface layer only was evaluated. Similarly, different binder layer mixtures were evaluated using the same surface layer material. Both plant and laboratory produced Lebanon and Hooksett mixtures were evaluated this way. In addition to the individual analysis, the six combinations of plant produced surface and binder layers in the field (as shown in Table 7 and Figure 54) were evaluated; four of these combinations were also able to be evaluated for the laboratory produced materials.

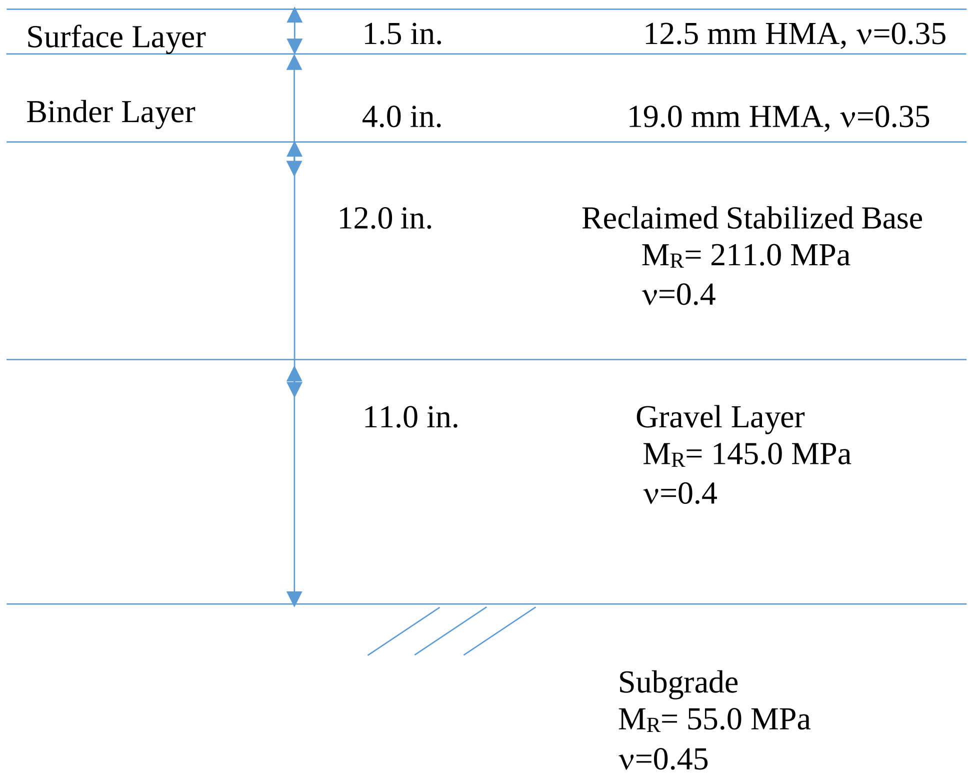


Figure 53- Westmoreland Pavement Cross Section

Table 7- Surface and Binder layers in Different LVECD Models

Section	Surface Layer	Binder Layer
1	PG 58-28, 12.5 mm, 28.3% RAP	PG 58-28, 19 mm, 31.3% RAP
2	PG 58-28, 12.5 mm, 18.5% RAP/RAS	PG 58-28, 19 mm, 20.4% RAP/RAS
3	PG 58-28, 12.5 mm, 18.9% RAP	PG 58-28, 19 mm, 20.4% RAP/RAS
4	PG 52-34, 12.5 mm, 18.9% RAP	PG 52-34, 19 mm, 20.4% RAP/RAS
5	PG 52-34 12.5 mm, 18.5% RAP/RAS	PG 52-34 19 mm, 20.4% RAP/RAS
6	PG 52-34, 12.5 mm, 28.3% RAP	PG 52-34, 19 mm, 31.3% RAP

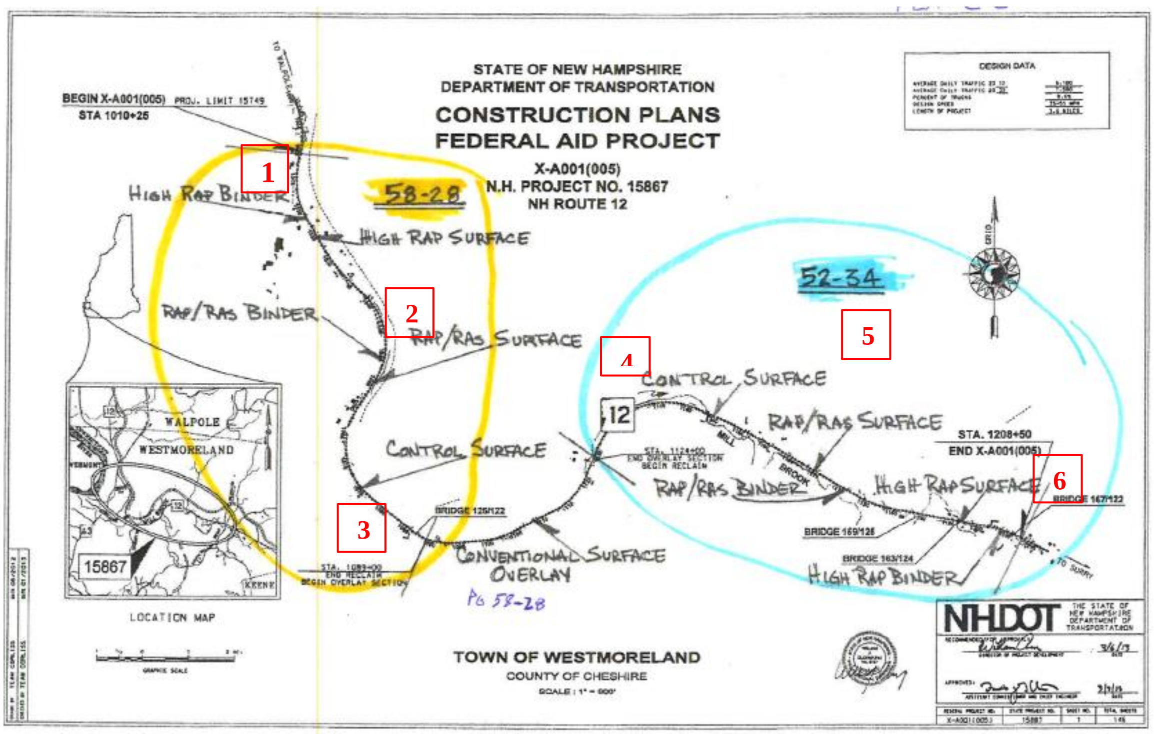


Figure 54- Westmoreland Construction Plan

Individual Analysis

The predicted relative performance of the Lebanon surface layer plant mixtures are shown in Figure 55. The PG 58-28 RAP/RAS mixture had by far the worst performance, followed by the PG 52-34 28.3% RAP mixture. The use of the softer PG 52-34 binder improved the performance of the RAP/RAS mixture, however for the 18.9% RAP mixtures, the softer binder did not provide any additional benefit and actually showed slightly worse behavior. The behavior of both PG 58-28 RAP only mixtures and the PG 52-34 RAP/RAS mixture was very similar. Four of the surface mixtures were also evaluated based on the results from the testing conducted on the laboratory produced material (Figure 57). All four laboratory mixtures showed similar behavior, with the PG 58-28 18.9% RAP mixture slightly worse than the other three. All of the laboratory produced mixtures showed more predicted damage than the plant produced mixtures.

Figures 56 and 58 show the predicted relative performance for the Lebanon binder layer plant and laboratory produced mixtures, respectively. In the binder layer, the plant produced PG 52-34 RAP/RAS mixture performed the worst followed by the PG 58-28, 31.3% RAP mixture. The other three had similar performance. The softer binder did not improve the performance of the RAP/RAS mixture, but did appear to improve the performance of the 30% RAP mixture. This could also be due to the difference in binder sources as well. The four lab produced mixtures that were evaluated all showed different performance and very different rankings from the plant produced mixtures. In some cases, the laboratory produced mixtures were worse than the plant produced mixtures and in other cases the opposite trend was observed.

