PERFORMANCE BASED SELECTION OF RAP-RAS IN ASPHALT MIXTURES

Final Report

SPR 755

Oregon Department of Transportation

PERFORMANCE BASED SELECTION OF RAP/RAS IN ASPHALT MIXTURES

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16. Abstract

Asphalt pavement technology has been driven by a desire to reduce the consumption of virgin oil products and improve the sustainability of vital ingredients required to produce pavement. The goal of the research study described in this report is to develop a strategy to select the type/quantity of recycled material, and PG grade for the virgin binder, of an asphalt mix to provide optimum performance in a given environment. This study compared the performance one mix design with five different quantities and combinations of recycled asphalt pavement (RAP) and recycled asphalt shingles (RAS) using an Asphalt Mixture Performance Tester (AMPT). Three different PG graded binders were utilized.

Based on the measurements of dynamic modulus and phase angles from the AMPT, it was concluded that a high RAP mixture with a soft binder grade could perform similarly to a low RAP mixture with a harder binder grade. Mixtures using RAS have different performance characteristics than those using RAP only. These mixtures were less susceptible to changes in loading frequency and temperature.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	millimeters squared	mm^2
ft^2	square feet	0.093	meters squared	m^2
yd^2	square yards	0.836	meters squared	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	kilometers squared	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	ml
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	meters cubed	m^3
yd^3	cubic yards	0.765	meters cubed	m^3
	NOTE: Volumes greater than 1000 L shall be shown in m^3.			
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams	Mg
		TEMPERATURE (exact)		
°F	Fahrenheit	(F-32)/1.8	Celsius	°C

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	millimeters squared	0.0016	square inches	in^2
m^2	meters squared	10.764	square feet	ft^2
m^2	meters squared	1.196	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	kilometers squared	0.386	square miles	mi^2
		VOLUME		
ml	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	meters cubed	35.315	cubic feet	ft^3
m^3	meters cubed	1.308	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.205	pounds	lb
Mg	megagrams	1.102	short tons (2000 lb)	T
		TEMPERATURE (exact)		
°C	Celsius	1.8C+32	Fahrenheit	°F

*SI is the symbol for the International System of Measurement

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DISCLAIMER

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1.0 INTRODUCTION

In recent years, asphalt pavement technology has been driven by a desire to reduce the consumption of virgin oil products and improve the sustainability of vital ingredients required to produce pavement. The goal of the research study described in this report is to develop a strategy to select the type and quantity of recycled material, and, PG grade for the virgin binder, for an asphalt mixture to provide optimum performance in a given environment. This study compared the performance of one mix design with five different quantities and combinations of recycled asphalt pavement (RAP) and recycled asphalt shingles (RAS) using an Asphalt Mixture Performance Tester (AMPT). In addition, three different binder grades were utilized.

Based on the measurements of dynamic modulus and phase angles from the AMPT, it was concluded that a high RAP mixture with a soft binder grade could perform similarly to a low RAP mixture with a harder binder grade. Mixtures using RAS have different performance characteristics than those using RAP only. These mixtures were less susceptible to changes in loading frequency and temperature.

1.1 BACKGROUND

Incorporating recycled asphalt material into hot mix asphalt has become very common practice for pavement construction due to the potential benefits. The majority of asphalt binder used in pavement originates from petroleum refining and it is known that petroleum is not a sustainable resource. Due to the rising cost of petroleum, recycling binder can reduce the cost of pavement construction. Utilizing reclaimed binder from recovered pavement and other recycled materials reduces the consumption of fossil fuels and improves the sustainability of binder. Reclaimed asphalt pavement (RAP) binder is the most convenient way to utilize recycled materials because both the aggregate and binder are being reused. However, there is also considerable potential to utilize recycled asphalt shingles (RAS) which contain a very hard binder with a much smaller and finer proportion of aggregate. Collectively, these two sources are referred to as recycled asphalt materials.

Current practice in hot mix asphalt (HMA) technology is driven by a desire to reduce the consumption of virgin binder products and improve the sustainability of vital ingredients required to produce pavement. Developing strategies to incorporate more recycled binder reduces cost of production and, if used properly, can improve the performance of asphalt pavement. A major challenge for using recycled material to replace virgin binder is the stiffening performance properties of the aged binder in the RAP or RAS.

1.2 PROBLEM STATEMENT

Currently, the Oregon Department of Transportation (ODOT) limits RAP to replace no more than 30% of the virgin binder and RAS to replace no more than 20% virgin binder (5% by weight). This is due to the risk of premature cracking associated with high quantities of recycled binder. Strategies designed to reduce the risk of premature cracking from high RAP/RAS must be investigated to determine the overall effects on the performance. The performance measures include:

- Viscoelastic properties
- Cracking resistance
- Rutting resistance

These performance measurements are necessary in designing HMA for predicted loads and determining how the pavement will experience distress over time.

1.3 OBJECTIVES

The goal of this research is to help develop a strategy for ODOT to select the type/quantity of recycled material, quantity of and the PG grade for the virgin binder of an asphalt mix to provide optimum performance in a given environment. The objectives of this research are as follows:

- Develop master curves to compare the viscoelastic properties for specimens with different amounts/types of recycled material.
- Estimate the effects of changing the virgin binder grade with respect to cracking resistance and rutting resistance.
- Interpret any relationships between the effects of changing the virgin binder and recycled binder.

1.4 SCOPE

This laboratory study investigated the effects of using RAP and RAS to replace virgin binder for HMA and the effects of selecting softer virgin binder grades. Comparisons were drawn from different combinations of the recycled material that replaced 20%, 30%, and 40% virgin binder. The aggregate gradation, binder quantity, and air content for all the specimens were held constant to isolate the effects of the recycled material and virgin binder selection. No long term aging effects were investigated in this study.

This laboratory study was preceded by a literature review developed in 2013 by Uma Dharmadasa who was the graduate research assistant for this project until the summer of 2013 *(Charmadasa 2013)*. The review analyzed similar asphalt research that had investigated the effects of high RAP and RAS content in HMA. Following completion of the literature review, the initial scope of the laboratory study was modified. Please see appendix A for the change of scope details.

This study compared the performance of one mix design with various quantities and combinations of recycled asphalt pavement (RAP) and recycled asphalt shingles (RAS) using an

Asphalt Mixture Performance Tester (AMPT). In addition, three different binder grades were utilized.

The AMPT device is capable of measuring the dynamic modulus for a range of loading times and temperatures resulting in master curves than enable comparison of mixture performance. The comparisons can be made from high to low temperatures and slow to fast loading rates. The AMPT also produces phase angles and Flow number data which were also analyzed in this study.

The following chapters present the material, specimen preparation, testing methods, testing results, and conclusions for this study. In addition, this report provides recommendation for future research to extend and compare the data from this study to maximize the results. The most notable recommendation is to perform a Mechanical Empirical Performance Design Guide (MEPDG) analysis on the data to model the performance of the mixtures tested for appropriate pavements and climatic conditions. It is also recommended that a thorough comparison of the results of this study is made with the results from a study by the National Center for Asphalt Technology (NCAT) on the use of high recycled content mixes for thin overlays *(Taylor 2015)*. The NCAT study was done in collaboration with the Asphalt Pavement Association of Oregon (APAO) and used materials from the same sources reported here.

2.0 MATERIALS

The following chapter discusses the material used in this study including the supplier, quality tests conducted and other relevant data. All material was supplied by local vendors to better relate the results of this study to local Oregon region.

2.1 AGGREGATE

The virgin aggregate used in this research was donated by Old Castle from their River Bend Sand and Gravel source in Salem, Oregon. The aggregate was separated into ½ to #4, #4-#8, and #8-0 stockpiles with no bag house. The gradation and dust content for each stockpile was analyzed by the Asphalt Pavement Association of Oregon (APAO) laboratory. AASHTO T-84 *(AASHTO T-84-10 2010)* and AASHTO T-85 *(AASHTO T-85 2010)* were used to determine the specific gravity for the coarse and fine aggregate. See Appendix B for the individual stockpile aggregate specific gravities design summary.

2.2 BINDER

The virgin binder used for this study was provided by McCall Oil and Chemical Corporation in Portland, Oregon (McCall) in three different binder grades; 64-22, 58-28, and 58-34. The temperature curve used to determine the mixing and compaction range for each binder grade was provided by McCall. Please see Appendix D for the temperature curves for the binder.

2.3 RECYCLED ASPHALT PAVEMENT (RAP)

All RAP used was provided by Old Castle from the local stockpile and was tested by both ODOT and APAO using ODOT TM 319 *(ODOT TM 319 undated)* to measure the theoretical maximum specific gravity. AASHTO T-308 *(AASHTO T-308 2010)* was used to determine the binder content of the RAP which was determined to be 6.0%. AASHTO T-30 *(AASHTO T-30-10 2010)* was used to determine the gradation of the RAP after AASHTO T-308 *(AASHTO T-308 2010)* was conducted.

2.4 RECYCLES ASPHALT SHINGLES (RAS)

All RAS used was provided by Old Castle from the local stockpile and was tested by both ODOT and APAO using ODOT TM 319 *(ODOT TM 319 undated)* to measure the theoretical maximum specific gravity. AASHTO T-308 *(AASHTO T-308 2010)* was used to determine the binder content of the RAS which was determined to be 18.2%. AASHTO T-30 *(AASHTO T-30-10 2010)* was used to determine the gradation of the RAS after AASHTO T-308 *(AASHTO T-308 2010)* was conducted. RAS used in this study contained two parts roof tear off and one part factory waste. This blend of RAS is the current supply for the state of Oregon but if the use of RAS is increased then the blend of RAS will likely result in a higher concentration of roof tear off. The true RAS blend in the United States is 95% roof tear off and 5% factory waste.

3.0 SPECIMEN PREPARATION

The following chapter discusses the specimen preparation process for the AMPT specimens including the quality control tests used. The main goal in preparing the specimens was to isolate the variables of interests to better measure the effects of changing these variables. The two variables of interest in this study are the recycled material quantities and the virgin binder grade.

In order to compare the effects from changing the recycled content for each mix, it was required to maintain equivalent air content, gradation, and physical dimensions. This required conducting multiple quality control checks to ensure that the only significant difference between the specimens is the quantity and type of recycled binder in the mix. The mix designs chosen for comparison are listed in Table 3.1.

Table 3.1: RAP and RAS Combinations and Binder Grades Used in this Study

Combination #	RAP %	RAS %	Virgin Binder Replaced	Binder Grade	# of Specimens Tested
1	0	5	20%	64-22	2
1	0	5	20%	58-28	2
2	30	0	30%	64-22	2
2	30	0	30%	58-28	2
2	30	0	30%	58-34	2
3	17	3	30%	64-22	2
3	17	3	30%	58-28	2
4	40	0	40%	64-22	2
4	40	0	40%	58-28	2
4	40	0	40%	58-34	2
5	19	5	40%	64-22	2
5	19	5	40%	58-28	2

Each row of cells in Table 3.1 indicates one recycled binder combination at one binder grade. The 0% RAP, 5%RAS combination replaces about 20% of the total binder used with recycled binder from the shingles. The 30% RAP and 17% RAP, 3%RAS both replace 30% of the total binder used with recycled binder and the 40% RAP and 19%RAP, 5% RAS both replace 40% of the total binder used with recycled binder.

It required two to four weeks to prepare specimens for each row of cells and an additional week to test. A minimum of two specimens were tested for each cell in the test matrix. The long preparation time is due to the laboratory limitations and quality control measures each combination had to undergo. Please see Appendix A for a list of the quality control tests.

For the scope of this study, it was decided by the Technical Advisory Committee to not include a pure virgin binder/virgin aggregate combination because the majority of the mixtures placed in Oregon contain recycled material.

3.1 GRADATION

It is the intent of this study to isolate and compare the effects of virgin and recycled binder on the performance of hot mix asphalt concrete. This required keeping the aggregate gradation for each mix design identical with respect to the recycled content. The virgin aggregate originates from three stockpiles which are ½-#4, #4-#8, and #8-0. Each stockpile had multiple samples dry-sieved and wet-sieved to determine the approximate gradation for each stockpile and dust content for each aggregate size. The specific gravity for each stockpile was measured following the process from AASHTO T-84 *(AASHTO T-84-10 2010)* and AASHTO T-85 *(AASHTO T-85-10 2010)*. The gradation of the recycled material was measured using AASHTO T-30 *(AASHTO T-30-10 2010)* which measured the gradation of the recycled material after removal of the binder. The target job mix formula (JMF) gradation is based on an ODOT Level 4 dense graded mix design and is show in Table 3.2 with the measured stockpile gradations for virgin aggregates and recycled materials. Appendix C shows an example of aggregate blending and batching calculations required for each mixture.

Table 3.2: Target JMF Gradation for All Mixtures and Measured Stockpile Gradations

Stockpile	Target	1/2" - #4	#4 - #8	#8 – 0	RAP Aggr.	RAS Aggr.
Percentage, P_{Sj}	%Pass	Gradation for each aggregate source				
3/4"	100	100	100	100	100	100
1/2"	98	94.94	100	100	97.3	99.7
3/8"	83	53.5	99.1	100	88	99.4
1/4"	59	16	65	100	71	99
#4	49	9	43	99.68	61.2	97.3
#8	31	2.5	12.5	81.12	43.1	94.4
#16	22	2	10	55.82	30.5	77.3
#30	16	2	8	38.06	22.7	59.1
#50	11	0.96	2.78	28	16.6	51.4
#100	8	0.92	2.24	19	12.2	43.4
#200	6.3	0.79	2.05	15	8.61	35.4

3.2 BINDER CONTENT

The percentage of total binder for each specimen is targeted for 6.0% by weight of mix including the recycled binder. For this study, it was assumed that all the recycled binder from the RAP and RAS would be effectively mobilized in the final mixture. The procedure AASHTO T-308 *(AASHTO T-308 2010)* was used to determine the quantity of binder from the recycled material and it was revealed that the RAP contained 6.0% binder by weight and the RAS contained 18.2% binder by weight.

3.3 COMPACTION

All specimens were compacted with a gyratory compactor inside a 150 mm diameter mold to a target height depending on the air content curve. With a dense mix design and high target air content, the number of gyrations needed to compact the specimens were very low ranging from 15 to 45 gyrations. The low compaction made removing the specimens from the mold very sensitive and could take up to 45 minutes of cooling before removal. The material had to be poured evenly inside the mold to prevent segregation of the aggregate. Please see Appendix A for the compaction results for the specimens used in the study.

3.4 AIR CONTENT

The target air content for all specimens is 7.0% +/ – 0.5% and must be uniform throughout the specimen. Each design corresponding to each cell in Table 1 required two specimens to be cut into thirds for a bulk specific gravity test to determine if the air within the specimen was uniformly distributed. Specimens with non-uniform air content will distribute internal loads differently which could lead to misleading results. The overall air content of the specimen is controlled by the gyration process and volume of material. The uniformity of the air content is controlled by pouring the material into the gyratory molds after curing the specimen. Please see Appendix A for examples of the measured air contents.

3.5 DIMENSIONS

All specimens prepared for the dynamic modulus test via the Asphalt Mixture Performance Tester (AMPT) are required to be 150mm tall +/– 2.5mm and must be level within 0.5mm. The specimen must have a diameter of 100mm with a variability of 2.5mm. This will assure that all specimens being compared will receive and transfer loads relatively equivalent. This was achieved by coring the material after compaction and trimming the top and bottom. A wet grinder was used to make sure the ends of the specimen were parallel.

3.6 VARIABILITY

Even with extensive quality control checks and consistent mixing practices, the specimens being prepared showed enough variability that additional specimens had to be prepared until two specimens met the air void content required. This added an unexpected amount of lab work, slowing down the progress of the research. The variability did reduce over time but was still significant enough to make the specimen fail the air content requirements periodically. According to experienced asphalt technicians, the AMPT specimen preparation success rate can be as low as 30% where 7 out of 10 specimens are invalid. The success rate is highly dependent on the available equipment and level of experience of the technician. This study was able to increase the success rate to over 50% by the end of test program. This improvement was mainly due to the use of a wet grinder and professional laboratory practices. This latter expertise was acquired through significant training of the OSU researcher by Oregon Department of Transportation (ODOT) and Asphalt Pavement Association Oregon (APAO) staff.