The predicted relative performance of the Hooksett laboratory and plant produced surface mixtures is shown in Figures 59 and 60, respectively. The relative performance of the three mixtures was different for both the plant and lab produced materials, but the rankings are completely different and there was not a consistent trend from plant to lab.

Field section analysis

The predicted performance of the field cross sections is shown in Figures 61-70. The results from both the laboratory and plant produced mixtures are shown in cases where data was available for both sets of mixtures. The PG 58-28 high RAP (section 1, Figs 61 & 62) plant mixtures indicated bottom up cracking will occur whereas the laboratory mixtures indicated top down cracking will also occur with the same relative amount of bottom up cracking. The PG 58-28 control surface layer over the RAP/RAS binder (section 3, Figs 64 & 65) showed much more extensive cracking from the laboratory mixtures in both the surface and binder layers. The PG 52-34 RAP surface layer over the PG 52-34 RAP/RAS binder layer (section 4, Figs 66 & 67) showed more bottom up cracking from the plant mixture evaluation and more top down cracking from the laboratory mixture. The use of the softer binder did not provide improvement in the plant mixtures (comparison of sections 3 & 4), but did improve the bottom up cracking observed in the binder layer. The PG 52-34 high RAP (section 6, Figs 69 & 70) laboratory mixtures indicated better performance over the plant mixtures for both layers. The use of the softer binder (comparison of sections 1 and 6) appears to improve the cracking in the binder layer, but made the cracking in the surface layer worse.

Comparison of the PG 58-28 and PG 52-34 RAP/RAS sections (sections 2 & 5, Figs 63 & 68) shows that use of the softer binder helped the surface layer, but resulted in more cracking in the binder layer. In both cases, the overall performance of the cross section was the worst combination.

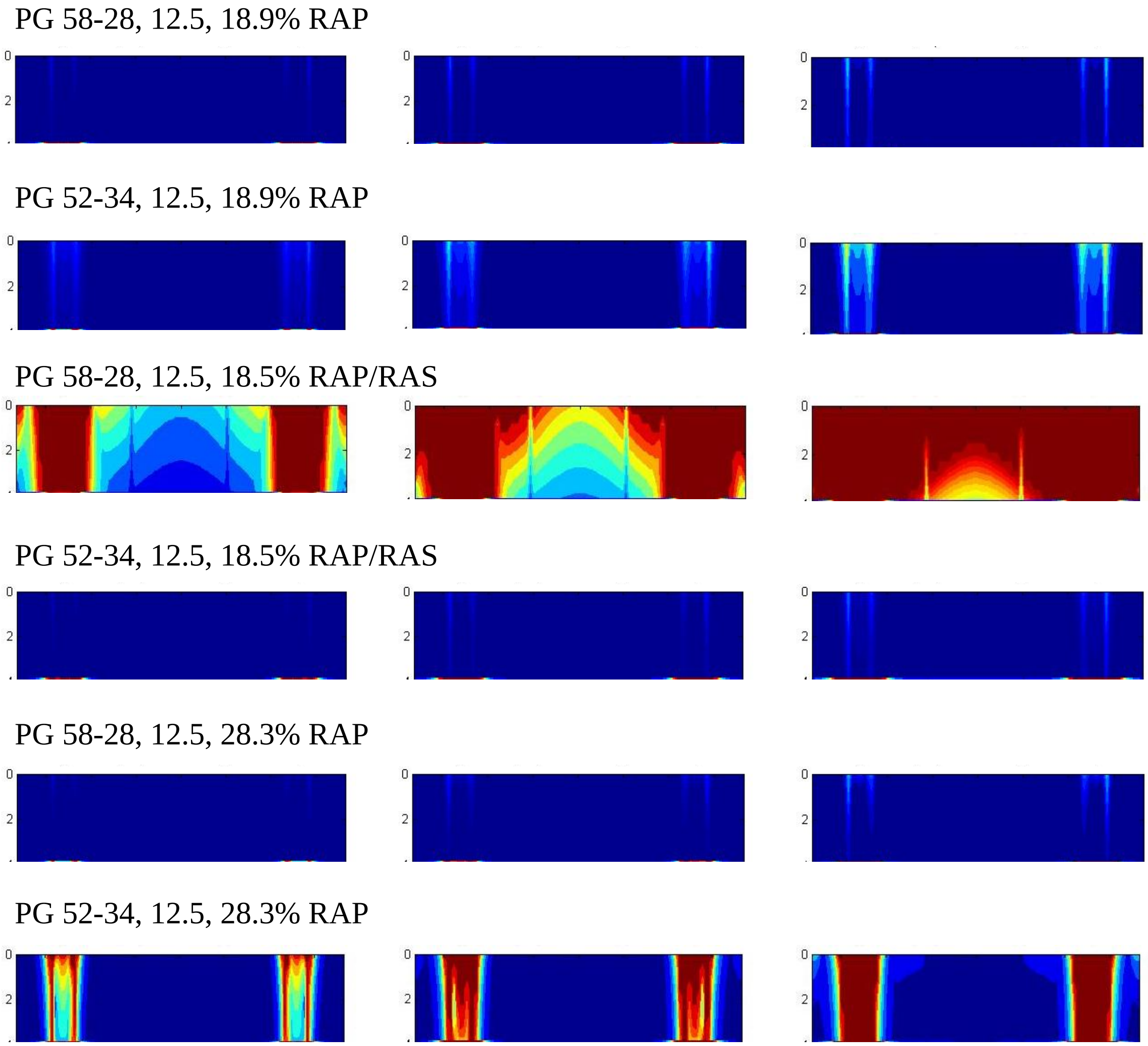
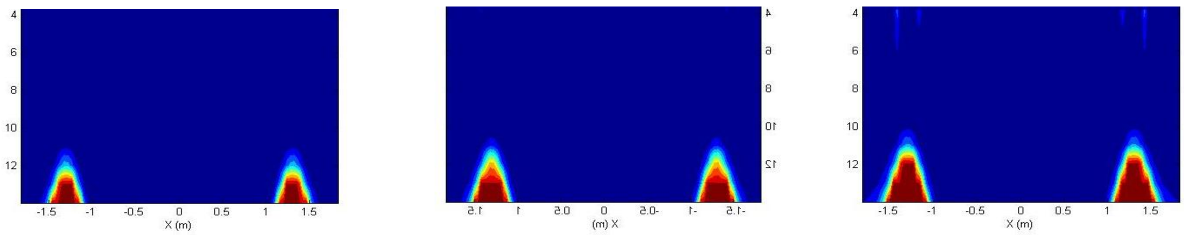
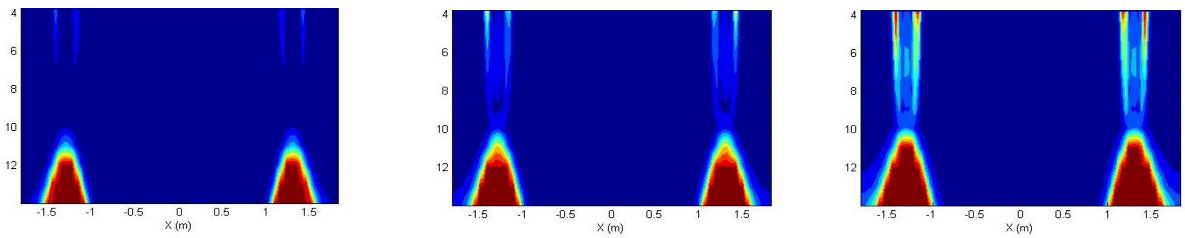


Figure 55- Plant Produced, Westmoreland, Surface Mixtures (5, 10, 20 years)

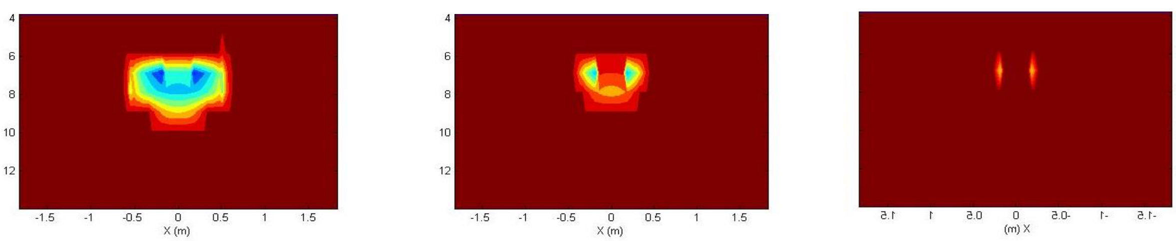
PG 58-28, 19, 20.8% RAP



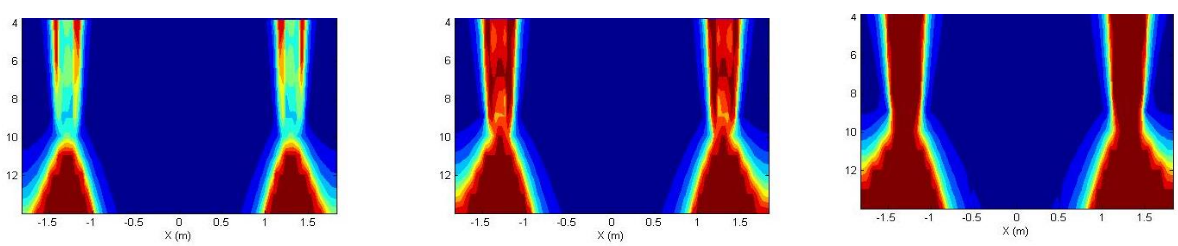
PG 58-28, 19, 20.4% RAPRAS



PG 52-34, 19, 20.8% RAPRAS



PG 58-28, 19, 31.1% RAP



PG 52-34, 19, 31.3% RAP

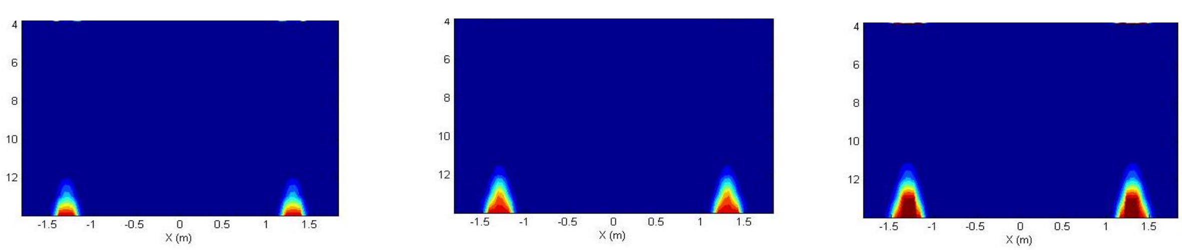
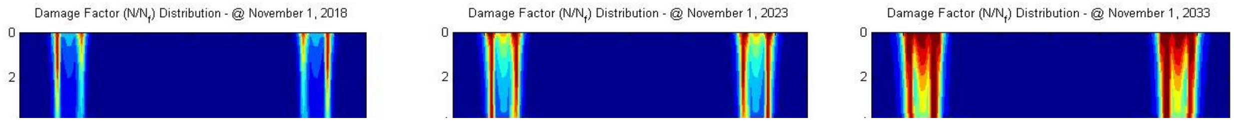
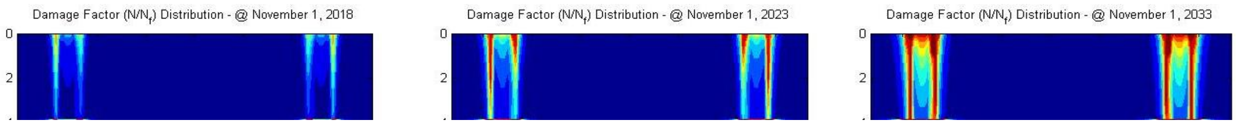


Figure 56- Plant Produced, Westmoreland, Binder Mixtures (5, 10, 20 years)

PG 58-28, 12.5, 18.9% RAP



PG 52-34, 12.5, 18.9% RAP



PG 58-28, 12.5, 28.3% RAP

PG 52-34, 12.5, 28.3% RAP

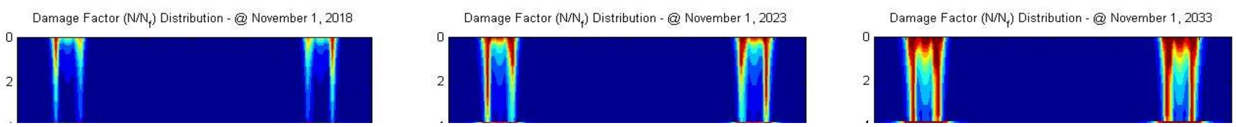
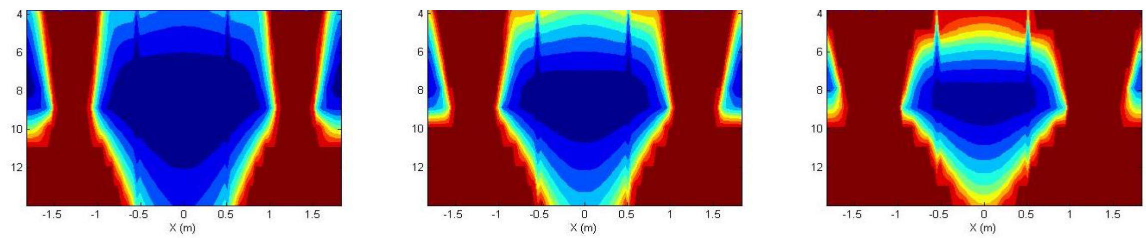
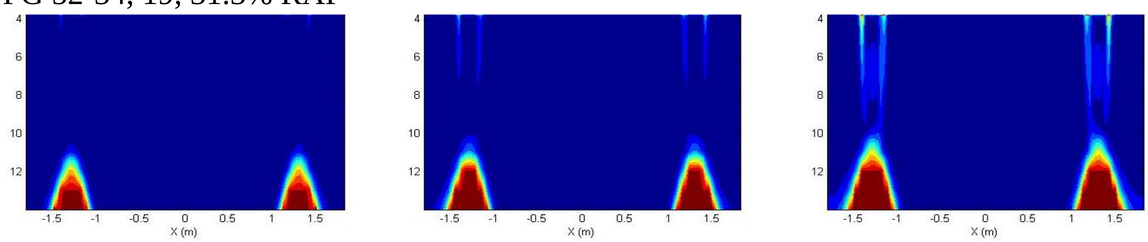


Figure 57- Lab Produced, Westmoreland, Surface Mixtures (5, 10, 20 years)

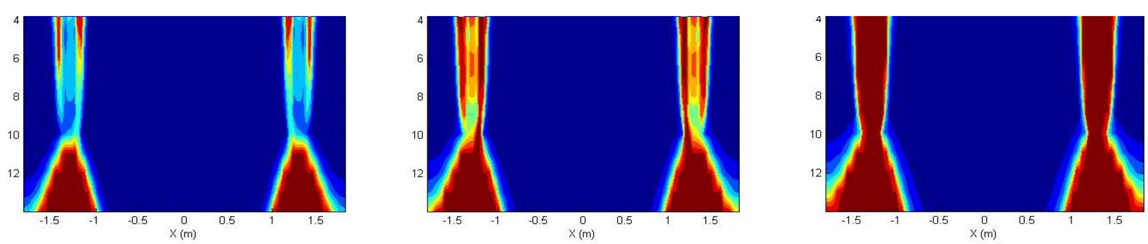
PG 58-28, 19, 20.4% RAP/RAS



PG 52-34, 19, 31.3% RAP



PG 58-28, 19, 31.3% RAP



PG 52-34, 19, 20.4% RAPRAS

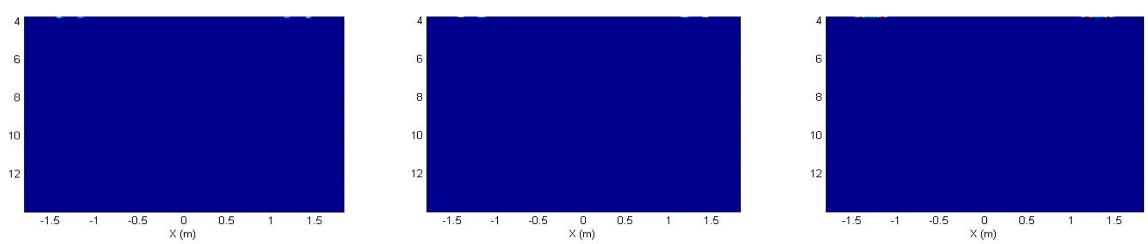


Figure 58- Lab Produced, Westmoreland, Binder Mixtures (5, 10, 20 years)