During the early stages of the research, it would take almost three days to determine the air content of a specimen after compaction of the material, by the end of the research this time was reduced to two days thanks to the installation of a cooling and drying station in the laboratory. Every specimen that failed to meet the 7.0% +/- 0.5% air content requirement consumed an additional 2 hours of sieving, 5 hours of mixing, 8 hours of cooling and drying, and 2 hour of batching, specimen preparation, and testing. Once this is complete, the specimen would undergo the 2 day process to measure air voids.

3.7 CONDITIONING

AASHTO R 30-10 *(AASHTO R 30-10 2010)* section 7.1, mixture conditioning for volumetric design, was followed for the conditioning procedure of the specimens instead of section 7.2, short term conditioning for mixture mechanical property testing. Section 7.1 requires 2 hours of oven aging at 135 Celsius rather than 4 hours of oven aging at the mix compaction temperature. The impact of following the procedure in section 7.1 instead of 7.2 is a reduction of the measured stiffness of the material. The relationship between each combination of RAM and virgin binder grade should not be impacted.

4.0 TESTING METHODS

To achieve the goal of this study, it was necessary to compare the performance of HMA mixtures with different types and quantity of recycled material and different binder grades. Specimens were prepared following procedure AASHTO PP 60-14 *(AASHTO PP 60-14 2014)*, specimen preparation for dynamic modulus test. Master curves were then developed from the data using procedure AASHTO PP 61-13 *(AASHTO PP 61-13 2013)*. Master curves for dynamic modulus and phase angle enable mixtures to be compared and their fatigue and deformation performance to be inferred. The data from the dynamic modulus tests can also be used to predict field fatigue cracking and rutting of the asphalt pavements via Mechanistic Empirical Pavement Design Guide (MEPDG) *(Zhou et al. 2015)*. A flow number test was conducted on the majority of specimens used for the dynamic modulus tests to provide an additional evaluation of susceptibility to rutting.

There is considerable recent literature available concerning the determination of dynamic modulus and phase angle and other approaches to characterize HMA mixtures (*Bonaquist 2001; Bowers 2015; Christensen and Bonaquist 2015; Cooper et al. 2015*; *Ma et al. 2015; Mangiafico et al. 2015; Mogawer et al. 2015a; Mogawer et al. 2015b*; *Moraes and Bahi 2015; National Center for Asphalt Technology 2014; Robbins et al. 2015; Sabouria et al. 2015; Wang et al. 2015; Yin and Ishee 2015; Zhou et al. 2015)*. Much of this relates to recycled materials.

4.1 DYNAMIC MODULUS

The dynamic modulus is used to evaluate the performance of asphalt mixtures for a range of temperatures and load frequencies. The testing procedure described in AASHTO TP 79-13 *(AASHTO TP-79-13 2013)* was used for this study. Temperatures of 4, 20 and 40°C, and frequencies of 0.01, 0.1, 1 and 10 Hz were used. The 0.01 Hz frequency was used only at 40°C. Therefore, each specimen was tested at 10 combinations of temperature and frequency of loading.

The parameters for this test included maintaining the temperature, confining pressure, drift for the applied load, standard error for the applied load, average drift of deformations, standard error for deformations uniformity coefficient for the deformations and the phase angles.

The dynamic modulus and phase angle data are strong indicators of mixture performance. Essentially, a mixture with a high dynamic modulus should be very resistant to rutting but could be susceptible to premature cracking. Conversely, a mixture with low dynamic modulus should be very resistant to premature cracking but could be susceptible to rutting *(National Center for Asphalt Technology 2014)*. The phase angle is an indication of the viscous response of a mixture, with lower phase angles suggesting a higher tendency to cracking but resistance to deformation.

The dynamic modulus data obtained using the Asphalt Mixture Performance Tester (AMPT) for each mixture was converted into a master curve displaying the dynamic modulus with respect to the load frequency. Appendix E includes examples of the full set of data generated for replicate specimens, including details of how the data can be presented as master curves.

Chapter 5 includes a full set of master curves for all specimens tested and a discussion of the results. The chapter also includes master curves of phase angle with respect to load frequency. The phase angle is the delay between the maximum stresses applied to a specimen and the maximum stress a specimen experiences.

Although master curves are typically used to display dynamic modulus and phase angle, the same data can be displayed in in a more conventional format showing curves for each test temperature as well as the variation with loading frequency. Such plots are provided in Appendix F in Figures F1 to F24.

4.2 FLOW NUMBER TEST

The flow number test measures the rutting performance of the asphalt involving a specific stress level in a dynamic form. The procedure described in AASHTO TP 79-13 *(AASHTO TP-79-13 2013)* for an unconfined test was followed for this study. The test is conducted at 54.7°C with an average deviator stress of 600 kPa. This test is intended to represent field loading from free flowing (rather than slow moving) traffic. The flow number corresponds to the minimum rate of change of compliance for an HMA mixture. Higher flow numbers indicate a higher resistance to rutting under free flow speeds *(Bonaquist 2011)*. The flow tests were completed with the same specimens produced for the dynamic modulus tests. This is not recognized as the current standard of practice. However, additional information regarding rutting was obtained with little additional time or expense.

5.0 RESULTS AND DISCUSSION

This chapter presents the results of the dynamic modulus tests for the five different RAP/RAS mixture combinations with three virgin binder grades. The Dynamic Modulus Master Curves are presented and discussed, followed by presentation and discussion of the corresponding Phase Angle diagrams. The Flow Numbers are also presented and discussed, followed by sections that discuss the effects of the recycled binder, virgin binder and RAP/RAS content.

5.1 DYNAMIC MODULUS

This section presents the Dynamic Modulus Master Curves for the five different RAP/RAS combinations and three virgin binder grades. Each Master Curve represents the average measurements of two specimens as recommended by AASHTO TP 79-13 *(AASHTO TP-79-13 2013)*. The coefficient of variation (CV) in the dynamic modulus measured for each pair of results is generated by the software used with the AMPT. These were compared with the value of 9.2 percent (for properly conducted tests) provided in AASHTO TP 79-13 *(AASHTO TP-79-13 2013)*. Figure 5.1 shows the dynamic modulus measured at 1Hz and 20°C for the two specimens at each RAP/RAS combination and each virgin binder grade. At these test conditions, only one pair of results has a CV higher than 9.2percent, i.e. for the specimens with 30 percent RAP and with the 64-22 binder.

As noted in Chapter 4, each specimen was tested at 10 combinations of temperature and frequency of loading. For the 24 specimens tested, the CV was less than 5.0 percent for the majority of paired specimens at all 10 combinations. Exactly 50 percent of the specimens had no CV values greater than 9.2 percent for all 10 combinations. The other 50 percent of specimens had CV values greater than 9.2 percent for measurements at 40°C. Only one pair of specimens (with 30 percent RAP and with the 64-22 binder) had CV values significantly greater than 13 percent; the value given in AASHTO TP 79-13 *(AASHTO TP-79-13 2013)* for "properly conducted dynamic modulus tests". It should be noted that in NCHRP Report 702 [10] Bonaquist shows that the CV is typically much more than 10 percent for low modulus mixtures (less than 1000 MPa or 150 ksi), and, could be more than 20 percent at very low modulus. Hence, it is not surprising that the highest CV values observed in this study were for tests conducted at 40°C.

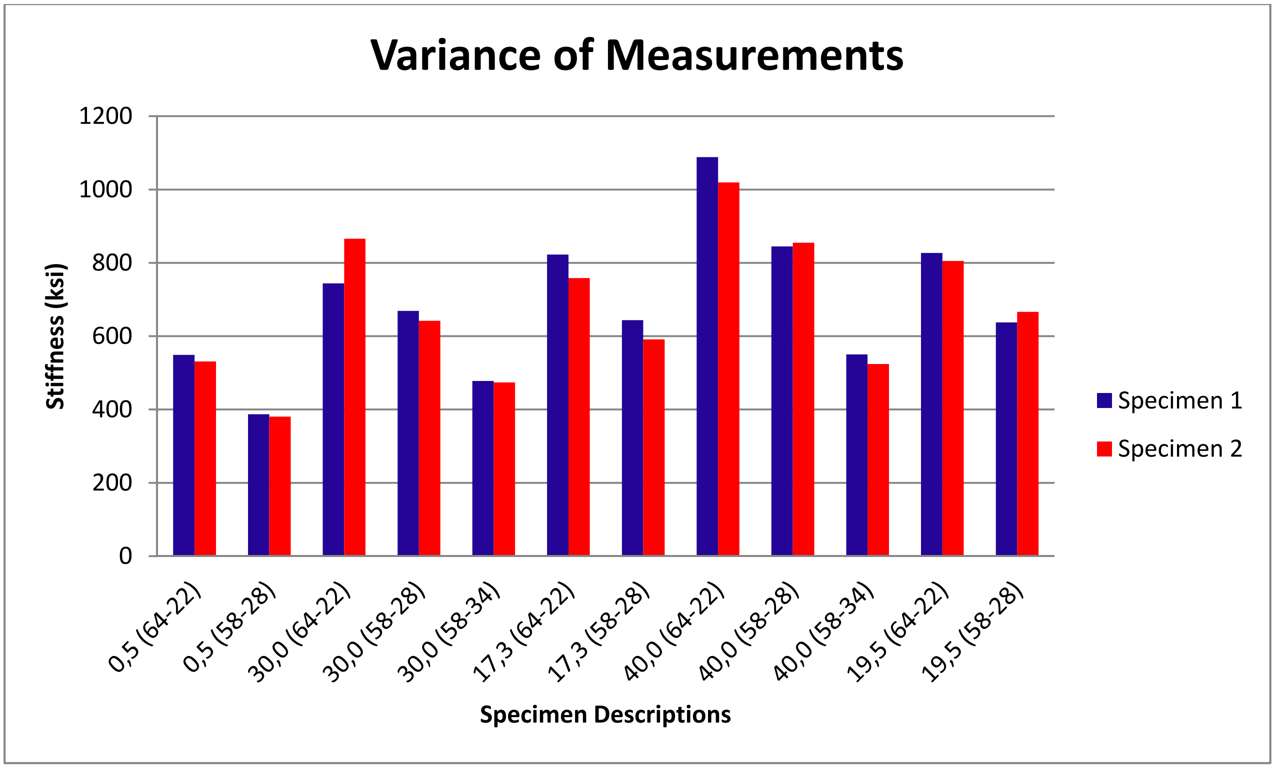

Figure 5.1: Variance of Stiffness at 20°C and 1 Hz Between the Specimens at Each RAP/RAS Combination and Virgin Binder Grade

Figures 5.2 through 5.6 show the Master Curves for each combination of RAP/RAS with different grades of virgin binder. Figure 5.7 is a comparison of the 30% RAP and the 17%RAP/3%RAS mixtures with the different grades of virgin binder. Both of these combinations replace 30% of the total binder with recycled binder. Figure 5.7 shows that the dynamic modulus response to frequency is affected by the virgin binder grade and the type of recycled material. Figure5.8 shows similar dynamic modulus comparisons between the 30% RAP and 40% RAP mixtures. Figure 5.9 shows comparisons for the 17%RAP/3%RAS and the 19%RAP/5%RAS mixtures. Figure 5.10 shows comparisons for the 40%RAP and 19%RAP/5%RAS mixtures.

Upper and lower limits of load frequency are included in Figures 5.7 to 5.10 to represent the typical range of highway traffic speeds. The upper limit represents traffic moving at free flow speeds on a highway while the lower limit represents a traffic jam (very slow moving traffic). The dynamic modulus values over this range of load frequency are also very similar to those measured at 20°C.

When the effects of the RAP mixtures are compared to the effects of the RAP/RAS mixtures, it is observed that the RAS reduces the slope of the dynamic modulus with respect to load frequency, particularly at low stiffness levels. This is seen in figures 5.7 and 5.10 where the 30% RAP and 17%RAP/3%RAS are compared and the 40% RAP and 19% RAP/5% RAS are compared. Similarly, Figure 5.9 shows that for the RAP/RAS mixture with the most RAS has the lower slope. Since the master curves of the RAP only specimens are not parallel with the RAP/RAS specimens, it seems that the mixtures with RAS have different performance characteristics than those with RAP only. Specifically, the deformation characteristics may be improved. However, cracking susceptibility may be compromised by somewhat higher stiffness at high stiffness conditions.

Similar observations can be made by reviewing the figures in Appendix F, i.e. Figures F1 through F12.

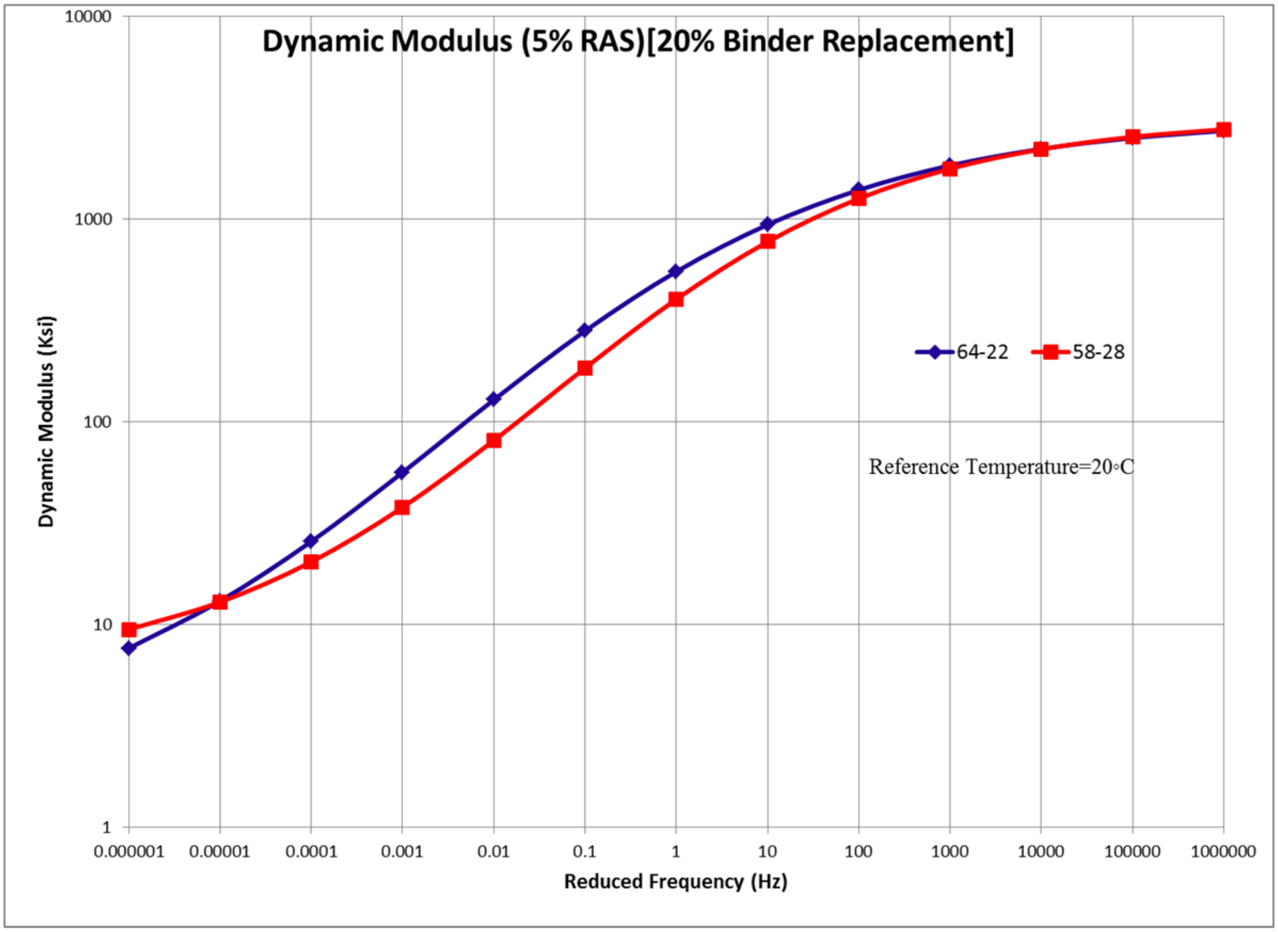

Figure 5.2: Dynamic Modulus for the 5% RAS Mixtures with Different Virgin Binder Grades