PG 58-28, 12.5, 22.4%RAP

PG 58-28, 9.5, 21.3%RAP

PG 64-28, 9.5, 16.4% RAP

Figure 59- Plant Produced, Hooksett, Surface Mixtures (5, 10, 20 years)

PG 58-28, 12.5, 22.4%RAP

PG 58-28, 9.5, 21.3%RAP

PG 64-28, 9.5, 16.4% RAP

Figure 60- Lab Produced, Hooksett, Surface Mixtures (5, 10, 20 years)

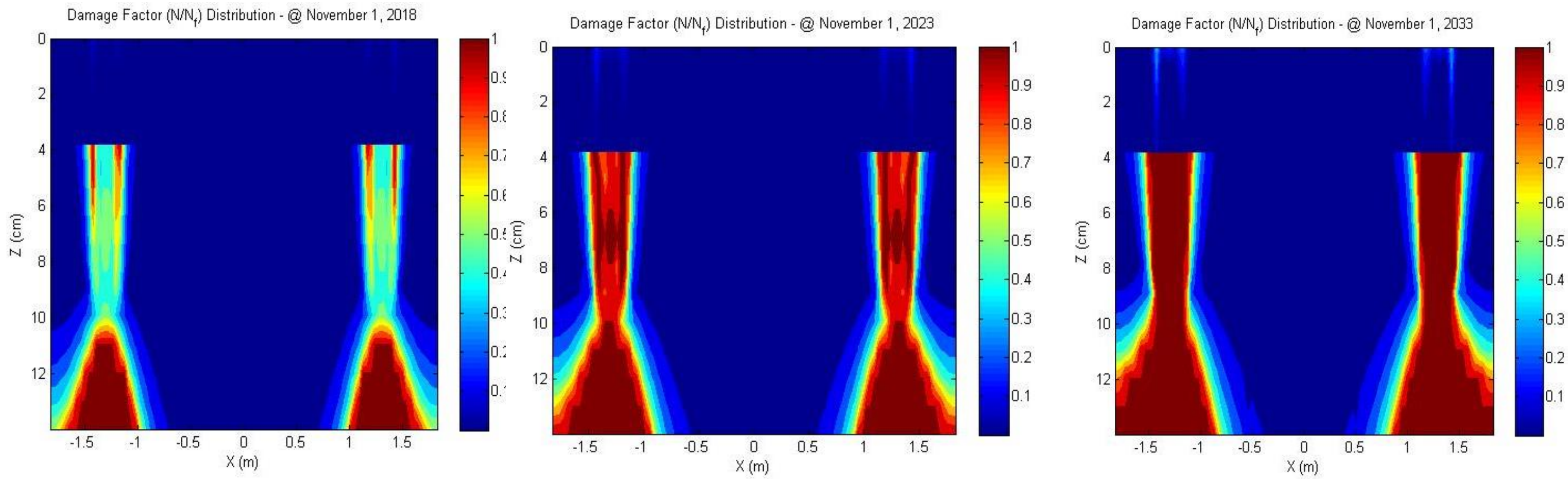


Figure 61–Plant Produced, PG 58-28, 12.5mm, 28.3% RAP (Surface layer) and PG 58-28, 19mm, 31.3% RAP (Binder layer) (5, 10, and 20 Years)

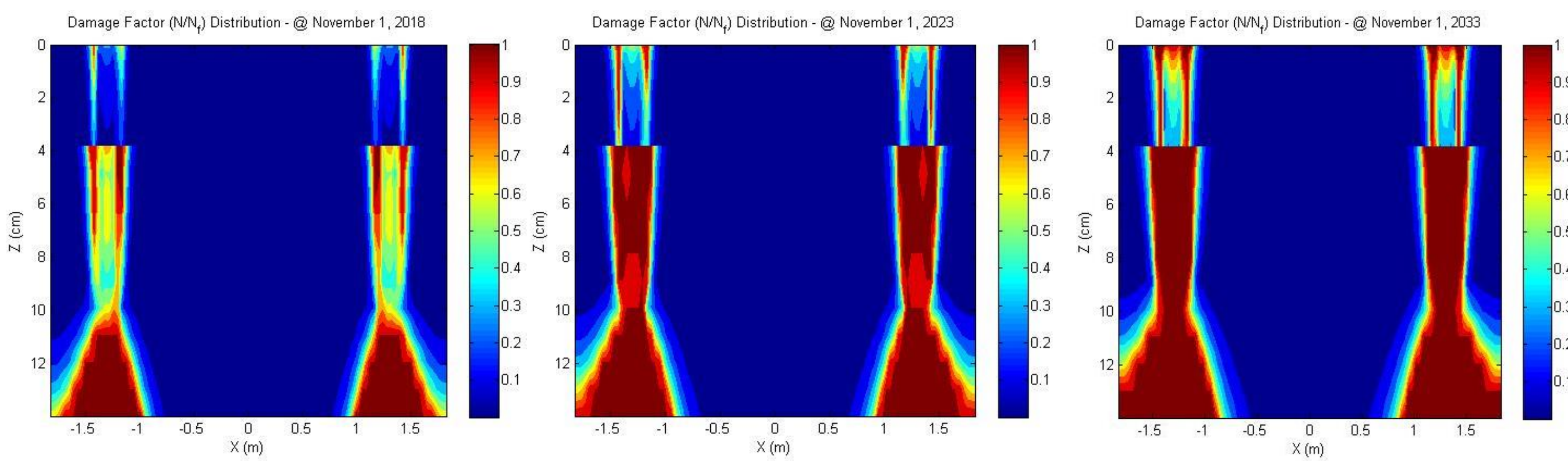


Figure 62– Lab Produced, PG 58-28, 12.5mm, 28.3% RAP (Surface layer) and PG 58-28, 19mm, 31.3% RAP (Binder layer) (5, 10, and 20 Years)

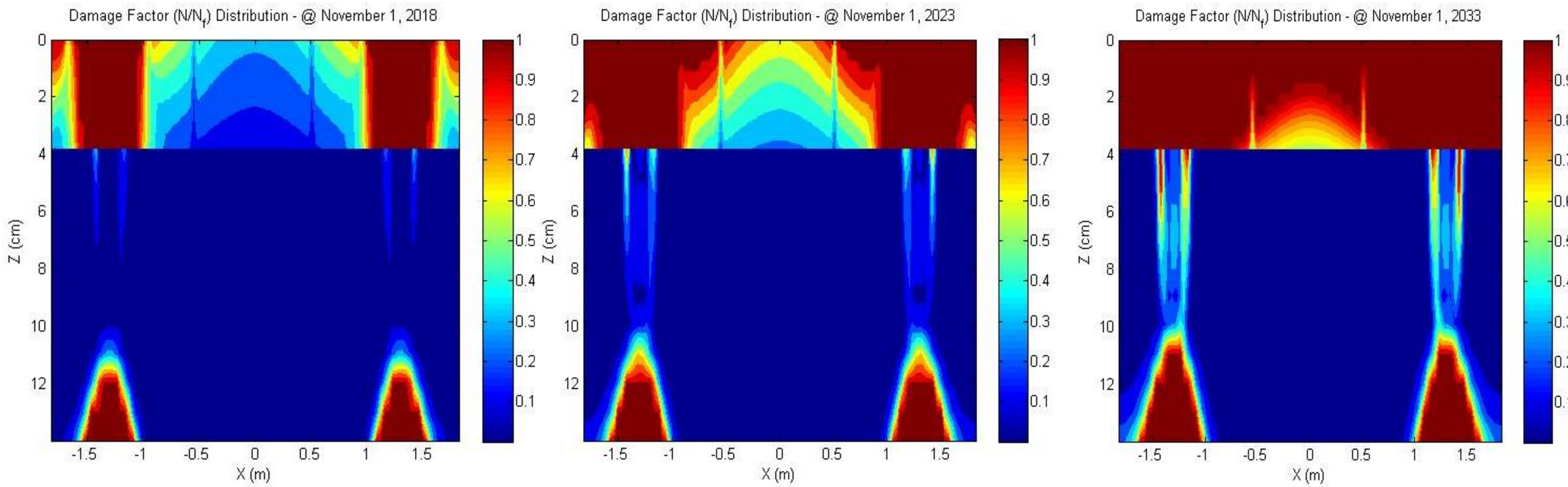


Figure 63– Plant Produced, PG 58-28, 12.5mm, 18.5% RAPRAS (Surface layer) and PG 58-28, 19mm, 20.4% RAPRAS (Binder layer) (5, 10, and 20 Years)

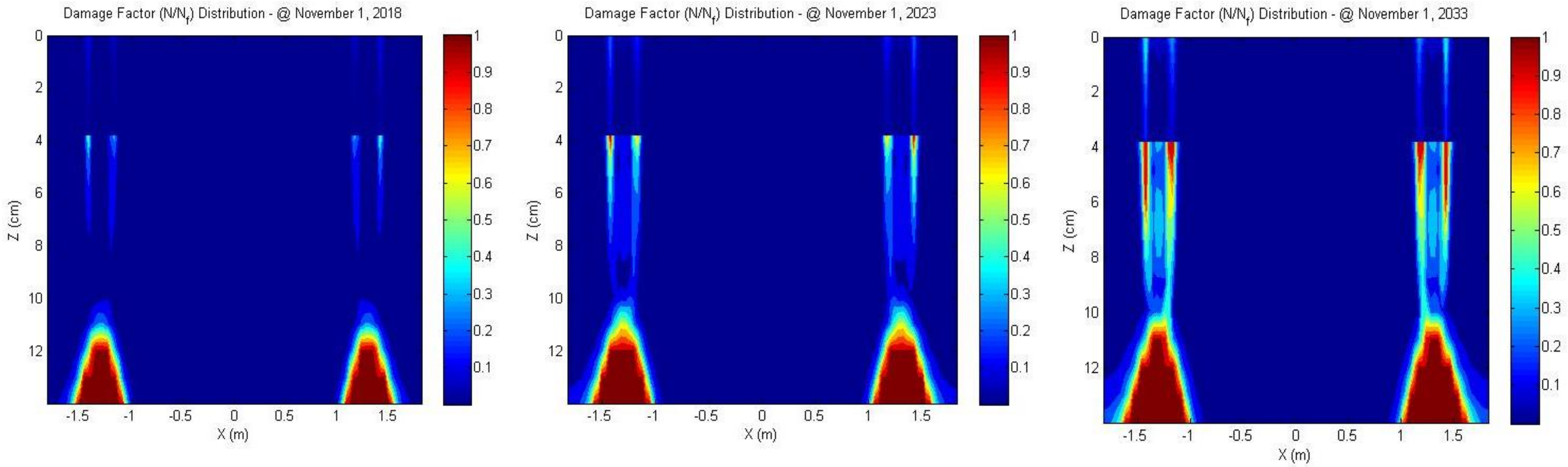


Figure 64– Plant Produced, PG 58-28, 12.5mm, 18.9% RAP (Surface layer) and PG 58-28, 19mm, 20.4% RAPRAS (Binder layer) (5, 10, and 20 Years)

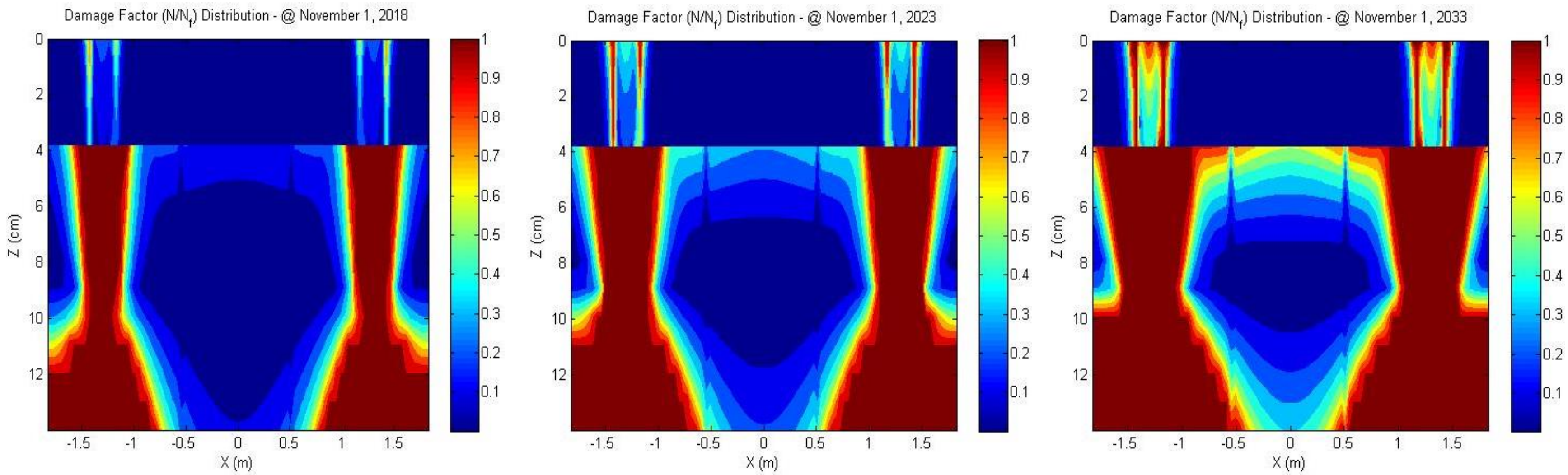


Figure 65– Lab Produced, PG 58-28, 12.5mm, 18.9% RAP (Surface layer) and PG 58-28, 19mm, 20.4% RAPRAS (Binder layer) (5, 10, and 20 Years)

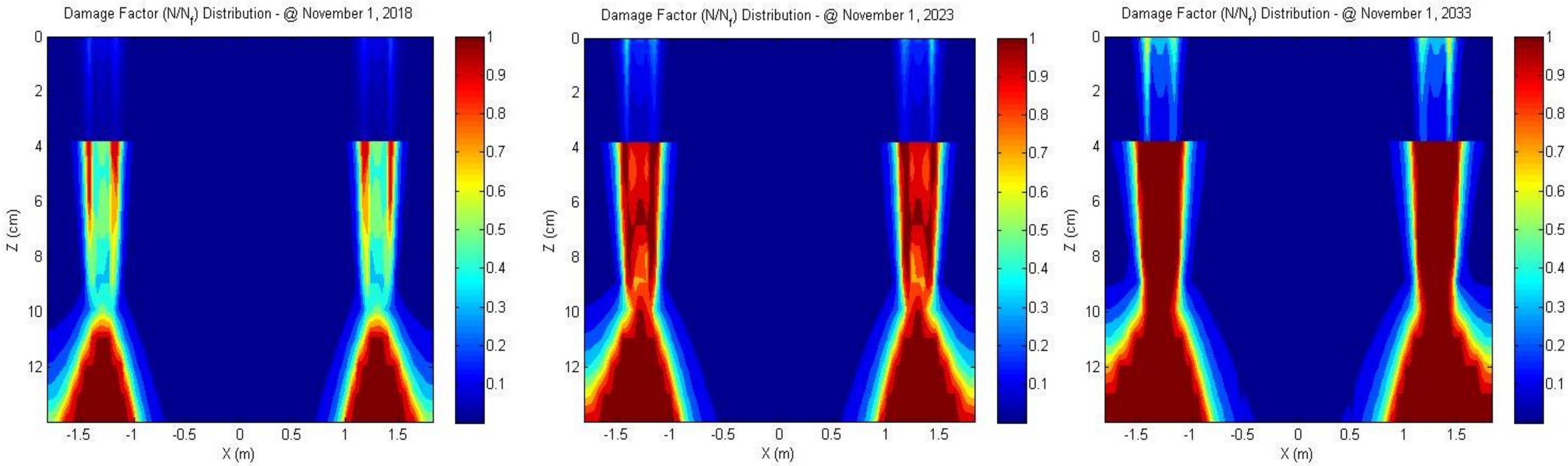


Figure 66– Plant Produced, PG 52-34, 12.5mm, 18.9% RAP (Surface layer) and PG 52-34, 19mm, 20.4% RAPRAS (Binder layer) (5, 10, and 20 Years)