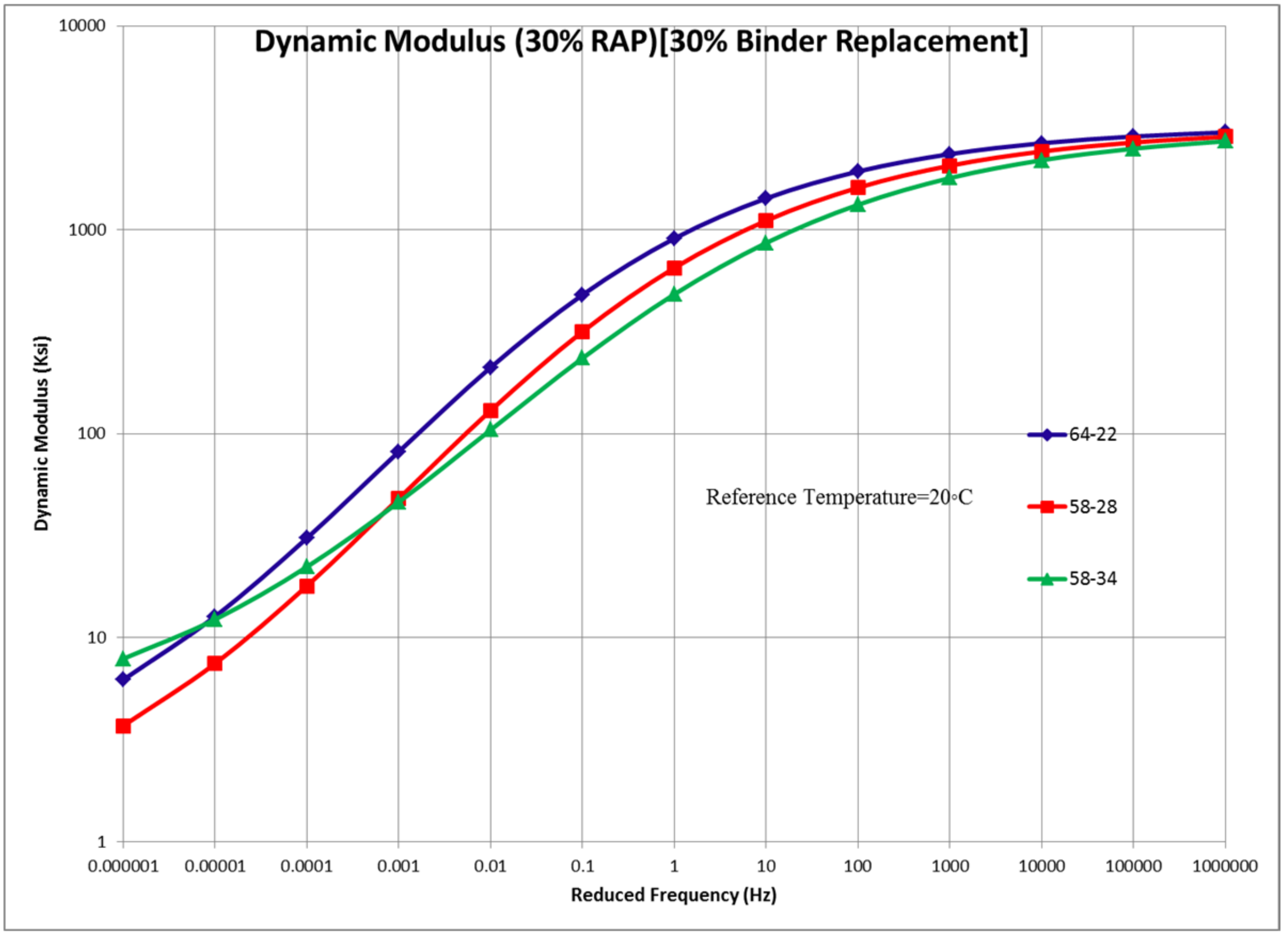

Figure 5.3: Dynamic Modulus for the 30% RAP Mixtures with Different Virgin Binder Grades

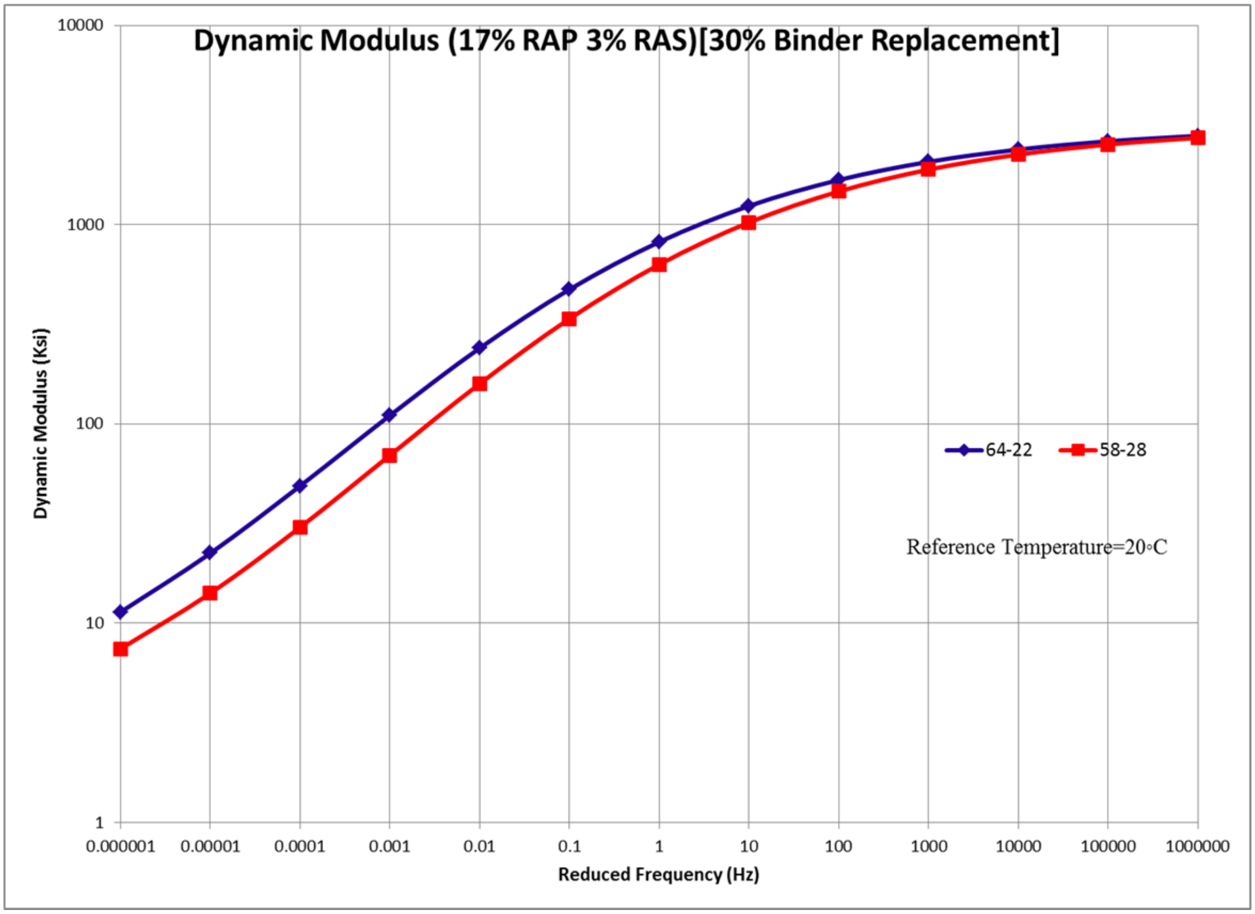

Figure 5.4: Dynamic Modulus for the 17% RAP/3% RAS Mixtures with Different Virgin Binder Grades

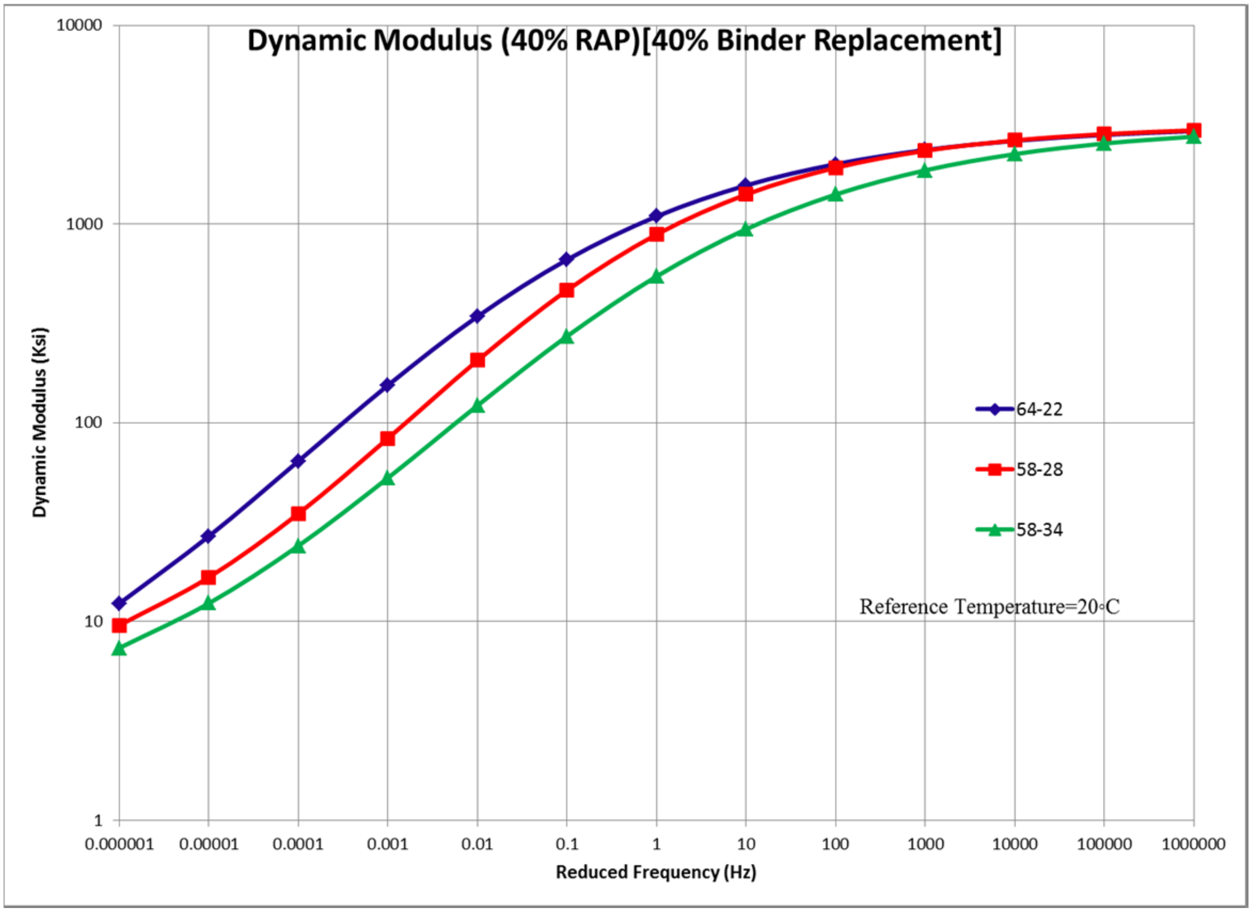

Figure 5.5: Dynamic Modulus for the 40% RAP Mixtures with Different Virgin Binder Grades

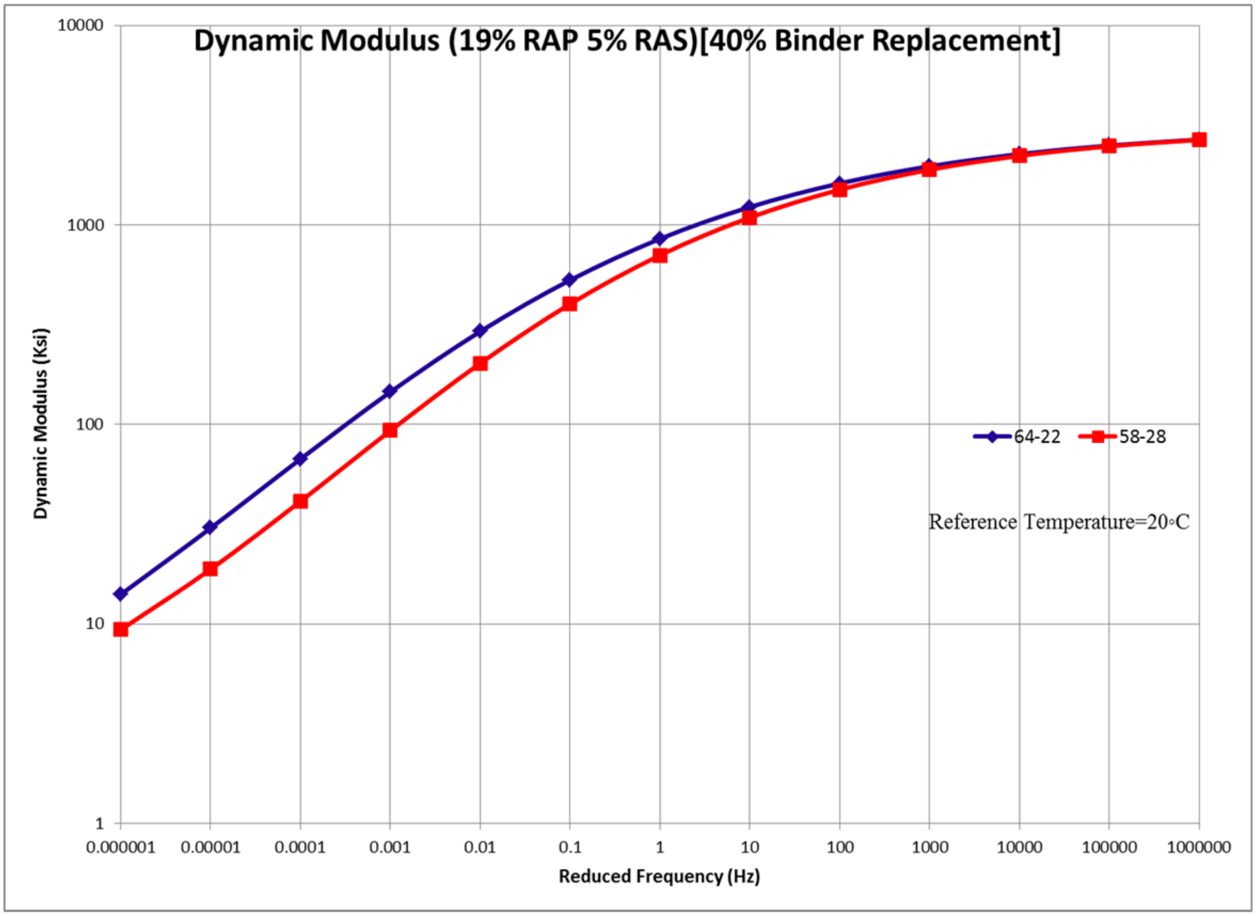

Figure 5.6: Dynamic Modulus for the 19%/5% RAS Mixtures with Different Virgin Binder Grade