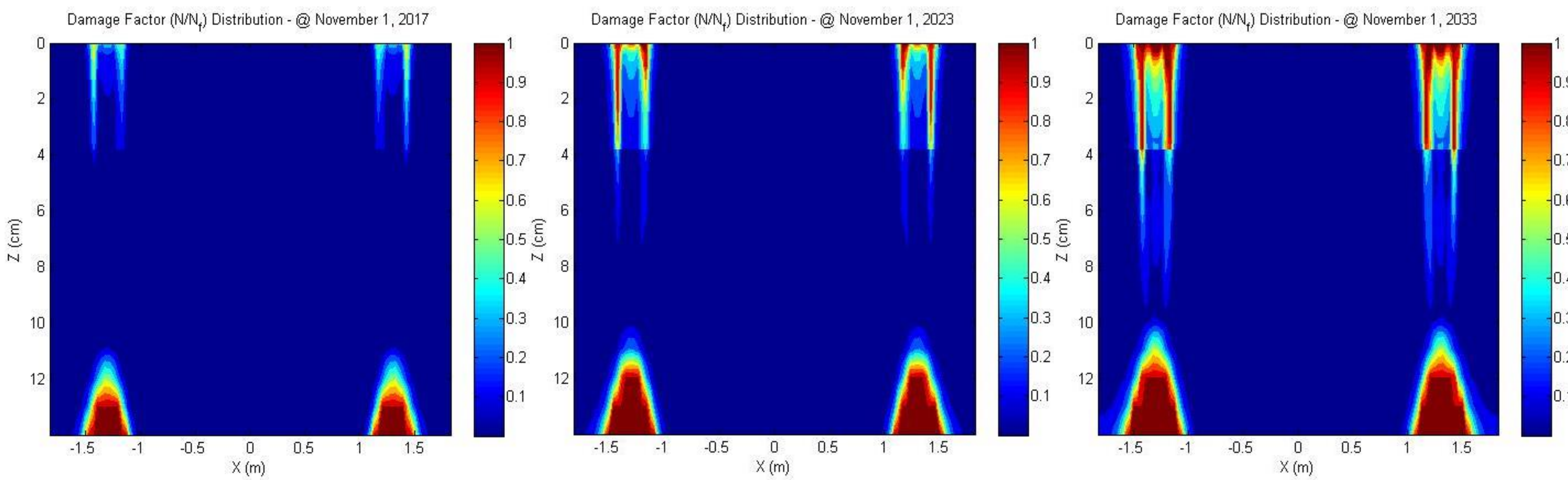


Figure 67– Lab Produced, PG 52-34, 12.5mm, 18.9% RAP (Surface layer) and PG 52-34, 19mm, 20.4% RAPRAS (Binder layer) (5, 10, and 20 Years)

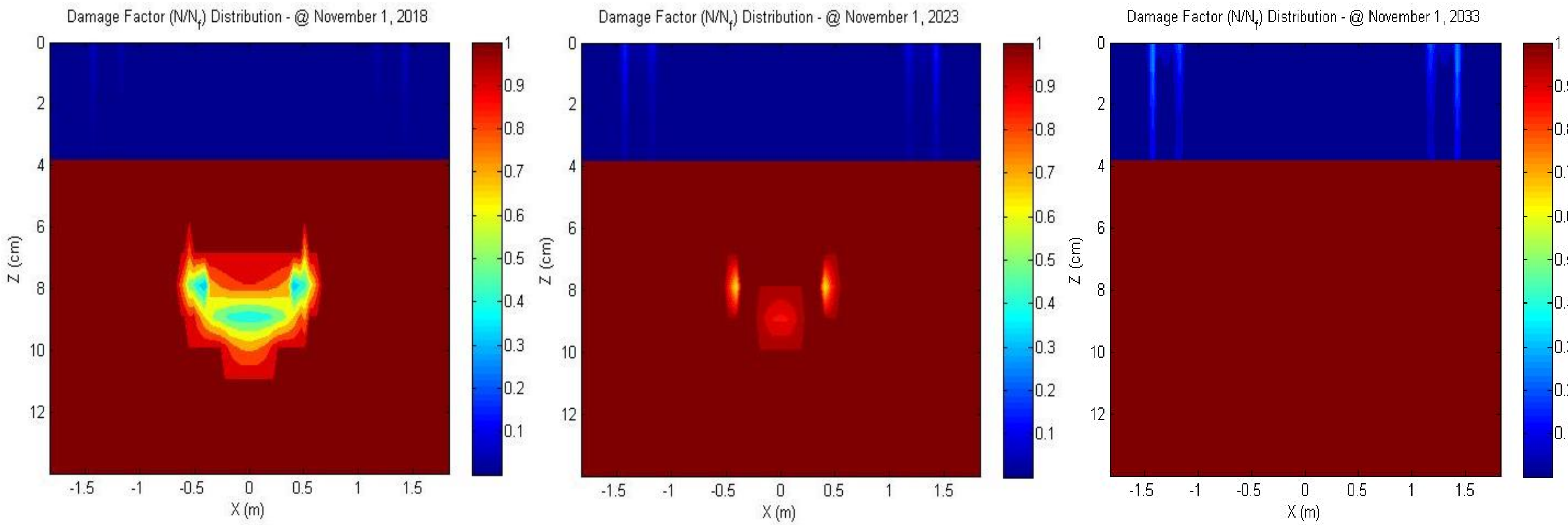


Figure 68– Plant Produced, PG 52-34, 12.5mm, 18.5% RAPRAS (Surface layer) and PG 52-34, 19mm, 20.4% RAPRAS (Binder layer) (5, 10, and 20 Years)

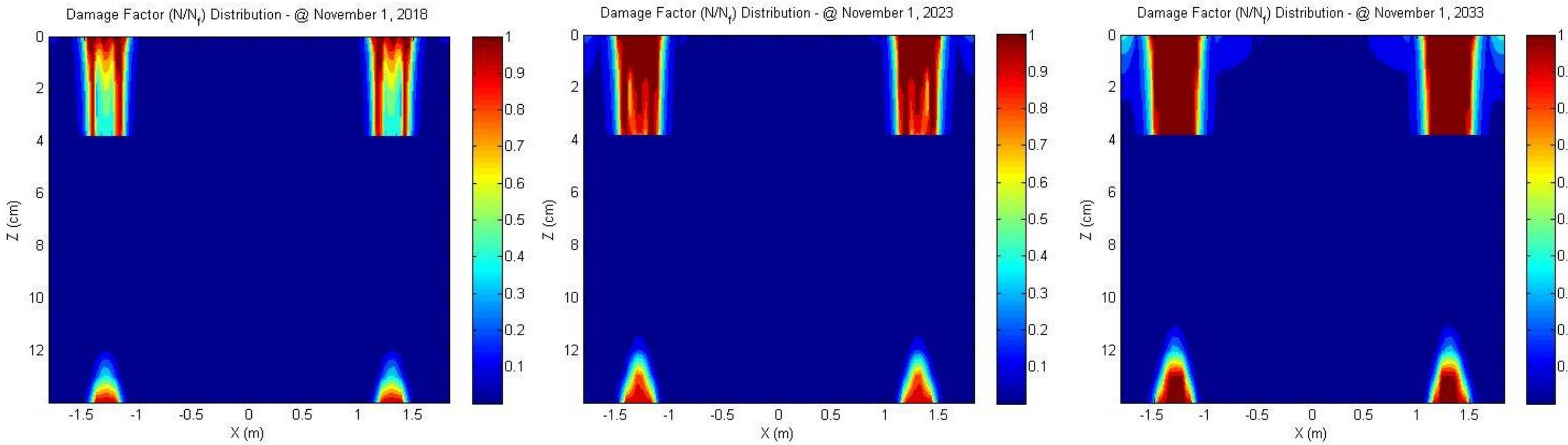


Figure 69– Plant Produced, PG 52-34, 12.5mm, 28.3% RAP (Surface layer) and PG 52-34, 19mm, 31.3% RAP (Binder layer) (5, 10, and 20 Years)

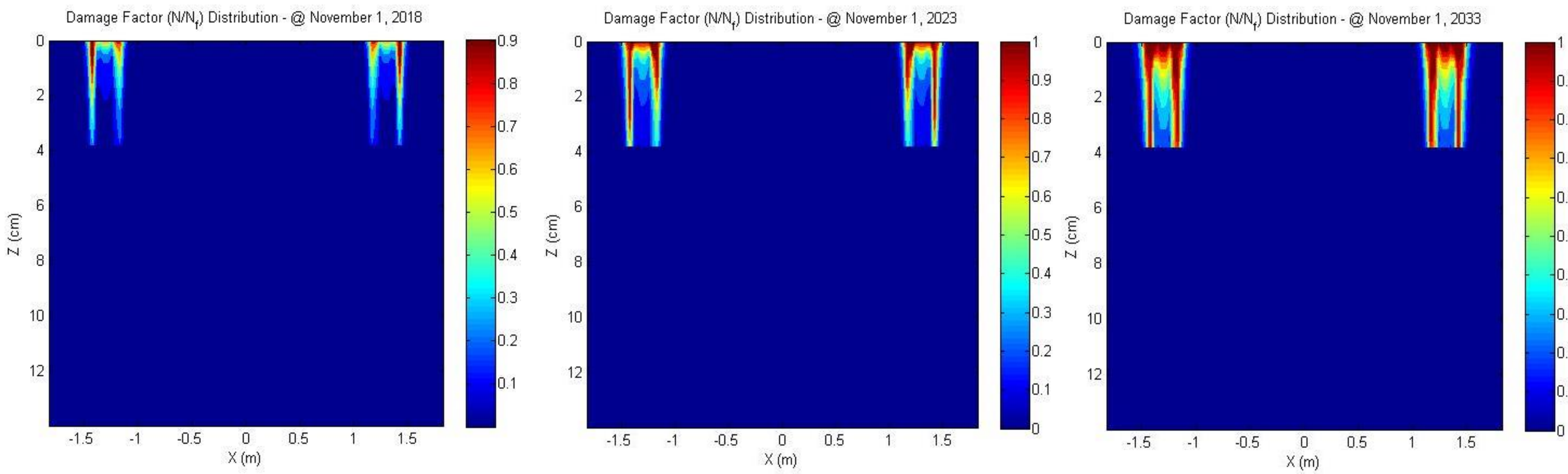


Figure 70– Lab Produced, PG 52-34, 12.5mm, 28.3% RAP (Surface layer) and PG 52-34, 19mm, 31.3% RAP (Binder layer) (5, 10, and 20 Years)

3.4. Plant versus Laboratory Production Comparisons

In this section, the overall rankings and comparisons of properties measured from plant produced and laboratory produced materials is presented.

3.4.1. Binder Comparison

Generally, the lab produced materials resulted in warmer high PG temperatures and warmer low PG temperatures than the plant produced materials from Lebanon. This means that the measurements from the laboratory produced materials would be more conservative in terms of making decisions on low temperature cracking performance of the materials. The ABCD cracking temperatures follow the same trend. The magnitude of the difference varies with the different binders and recycled content and while the differences are typically less than 6 degrees, in some cases the difference would result in a different PG grade for the material. The Hooksett materials showed the same trend for high PG temperature, but only the low RAP material showed colder low PG temp for plant produced materials. The G* master curves and associated rheological indices also generally showed that the lab materials are stiffer than the plant materials.

Tables 8 and 9 summarize the ΔT_{cr} and Glover-Rowe parameter values and relative rankings for the plant and laboratory produced Lebanon and Hooksett materials, respectively. The red color indicates that the value exceeded the proposed crack limit, yellow indicates the crack warning level has been exceeded and green indicates the value was below any of the limits and the material would be expected to have satisfactory performance.

The ΔT_{cr} values measured from the Lebanon plant materials were generally higher than lab produced 12.5 mm materials but lower than the 19 mm lab produced materials. The Hooksett plant materials all had lower ΔT_{cr} values than the lab materials. The results from the plant materials indicate that there are cracking concerns with all of the materials whereas the laboratory materials indicate some materials would perform satisfactorily. Depending on how the proposed limits translate to NH field performance of the materials, this could be an issue if decisions relied solely on testing of laboratory produced materials. In terms of ranking, the Lebanon lab materials produced similar rankings to the plant produced materials, however the Hookset materials rank completely different.

The values of the Glover-Rowe parameter measured from the laboratory materials were generally greater than those measured from the plant produced mixtures, which is more conservative from the perspective of making decisions regarding the use of the different materials. With one exception, the lab materials identified the same potential issues as the plant materials and the rankings between mixtures were very similar.

Table 8. Binder Parameter Rankings for Lebanon Plant and Laboratory Produced Materials

	Plant Material	Delta Tcr		G-R	
		Rank	Value	Rank	Value
Surface Layer	PG 58-28, 12.5mm, 28.3% RAP	1	-3.8	3	0.161
	PG 58-28, 12.5mm, 18.9% RAP	3	-6.4	2	0.123
	PG 52-34, 12.5mm, 28.3% RAP	2	-6.0	1	0.118
	PG 52-34, 12.5mm, 18.9% RAP	4	-7.7	4	0.316
Binder Layer	PG 58-28, 19.0mm, 31.3% RAP	1	-3.4	1	0.184
	PG 58-28, 19.0mm, 20.4% RAP/RAS	2	-7.0	3	0.577
	PG 52-34, 19.0mm, 31.3% RAP	3	-9.7	2	0.398
	PG 52-34, 19.0mm, 20.4% RAP/RAS	4	-13.8	4	0.716
	Lab Material	Delta Tcr		G-R	
		Rank	Value	Rank	Value
Surface Layer	PG 58-28, 12.5mm, 28.3% RAP	1	-1.9	4	0.491
	PG 58-28, 12.5mm, 18.9% RAP	2	-3.4	1	0.160
	PG 52-34, 12.5mm, 28.3% RAP	4	-6.3	2	0.163
	PG 52-34, 12.5mm, 18.9% RAP	3	-3.7	3	0.174
Binder Layer	PG 58-28, 19.0mm, 31.3% RAP	2	-6.5	1	0.321
	PG 58-28, 19.0mm, 20.4% RAP/RAS	1	-2.2	3	0.624
	PG 52-34, 19.0mm, 31.3% RAP	3	-7.5	2	0.350
	PG 52-34, 19.0mm, 20.4% RAP/RAS	4	-14.7	4	0.756

Table 9. Binder Parameter Rankings for Hooksett Plant and Laboratory Produced Materials

Plant Material	Delta Tcr	
	Rank	Value
PG 58-28, 12.5mm, 22.4% RAP	3	-3.85
PG 58-28, 9.5mm, 21.3% RAP	2	-3.31
PG 64-28, 9.5mm, 16.4% RAP	1	-1.24
Lab Material	Delta Tcr	
	Rank	Value
PG 58-28, 12.5mm, 22.4% RAP	1	-4.54
PG 58-28, 9.5mm, 21.3% RAP	3	-7.78
PG 64-28, 9.5mm, 16.4% RAP	2	-5.2

3.4.2. Mixture Comparison

The Lebanon plant produced mixtures had softer dynamic modulus values and higher phase angles than the lab produced mixtures but the opposite trend was observed for the Hooksett materials. This indicates that the laboratory short-term aging protocol was more severe than the aging that occurred in the Lebanon plant but less severe than the aging that occurred in the Hooksett plant. Tables 10 and 11 summarize the different mixture parameter rankings for the Lebanon and

Hooksett materials, respectively. The mixture-based black space parameter is the only parameter with suggested limits at this time (color coded similarly to the binder parameters); all of the other material parameter values have not been calibrated to field performance and are only used for qualitative assessments of relative performance. The LVECD rankings were determined from the contour plots presented previously even though not all sections showed failure happening after 20 years of loading. Also, aging over time was not considered in the analysis.