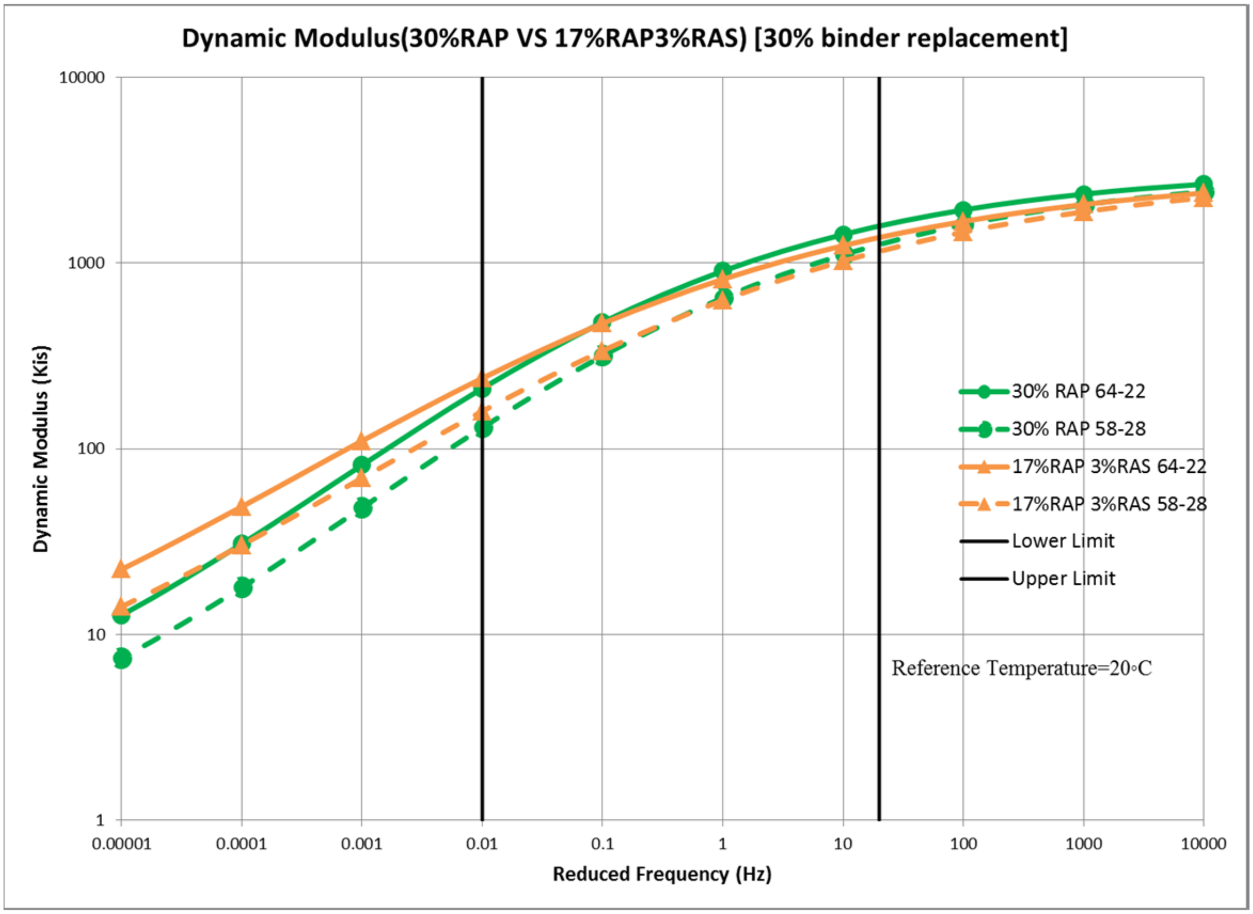

Figure 5.7: Comparison of Measured Dynamic Modulus for Mixtures Containing 30% RAP and 17% RAP/3% RAS

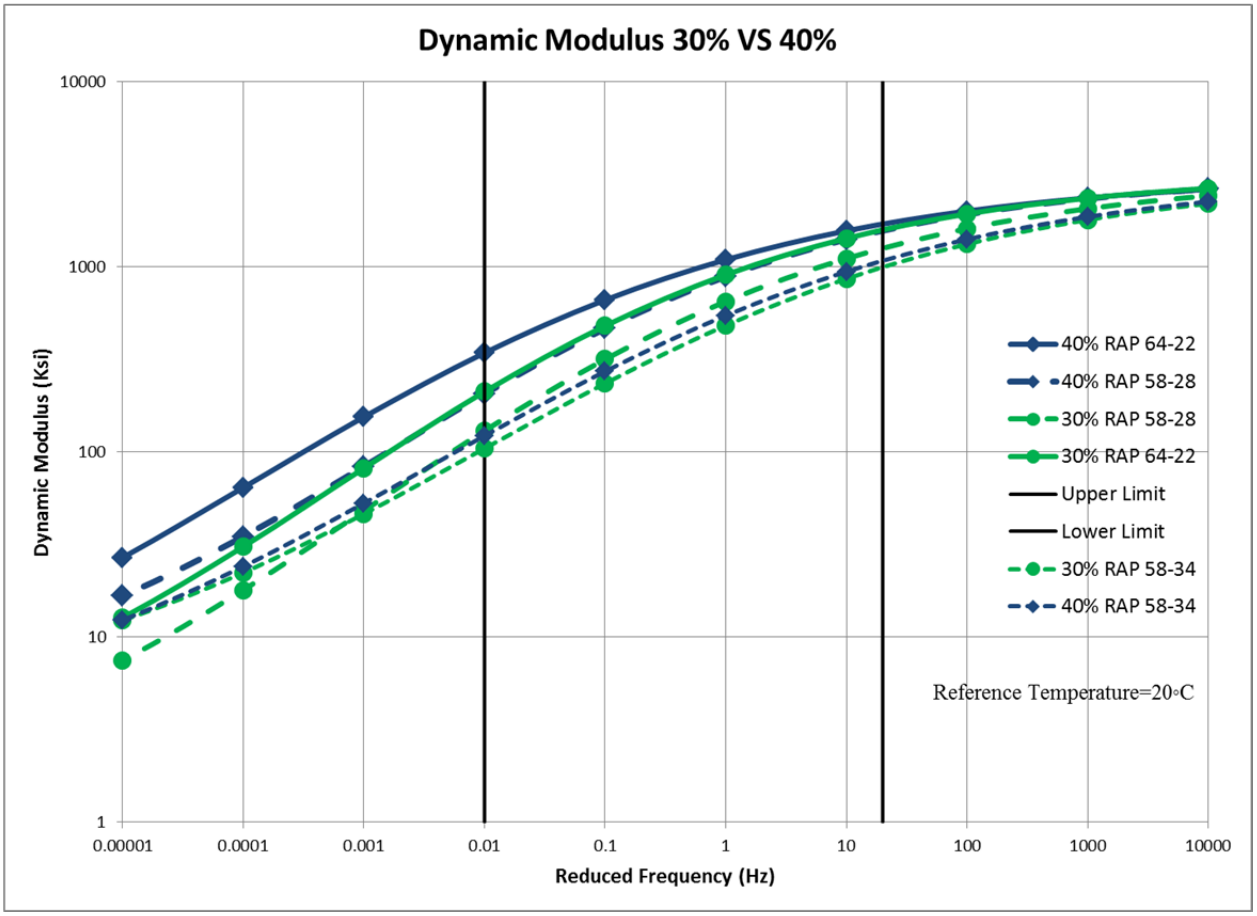

Figure 5.8: Comparison of Measured Dynamic Modulus for Mixtures Containing 30% RAP and 40% RAP

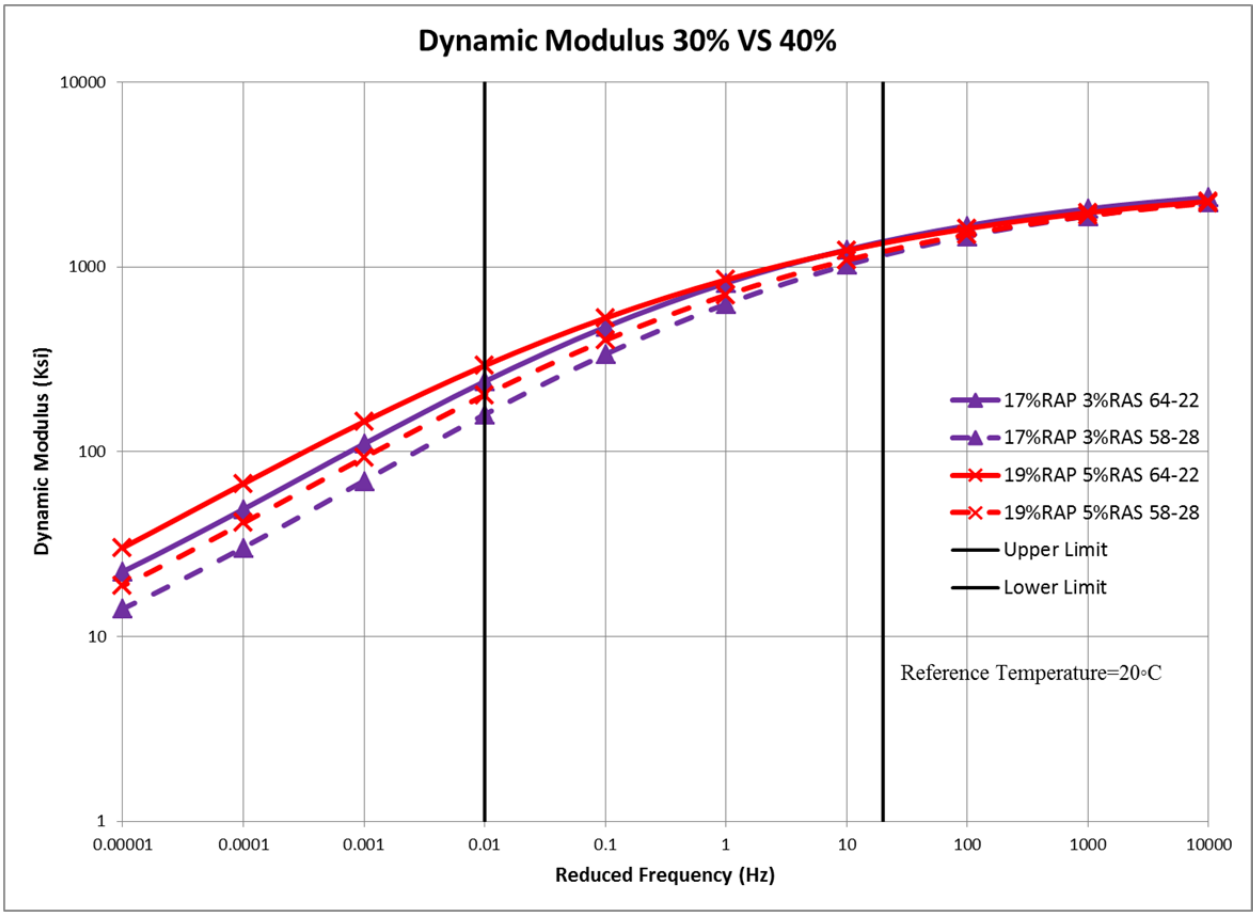

Figure 5.9: Comparison of Measured Dynamic Modulus for Mixtures Containing 17% RAP/3%RAS and 19% RAP/5% RAS

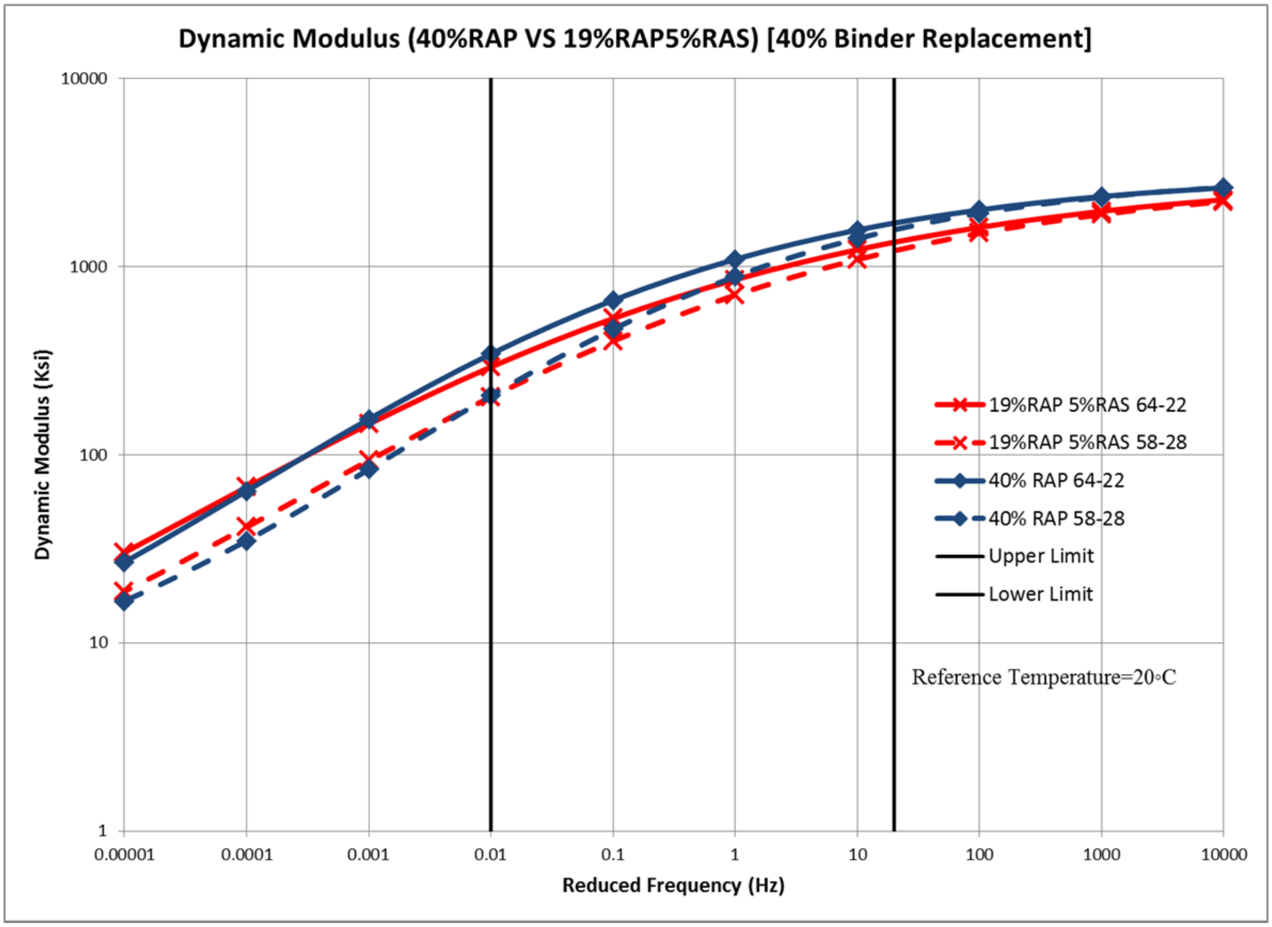

Figure 5.10: Comparison of Measured Dynamic Modulus for Mixtures Containing 40% RAP and 19% RAP/5% RAS.

5.2 PHASE ANGLES

The phase angle is the delay between the maximum stresses applied to a specimen and the maximum stress a specimen experiences. A specimen that is entirely elastic would have a phase angle of zero where a specimen that is entirely viscous would have a phase angle of 90 degrees *(National Center for Asphalt Technology 2014)*. The phase angle represents the amount of energy a specimen can absorb which indicates how well a specimen will resist cracking *(National Center for Asphalt Technology 2014)*. A large angle indicates that a specimen will tend to deform before it cracks. The phase angle is one of the testing parameters for the dynamic modulus test and is inversely related to the stiffness of the asphalt specimen. If the specimen has a relatively high stiffness at one frequency, it will tend to have a low phase angle at the same frequency.