The lab produced materials for the Lebanon materials reflect the expected similar performance of the plant produced surface mixtures for the LVECD analysis, with the exception of the PG 52-34 28.3% RAP mixture. However, the lab materials did not represent the relative performance of the plant materials for the Lebanon binder mixtures and Hooksett mixtures.

Laboratory rankings using the N_f @G^R=100 parameter did not represent the plant produced material rankings for any of the mixtures, although the magnitudes of the values were all within the same overall range. The mix-based black space parameters for the laboratory materials generally differentiated between the expected "good" and "poor" performing plant materials however the relative rankings between the "poor" mixtures were not the same. The DCT parameter for the Hooksett mixtures generally showed good relative ranking between the laboratory and plant produced materials, however, the range in magnitude of the values was much greater for the plant materials than the laboratory materials.

Table 10. Mixture Parameter Rankings for Lebanon Plant and Laboratory Produced Materials

Plant Material		LVECD		Nf @ GR=100		Mix-Based black space		DCT (Gf/m)	
		Rank	Failure Points @ 20 years	Rank	Value	Rank	Value	Rank	Value
Surface Layer	PG 58-28, 12.5mm, 28.3% RAP	1	0	3	7848	4	1.07E+05	2	375
	PG 58-28, 12.5mm, 18.9% RAP	2	0	1	8926	1	2.90E+04	-	-
	PG 52-34, 12.5mm, 28.3% RAP	4	244	2	8116	3	6.25E+04	-	-
	PG 52-34, 12.5mm, 18.9% RAP	3	0	4	6637	2	5.61E+04	1	522
Binder Layer	PG 58-28, 19.0mm, 31.3% RAP	3	304	2	7899	4	9.16E+04	1	507
	PG 58-28, 19.0mm, 20.4% RAP/RAS	1	0	4	7063	1	2.98E+04	3	328
	PG 52-34, 19.0mm, 31.3% RAP	2	24	1	14595	2	4.20E+04	2	342
	PG 52-34, 19.0mm, 20.4% RAP/RAS	4	1107	3	7324	3	7.78E+04	4	207
Lab Material		LVECD		Nf @ GR=100		Mix-Based black space		DCT (Gf/m)	
		Rank	Failure Points @ 20 years	Rank	Value	Rank	Value	Rank	Value
Surface Layer	PG 58-28, 12.5mm, 28.3% RAP	2	58	2	6337	2	4.49E+04	-	-
	PG 58-28, 12.5mm, 18.9% RAP	4	98	3	6316	1	3.28E+04	-	-
	PG 52-34, 12.5mm, 28.3% RAP	3	70	4	4014	4	1.76E+05	-	-
	PG 52-34, 12.5mm, 18.9% RAP	1	56	1	11964	3	1.08E+05	-	-
Binder Layer	PG 58-28, 19.0mm, 31.3% RAP	3	252	4	4653	1	6.62E+04	-	-
	PG 58-28, 19.0mm, 20.4% RAP/RAS	4	692	1	14243	4	1.99E+05	-	-
	PG 52-34, 19.0mm, 31.3% RAP	1	0	3	7842	2	1.09E+05	-	-
	PG 52-34, 19.0mm, 20.4% RAP/RAS	2	62	2	9399	3	1.10E+05	-	-

Table 11. Mixture Parameter Rankings for Hooksett Plant and Laboratory Produced Materials

Plant Material	LVECD		Nf @ GR=100		Mix-Based black space		DCT (Gf/m)	
	Rank	Failure Points @ 20 years	Rank	Value	Rank	Value	Rank	Value
PG 58-28, 12.5mm, 22.4% RAP	2	30	2	9973	2	2.18E+05	3	239
PG 58-28, 9.5mm, 21.3% RAP	1	0	1	15150	3	2.45E+05	2	345
PG 64-28, 9.5mm, 16.4% RAP	3	132	3	4180	1	4.19E+04	1	418
Lab Material	**LVECD**		**Nf @ GR=100**		**Mix-Based black space**		**DCT (Gf/m)**	
	Rank	Failure Points @ 20 years	Rank	Value	Rank	Value	Rank	Value
PG 58-28, 12.5mm, 22.4% RAP	1	0	3	9478	3	1.27E+05	2	234
PG 58-28, 9.5mm, 21.3% RAP	3	214	2	11220	1	3.11E+04	3	232
PG 64-28, 9.5mm, 16.4% RAP	2	22	1	11619	2	1.13E+05	1	262

3.5. Binder versus Mixture Comparisons

In this section, the overall rankings and comparisons of properties measured from plant produced binders and mixtures are presented. The purpose of this comparison is to evaluate under what circumstances testing of binders is a reasonable representation of the mixture performance.

With respect to stiffness, the binder G* master curves and the mixture E* master curves all show that the laboratory produced mixtures were stiffer than the Lebanon plant produced mixtures. The binder testing also generally showed the same trends with respect to PG binder grade and recycled material content, however the magnitude of differences were larger with the mixture results than with the binder results.

To evaluate the relative expected cracking performance, the rankings of the different binder and mixture parameters can be evaluated. For thermal cracking, the ΔTcr and DCT rankings can be compared. The rankings for the Hooksett surface layer and Lebanon binder layer materials were similar; only two points were available for the Lebanon surface layer and they showed opposite rankings. Although rankings were similar, actual field performance of the different materials is needed to determine if the binder testing can accurately screen poorly performing mixtures at the design stage. In terms of fatigue cracking, the binder parameters (both ΔTcr and G-R) did not rank the materials in the same order as any of the mixture parameters. Field performance information is needed to determine which parameter(s) best represent the field.

4- Summary and Conclusions

The primary objective of this project was to provide guidance on the best way to evaluate the performance of high RAP mixtures during the mix design stage. Currently, the requirements are to evaluate the properties of binders that are extracted and recovered from plant produced mixtures; this effectively restricts the amount of recycled material that is used in the state. Also, it is recognized that the properties of binders that are extracted and recovered from recycled mixtures may not accurately represent or rank the properties or expected behavior of the mixtures. In this project, 14 different plant produced mixtures were evaluated; 11 of those were also produced in the laboratory. The mixtures encompass three different binder grades, three binder sources, three aggregate sizes, and recycled materials contents ranging from approximately 15-30% and including both RAP and RAS. Extensive characterization of both extracted and recovered binders and mixtures was done, with the focus on low temperature and cracking behavior.

The results of the testing showed that there are differences in the results obtained from laboratory produced materials and plant produced materials and also between binder and mixture testing. However, depending upon the evaluations desired, there were cases where the respective results would provide similar guidance or direction on selection or approval of materials. Binder testing could represent mixture testing in terms of relative stiffnesses (G* vs E*) between mixtures with different PG grades and recycled material content; binder testing also represented the differences between laboratory and plant produced materials. However, when cracking parameters were evaluated, there were significant differences in the rankings in some cases, with the potential for laboratory produced materials indicating that mixtures would perform satisfactorily in the field whereas plant produced materials indicated otherwise.

There are differences in the trends observed with the materials produced in the two different plants; the current short term aging protocol does not accurately represent the aging that occurred in either plant. However, the impact of these differences on the actual field performance of the materials is not clear. Observation of the field performance of the Lebanon mixtures over time (Hooksett mixtures were not placed on state jobs and the location was not tracked) will help provide information needed to evaluate this, as well as to evaluate the applicability of the binder and mixture cracking criterion to NH conditions. The research team recommends that field evaluation be continued along with evaluation of the aging behavior of the materials in the upcoming NHDOT project.