Figures 5.11 through 5.15 display the phase angle master curves for each combination of RAP/RAS with different virgin binder. The results from comparing the phase angles for the 30% virgin binder replacement, 40% virgin binder replacement, and 30% vs 40% virgin binder replacement are displayed in Figures 5.16 through 5.19. The reference temperature for all the phase angle master curves is 20°C. Appendix F also includes plots of the phase angles measured at the 10 combinations of temperature and loading frequency.

It is important to note that the phase angle relationships shown in Figures 5.11 through 5.16 are not as smooth as the dynamic modulus master curves. Appendix E includes example data for replicate specimens tested with the AMPT. It may be seen that the dynamic modulus master curves are generated by “shifting” the modulus data for 4°C and 40°C to the left and right respectively to form a “best fit” curve of modulus versus “reduced frequency” at a reference temperature of 20°C. The shift factors developed for modulus are also used for the phase angles at each temperature. This leads to the discontinuities seen in Figures 5.11 through 5.19.

Figures 5.11 through 5.19 and F13 through F24 clearly show that there is a general trend of phase angle decreasing as stiffness increases, except at very low stiffness conditions. Mixtures using the PG 64-22 binder have lower phase angles and those with the PG 58-34 binder have higher phase angles at high stiffness conditions, but this reverses at low stiffness conditions. This implies that the mixtures using the PG 58-34 binder will be less susceptible to cracking at high stiffness conditions and less susceptible to deformation at low stiffness conditions. Phase angle tends to decrease as the amount of recycled material increases, accompanying the tendency for stiffness to increase as the amount of recycled material increases.

The phase angle measured at 40°C (low stiffness conditions) exhibits a maximum value that occurs between 32° and 35° for the mixtures tested in this study. This range appears to be fairly typical of dense graded mixtures. However, mixtures where the phase angle peaks at higher frequencies should be less susceptible to cracking and more susceptible to deformation.

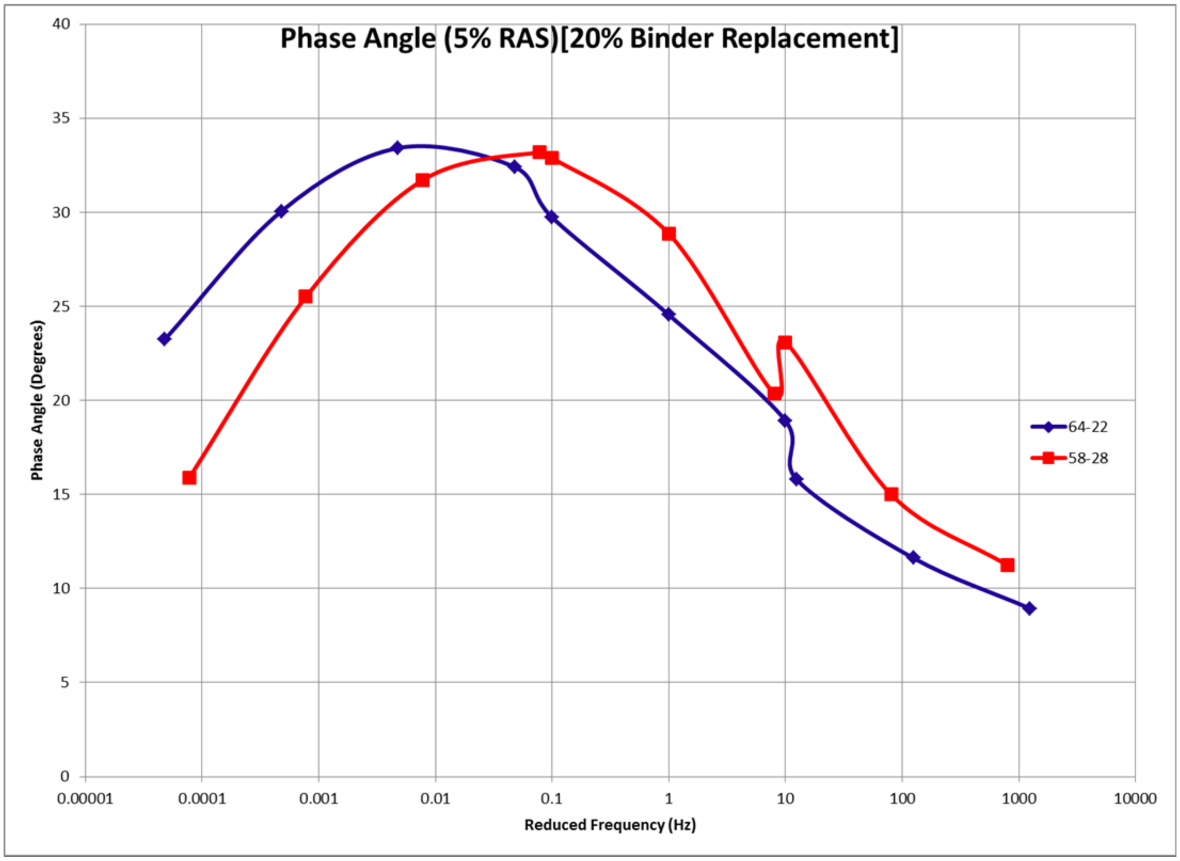

Figure 5.11: Phase Angle for Mixtures Containing 5% RAS

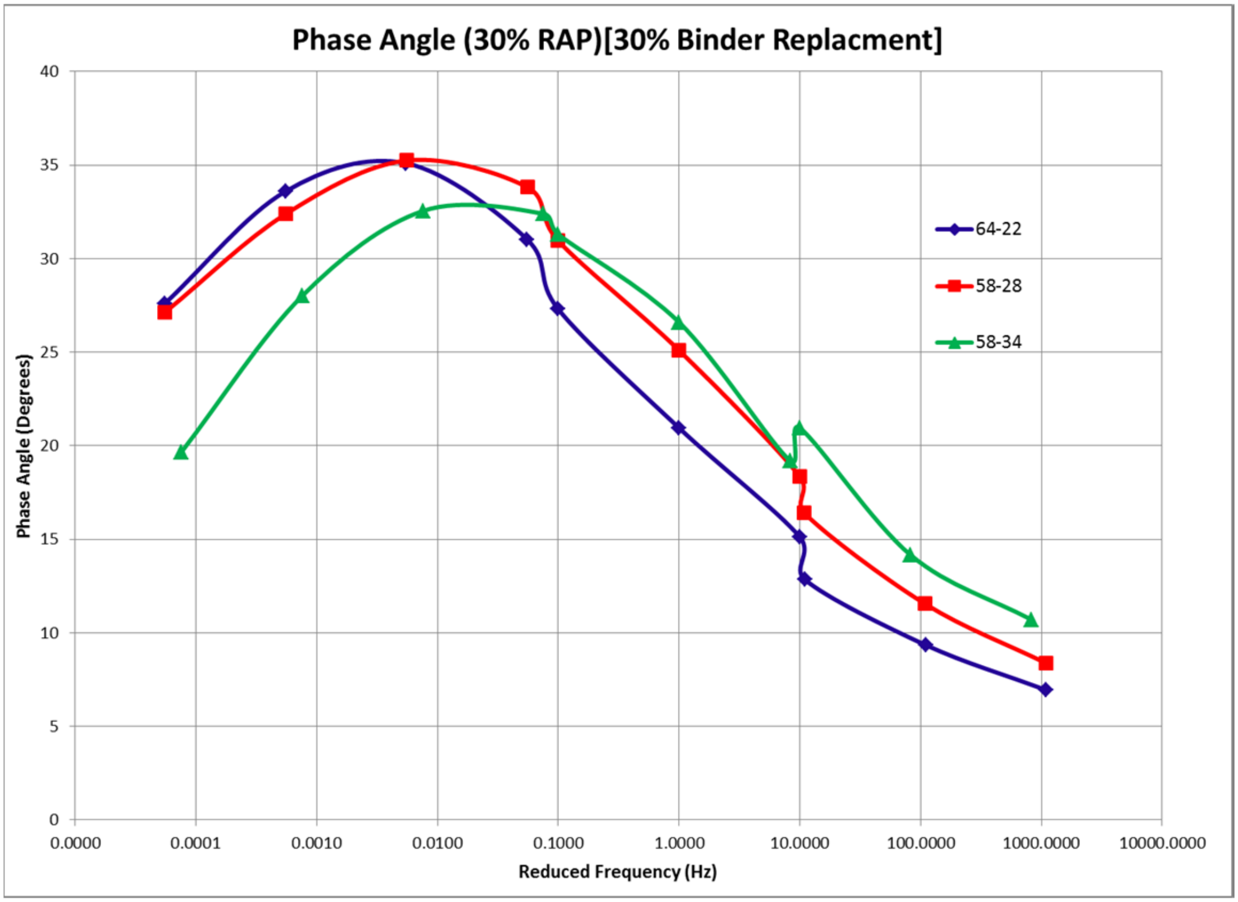

Figure 5.12: Phase Angle for Mixtures Containing 30% RAP

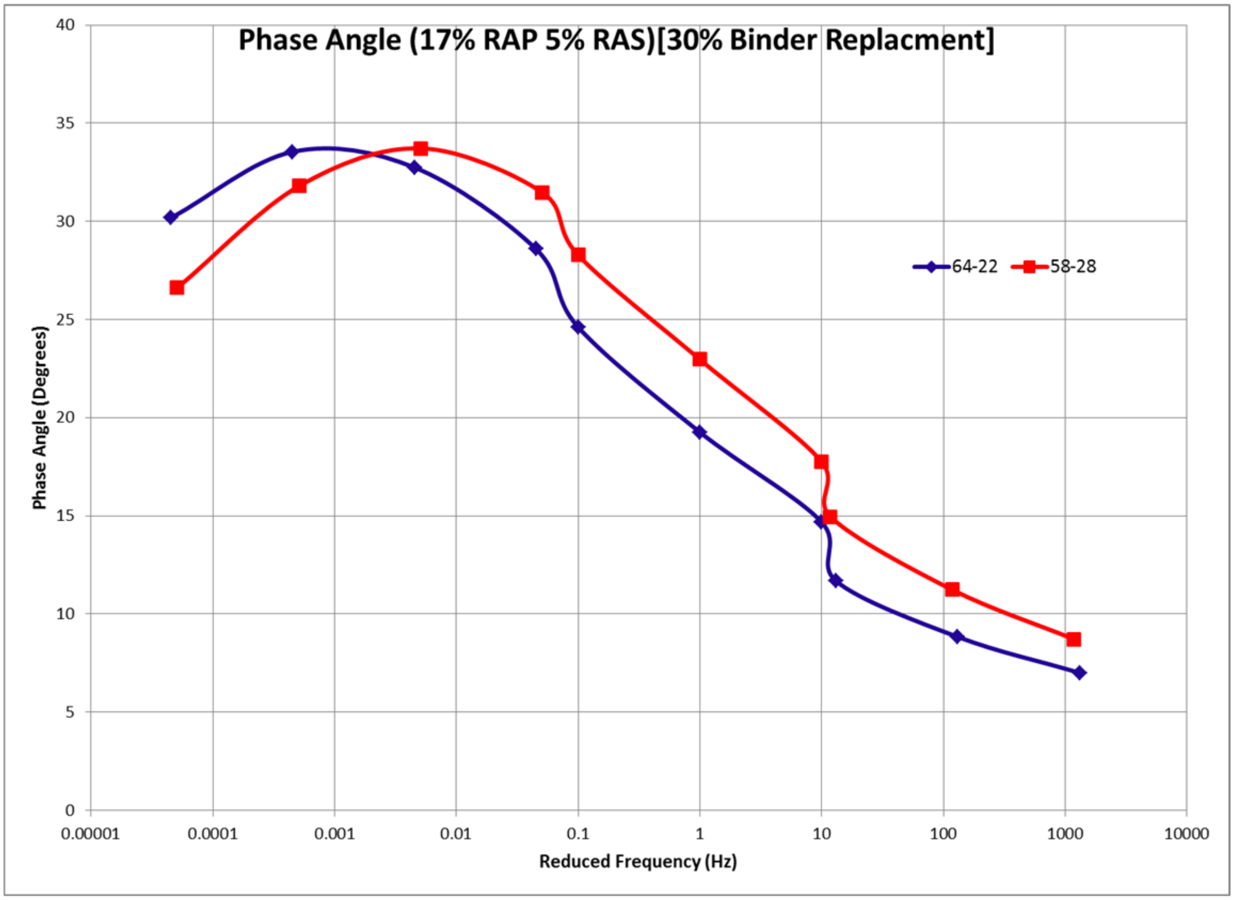

Figure 5.13: Phase angle for Mixtures Containing 17% RAP/3%RAS.

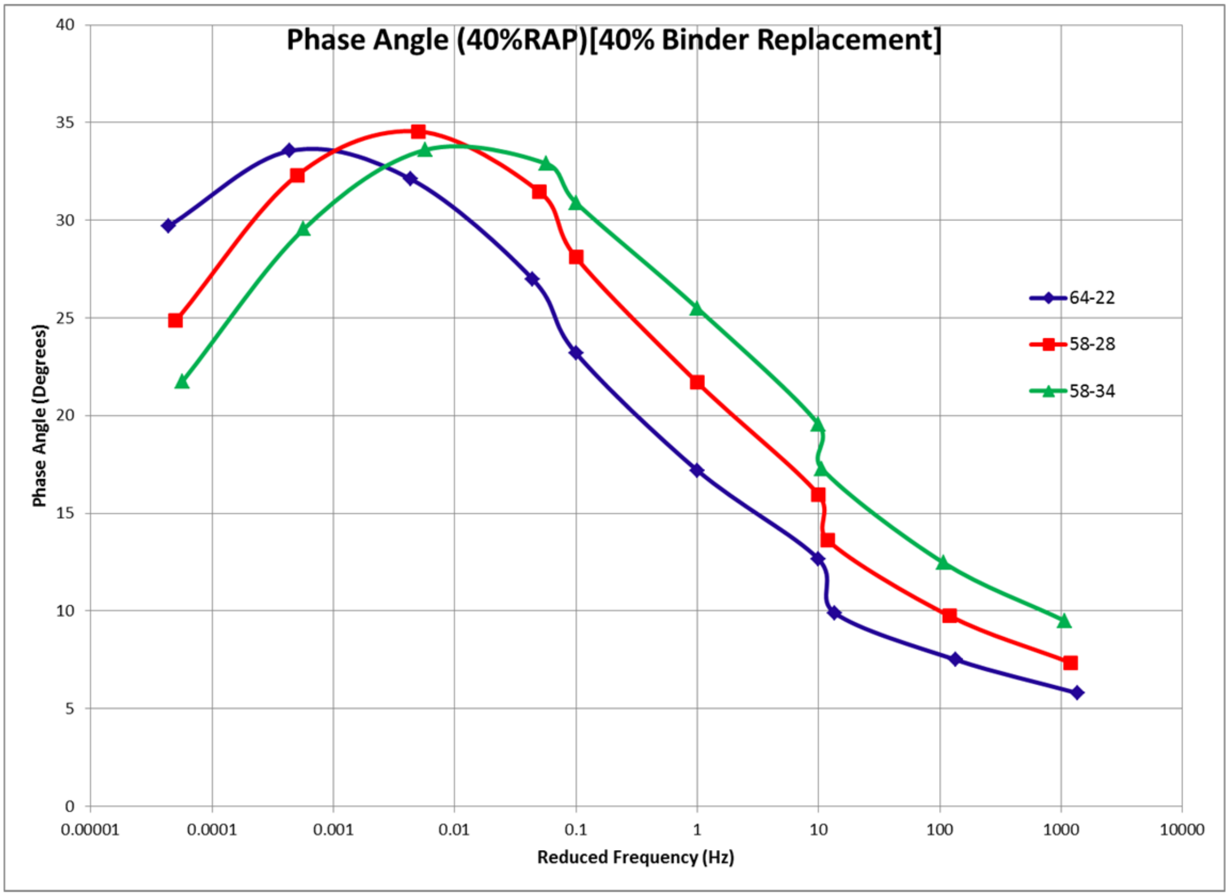

Figure 5.14: Phase angle for Mixtures Containing 40% RAP

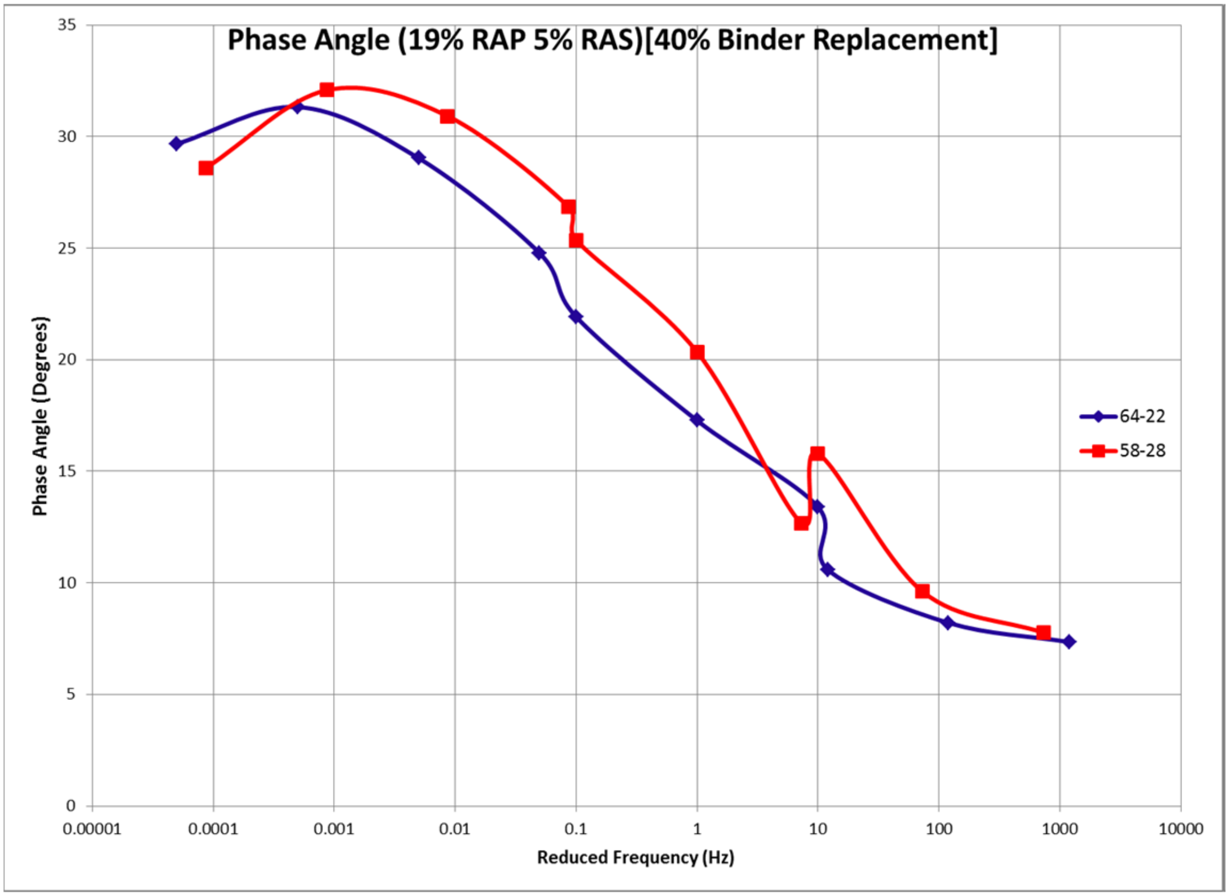

Figure 5.15: Phase angle for Mixtures Containing 19%RAP/5% RAS

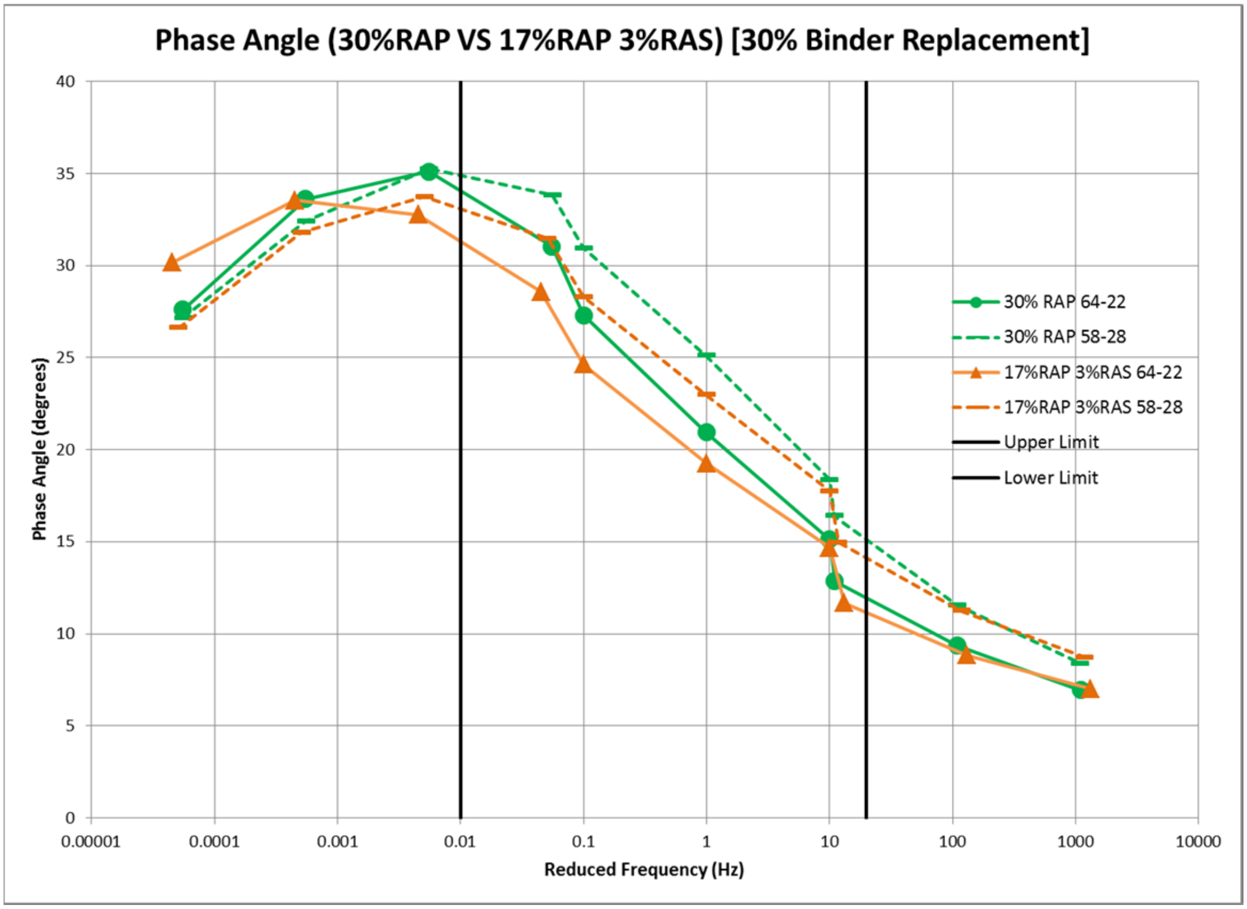

Figure 5.16: Comparison of Phase Angles for Mixtures Containing 30% RAP and 17%RAP 3%RAS

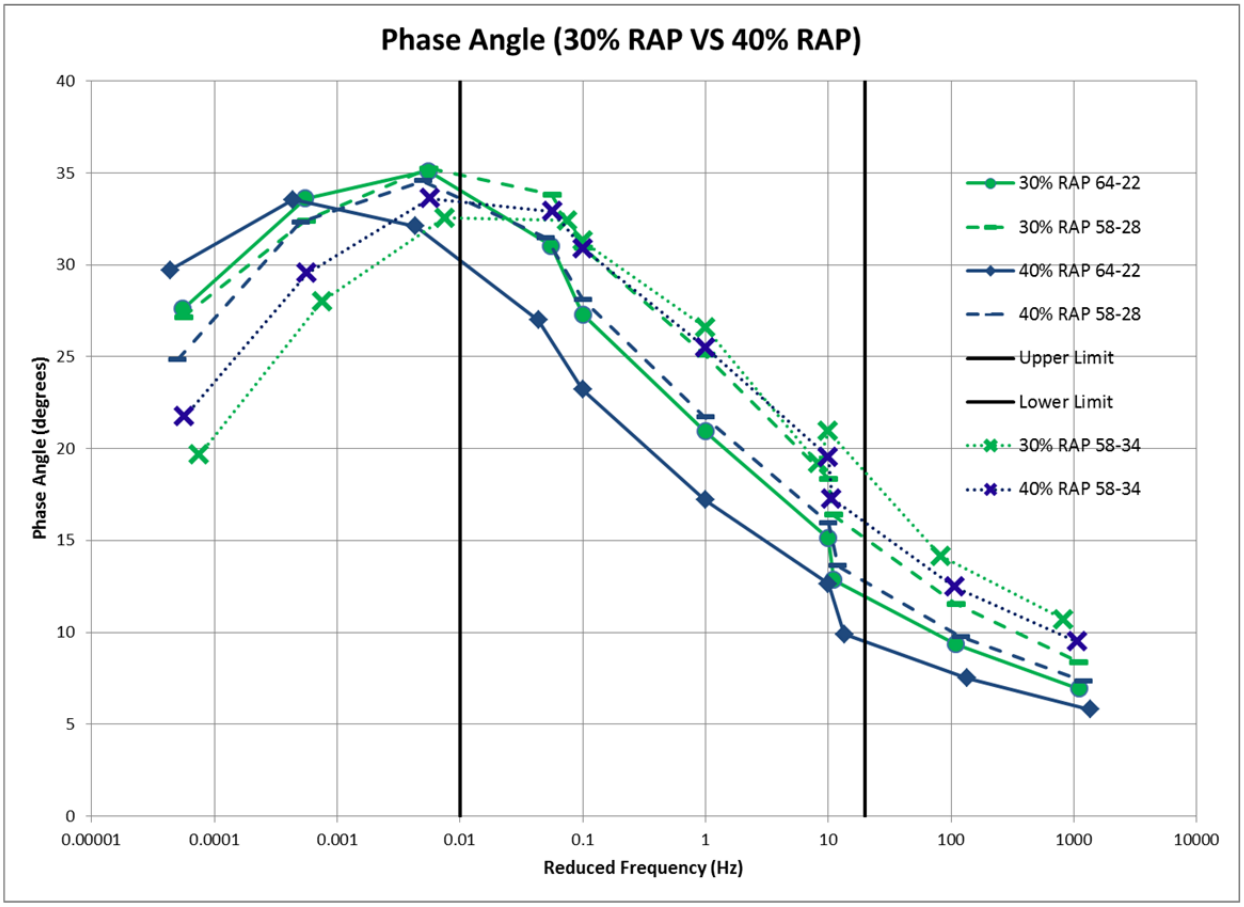

Figure 5.17: Comparison of Phase Angles for Mixtures Containing 30% RAP and 40% RAP

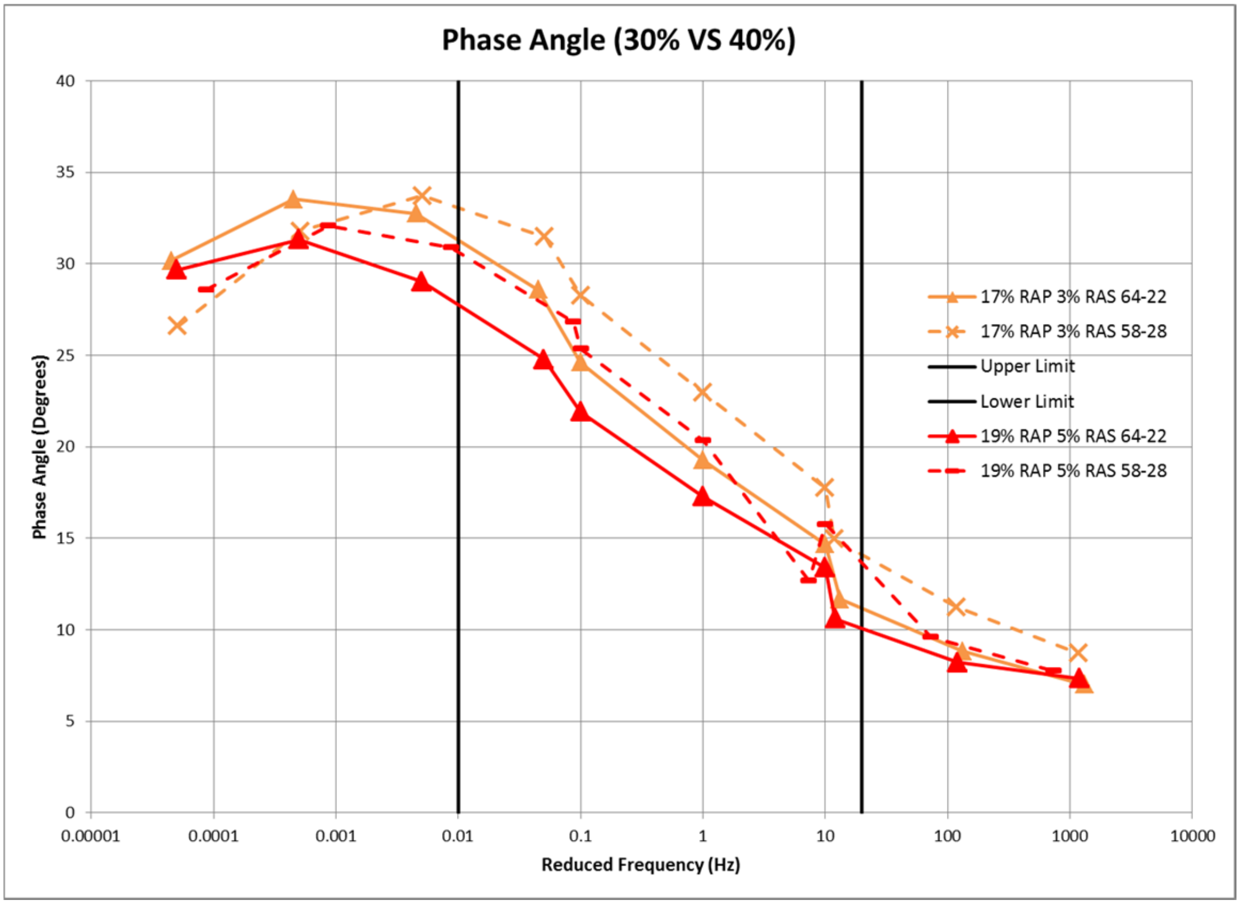

Figure 5.18: Comparison of Phase Angles for Mixtures Containing 17%RAP/3%RAS and 19% RAP/5% RAS

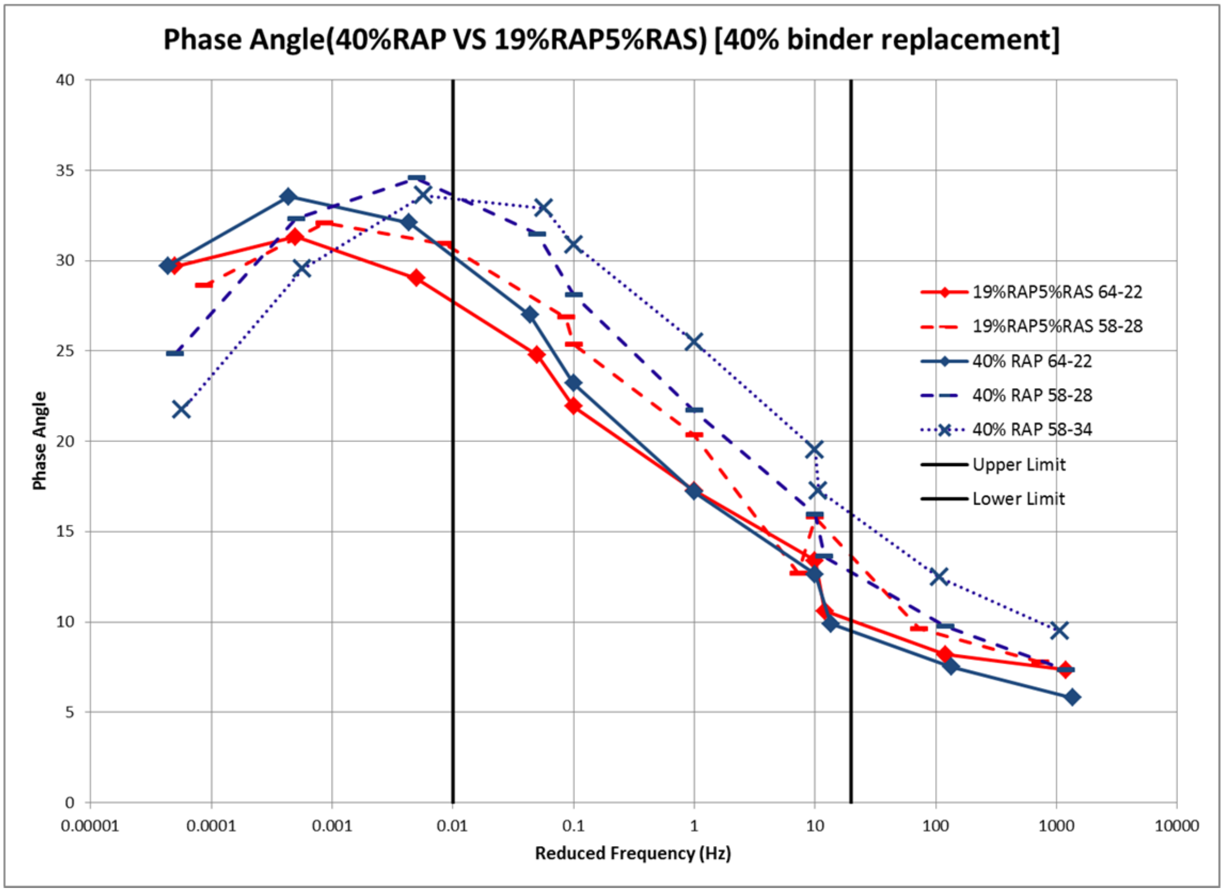

Figure 5.19: Comparison of the Phase Angles for the Mixtures Containing 40% RAP and 19% RAP/5%RAS.

5.3 FLOW NUMBERS

The flow numbers are an indicator of the rutting resistance of an HMA mixture, where a high flow number indicates a high rut resistance and a low flow number indicate a low rut resistance. Typical data from a flow test are shown in Appendix G.

As seen in Table 5.1 and Figure 5.20, the recycled binder combination with the highest resistance to rutting is for the 19% RAP/5% RAS specimens. As noted in Chapter 4, the test was not conducted according to recommended procedures, because specimens already used for the dynamic modulus tests were used. The values of the flow number obtained are likely to be higher than if the test was conducted on previously untested specimens. However, the relative performance should be similar.

Table 5.1: Flow Number for All Recycled Binder Combinations with Different Virgin Binder Grades

Sample #	RAP/RAS	PG Grade	Flow #
1	30	64-22	349
4	30	64-22	599
1	30	58-28	383
2	30	58-28	390
5.3	30	58-34	227
7.3	30	58-34	175
5.1	40	64-22	1210
5.2	40	64-22	1490
3.1	40	58-28	447
3.2	40	58-28	458
3.3	40	58-34	323
4.3	40	58-34	257
2.1	0,5	64-22	211
6.1	0,5	64-22	235
1.2	0,5	58-28	112
2.1	19/5	64-22	1782
3.1	19/5	64-22	1701
3.2	19/5	58-28	482
5.2	19/5	58-28	498

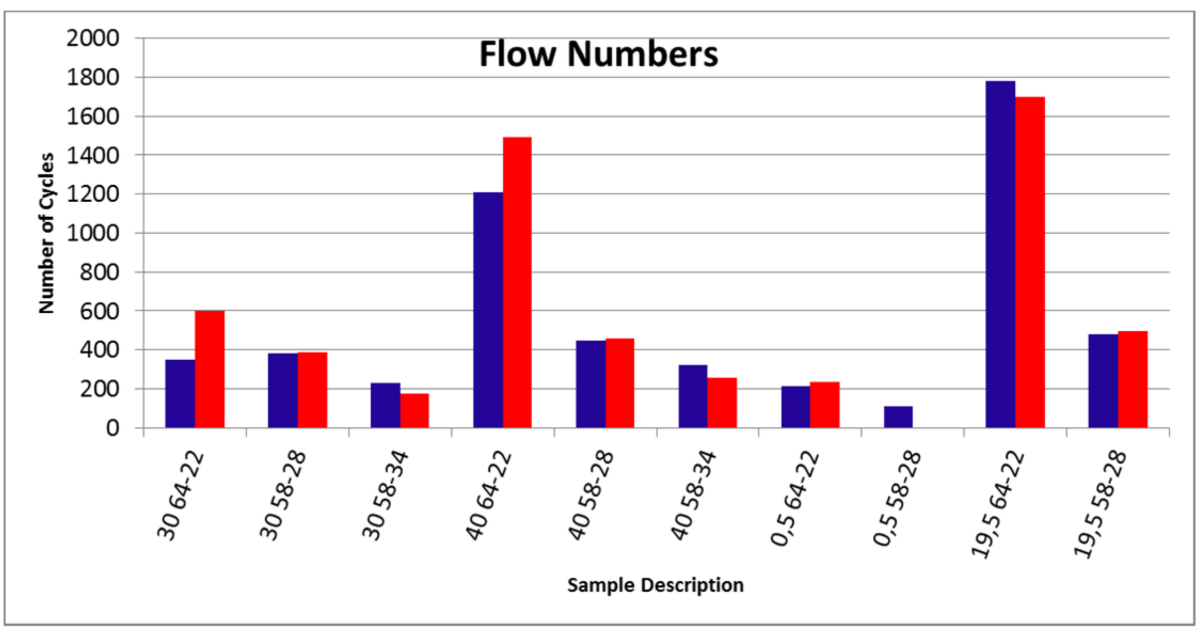

Figure 5.20: Flow Numbers for Each Recycled Binder Combination

Due to some issues with storage of the specimens after the dynamic modulus tests, specimens with 17% RAP/3%RAS were not tested, and only one specimen with 5%RAS was tested.

The coefficient of variation (CV) for replicate tests specimens was less than or close to the 14.1 percent recommended for flow number in AASHTO TP-79-13 *(AASHTO TP-79-13 2013)*. CV data reported by Bonaquist *(Bonaquist 2011)* for multi-laboratory tests are above 20 percent in many cases.

The data in Figure 5.20 show that specimens with the "hardest" (64-22) virgin binder exhibited the best performance. This is to be expected, since the test is conducted at 54.7°C. The data also show that for the RAP/RAS combinations where all three binders were used, the "softest" (58-34) binder was always the most susceptible to rutting. These data compare favorably with those reported by Bonaquist *(Bonaquist 2011)* that are typically in the range 100 to 200 cycles. Bonaquist also refers to recommended minimum flow numbers from NCHRP Project 9-33 as follows:

Traffic Level, Million ESALs	Minimum Flow Number, Cycles
< 3	--
3 to < 10	50
10 to < 30	190
>30	740

Only one specimen in Figure 5.20 has a flow value of approximately 100 cycles. Unfortunately, no replicate specimen could be tested, so this value is questionable. Conversely, flow numbers for the mixtures with 40% RAP and 19% RAP/5% RAS are very high; these mixtures are also very stiff at lower temperatures with the potential for cracking.

5.4 RECYCLED BINDER

Analysis of the dynamic modulus and phase angles results indicates that increasing the recycled binder content increases the dynamic modulus and reduces the phase angle. Figures 5.7 and 5.8 clearly show an increase of the dynamic modulus as more recycled binder is incorporated while holding the virgin binder grade constant. Similarly, figures 5.17 and 5.18 shows a decrease of the phase angle as more recycled binder is incorporated while holding the virgin binder grade constant. These observed trends were expected and suggest that including more recycled binder in the asphalt will reduce the likelihood of rutting but increase the potential of premature cracking. However, as shown in the next section, use of a "softer" grade of virgin binder will offset the tendency to cracking.

5.5 VIRGIN BINDER

Figures 5.2 through 5.19 can be examined to indicate the effects of the virgin binder grade. It is clear that selecting a softer binder grade (temperature range is cooler) for a mixture reduces the dynamic modulus and increases the phase angle. This was another expected trend since HMA mixtures with softer binders are more resistant to premature cracking. These results support the idea that using a softer virgin binder will allow more recycled material to be incorporated. It was also noticed that the results from changing the binder were somewhat parallel to each other within the upper and lower frequency limits shown in Figures 5.7 through 5.10 and Figures 5.16 through 5.19. Figure 5.21 shows the reduction of stiffness due to selecting a softer binder than the 64-22 grade (i.e. 58-28 and 58-34) at 10, 1, and 0.1 Hz for each RAP/RAS combination. The reductions are very consistent for the PG 58-22 binder; averaging 30 percent at 0.1 HZ loading frequency. The use of the PG 58-34 binder results in a 50 to 60 percent reduction at 0.1 Hz loading frequency.

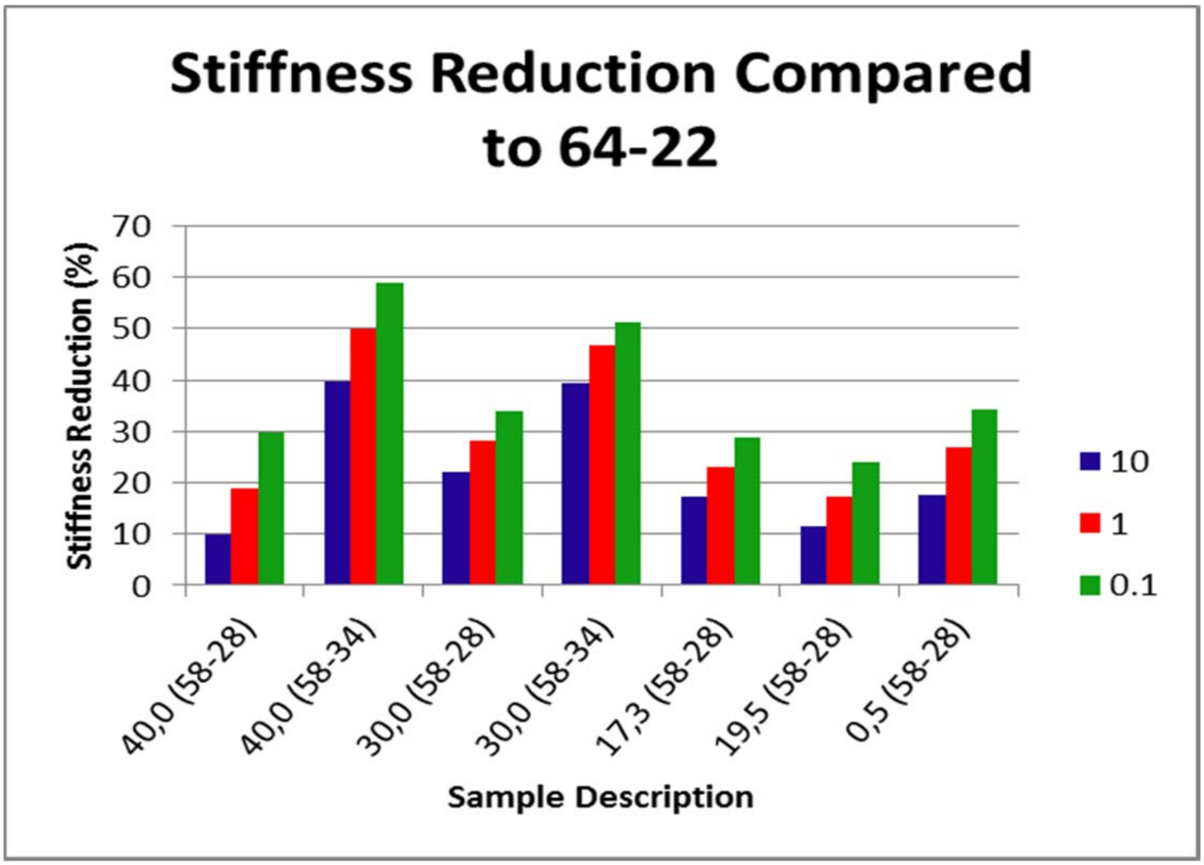

Figure 5.21: Reduction of Stiffness at 20°C for Each RAP/RAS Combination at 3 Different Loading Frequencies

5.6 RAS

The mixtures using RAS and RAP/RAS resulted in dynamic modulus curves that were less susceptible to changes in frequency (smaller slope) compared to the RAP only specimens. The RAP only specimens seem to be more susceptible to changes in frequency (larger slope). This could indicate that incorporating RAS can improve resistance to rutting but reduces the resistance to premature cracking. The specimens containing RAP and RAS have a lower phase angle than the RAP only combinations which indicates that the RAP/RAS specimens do not absorb energy as efficiently. This trend suggests that use of RAP/RAS combinations will make the asphalt more brittle than only using RAP and there is low probability that the specimens with RAP/RAS will have identical performance to specimens with only RAP.

This research had to make some assumptions about the binder recovery from the RAS including the percentage of binder recovered and how effective the binder blends throughout the material. For this study, it is assumed that 100% of the binder from the recycled shingles is recovered and the recycled binder is uniformly blended throughout the resulting mixture. Assuming complete recovery for the RAS binder is questionable due to the high probability that some of the binder is potentially over-oxidized. Two thirds of the RAS used was recycled from roofs that were exposed to the sun for multiple years accelerating the aging process of an already very stiff binder. If a binder is over-oxidized, there is a lower probability of recovering all the recycled binder without using rejuvenators (*Yin and Ishee 2015)*. Research conducted on the effects rejuvenators have on the RAS binder show that rejuvenators allow more binder to be reclaimed *(Mogawer et al. 2015b)*. The impact on the dynamic modulus and phase angle is more significant when RAS is included because RAS contains a high percentage of binder within the material. Other concerns about the RAS include the variance of binder content (16% to 30%), the use of fibers, the quality of the fine aggregate, and the stiffness of the binder.

5.7 BENEFICIAL FINDINGS

As shown in Figure 5.8, the dynamic modulus response of the 30% RAP mix with 64-22 PG binder is nearly identical to that for the 40% RAP mix with 58-28 PG binder. The same can be seen by comparing Figures F9 and F10. To date, ODOT has used a 30% RAP mix design with 64-22 virgin binder grade. This study shows strong evidence that using a “softer” virgin binder (using the next softer binder grade) will allow additional RAP to be incorporated in the asphalt. This kind of comparison can be extended to all 12 mixture combinations utilized in this study by displaying the data in a similar for to Figures 5.1, 5.20 and 5.21.

Figure 5.22 shows the dynamic modulus at 4°C for each mixture, ranked according to the highest stiffness conditions, i.e. at a loading frequency of 10 Hz. The rankings would be similar but not

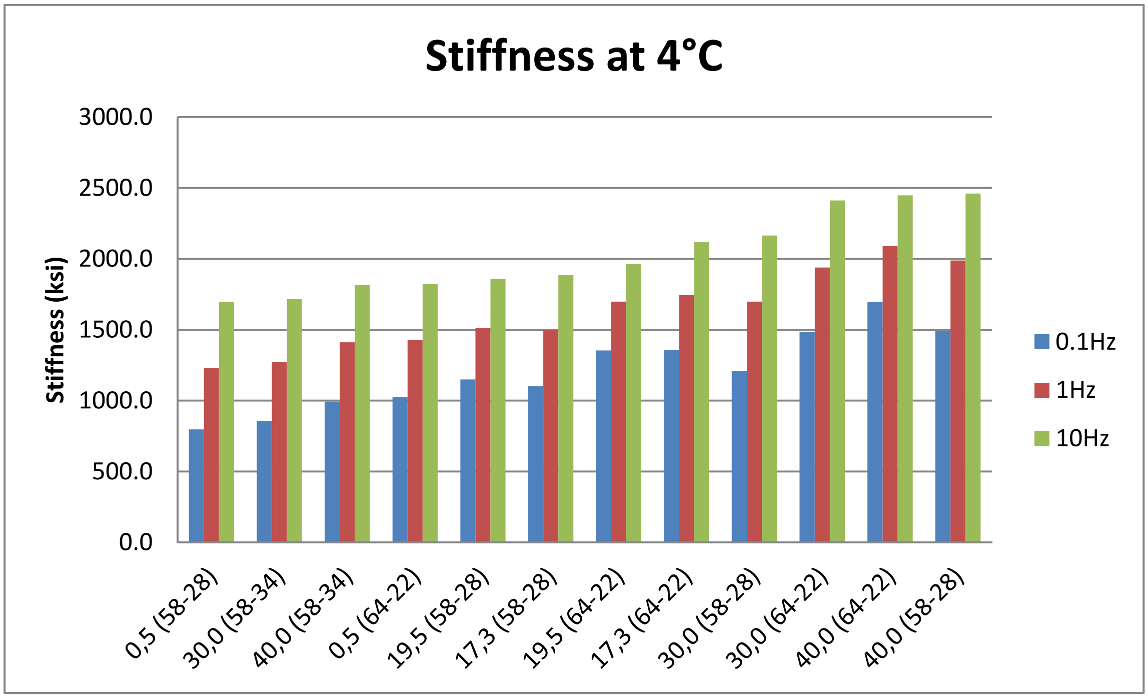

Figure 5.22: Ranking of Mixtures by Dynamic Modulus (Stiffness) at 4°C

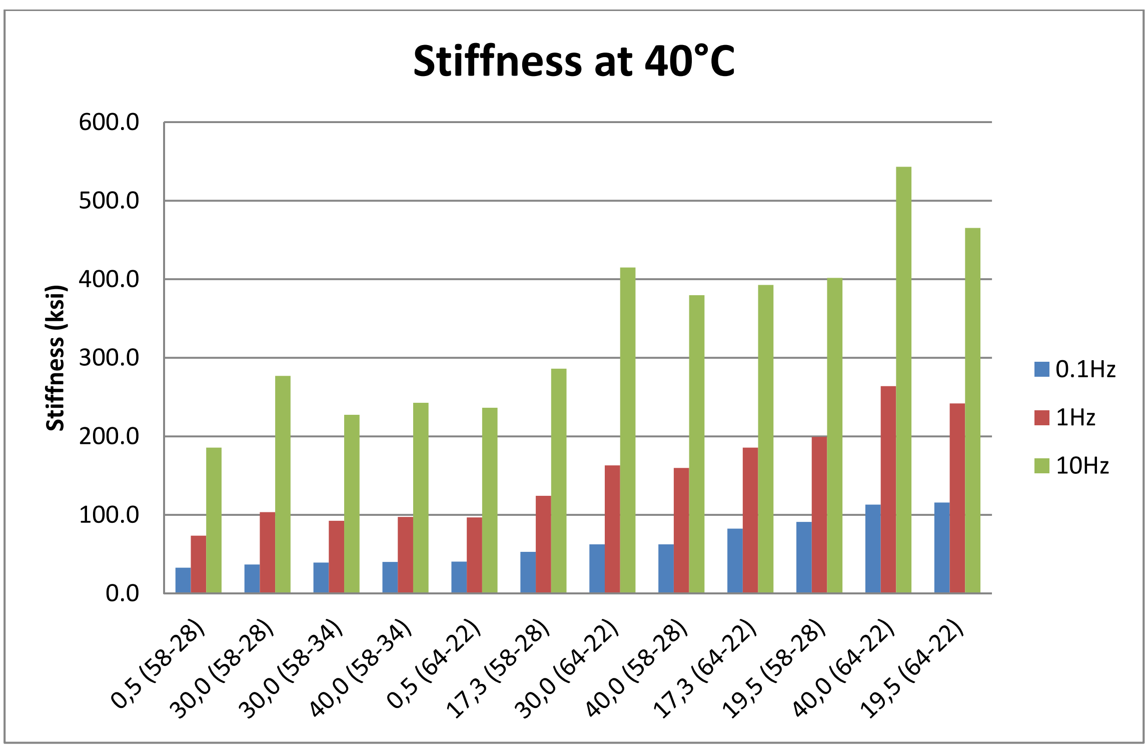

Figure 5.23: Ranking of Mixtures by Dynamic Modulus (Stiffness) at 40°C

the same if done at 0.1 or 1 Hz. As noted above it can be seen that the dynamic modulus response of the 30% RAP mix with 64-22 PG binder is nearly identical to that for the 40% RAP mix with 58-28 PG binder. However, it is also clear that these two mixtures are very stiff at these conditions and therefore likely to be much more susceptible to cracking. The stiffness at these conditions can be reduced substantially by using the PG 58-34 binder. It can also be seen that the six mixtures with the lowest (and likely more desirable) stiffness are very similar. As experience with this type of data is gained, it should be possible to select or reject mixtures for different climatic zones according to this kind of performance measurement, and, limiting the maximum stiffness to say 2,000 ksi.

A similar approach could be adopted for selecting or rejecting mixtures by examining their stiffness at low stiffness conditions, as shown in Figure 5.23. In this case the ranking is based on stiffness at a loading frequency of 0.1 Hz. As with the high stiffness conditions, the rankings would be similar but not the same if the ranking was done at 1 or 10 Hz. This figure shows some significant changes in ranking compared to Figure 5.22. For these conditions, a minimum stiffness could be used to select or reject mixtures, such as 100 ksi at 1 Hz. However, flow data could be considered, as discussed in section 5.3, or, phase angle data as presented in Figures 5.24 and 5.25. A combination of dynamic modulus (stiffness), flow and phase angle criteria could be considered.

The phase angle at high stiffness conditions should be sufficient to provide cracking resistance. An alternative (or additional) criterion is to require a minimum phase angle measured at 4°C and 10 Hz, as shown in Figure 24. The rankings in this figure show that the high RAP mixes with the PG 64-22 and PG 58-28 binder have relatively low phase angles, just as they showed high stiffness in Figure 22. The mixtures with RAP/RAS combinations and the PG 64-22 and PG 58-28 binder are similar. The high RAP mixtures with the PG 58-34 binder and the 5% RAS mixtures with PG 64-22 or PG 58-28 perform the best when considering both stiffness and phase angle at high stiffness conditions. These data suggest that the mixture with 19% RAP and 5% RAS may need a PG 58-34 binder to give good resistance to cracking at high stiffness conditions.

The phase angle at low stiffness conditions is shown in Figure 5.25. It seems that a relatively low phase angle is desirable, but, as may be seen, there is little variation and examining the phase angle at these conditions may not be beneficial. Recommendation of a selection criterion is not possible from the results of this study.

The results from this research (and other similar studies) provide support for using a softer binder grade (i.e. a PG 58-28 rather than a PG 64-22) when incorporating more recycled materials in HMA mixtures, i.e. for more than 30 percent binder replacement. The results also

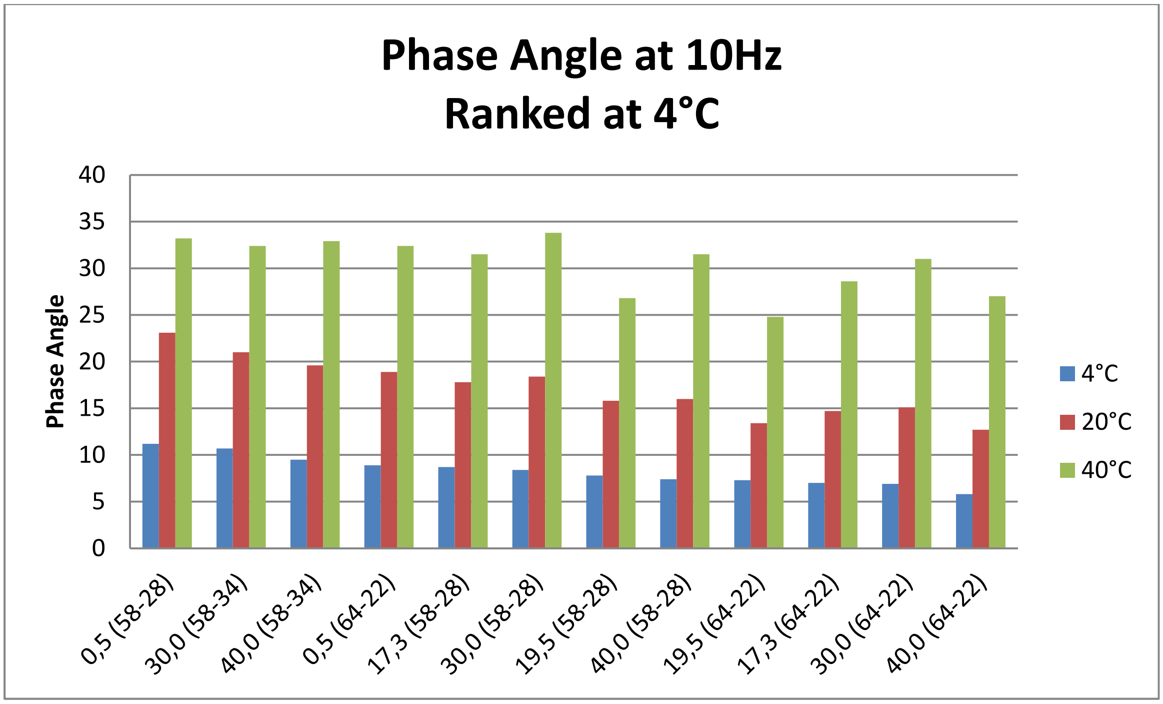

Figure 5.24: Ranking of Mixtures by Phase Angle at 4°C

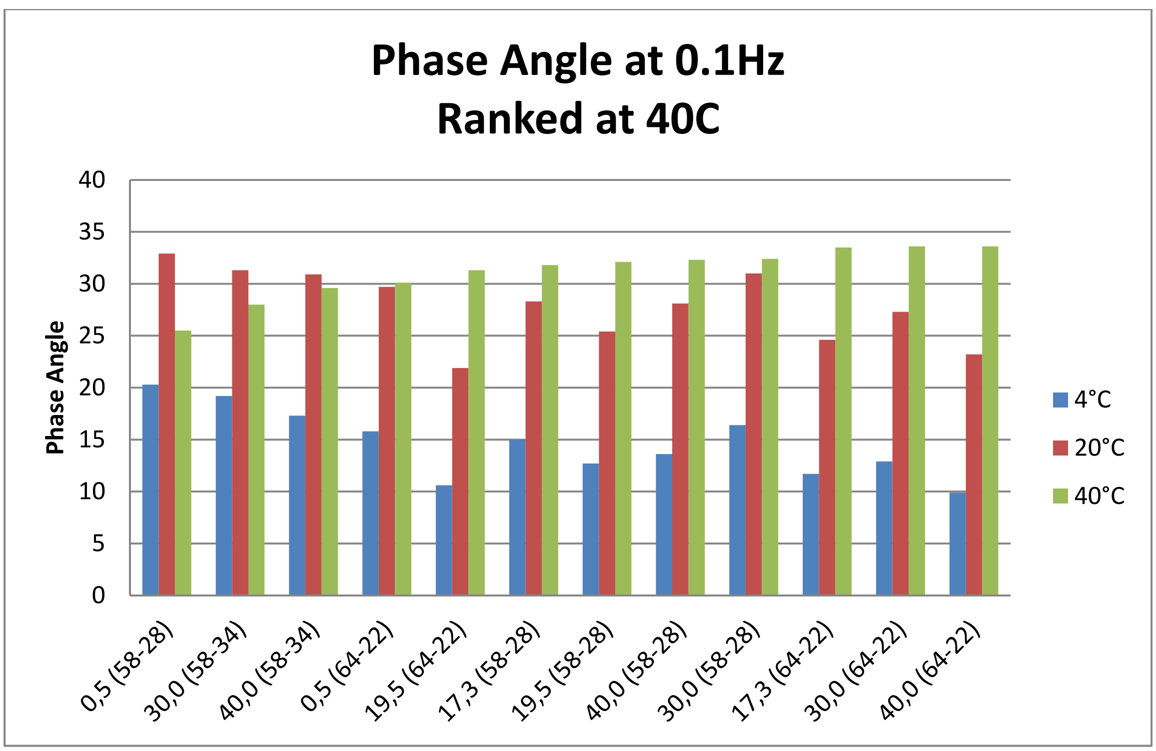

Figure 5.25: Ranking of Mixtures by Phase Angle at 40°C

suggest that using an even softer grade (i.e. a PG 58-34 rather than a PG 58-22) could be beneficial when incorporating RAS in a mixture, or, when using high RAP/RAS mixtures in a climatic regions where cracking is a particular concern.

5.8 PREDICTING PERFORMANCE WITH THE MECHANISTIC-EMPIRICAL DESIGN GUIDE (MEPDG)

An alternative to developing design criteria based on dynamic modulus and phase angle data is to use the data from dynamic modulus tests in the performance prediction models in the MEPDG. The performance prediction includes the extent of cracking and deformation for appropriate traffic and climatic conditions. Appendix E shows an example of a typical data set that could be used in the MEPDG.

It is beyond the scope of this study to conduct such a performance prediction.

6.0 CONCLUSIONS

Based on the results of this study, the following conclusions may be drawn:

1. From the results of the dynamic modulus and flow tests there are multiple relationships between the performance of the specimens with respect to the amount of recycled material and virgin binder grade used. In general, the results suggest that an increase in the amount of recycled material made the HMA mixture more resistant to rutting but more susceptible to cracking. However, use of a "softer" grade of virgin binder has the opposite effect. The results indicate that HMA mixtures with a high content of recycled asphalt materials should "bump" the binder grade to at least one grade softer, but possibly two grades, i.e. a PG 58-28 rather than a PG 64-22 or a PG 58-34 rather than a PG 58-28.

2. Increasing the RAP content from 30% to 40% increased the measured dynamic modulus and reduced the phase angle, indicating the HMA mixture is becoming more susceptible to premature cracking. The Technical Advisory Committee (TAC) for this project has identified this as the primary performance concern for HMA mixtures with high levels of recycled asphalt materials content. The current ODOT specification allows no more than 30% binder replacement by recycled asphalt material (RAP plus RAS) with no more than 5% RAS content.

3. ODOT's current practice is to use a PG 64-22 binder for the majority of mixtures using recycled asphalt materials. For this study, selecting virgin binder softer than 64-22 (either 58-28, 58-34) reduced the measured dynamic modulus and increased the phase angle indicating that the mixture is becoming more resistant to premature cracking. It was observed that choosing a softer virgin binder for the 40% RAP such as PG binder grade 58-28 or 58-34 results in equivalent or reduced dynamic modulus with respect to the 30% RAP mixture with a virgin PG binder grade of 64-22. This is strong evidence that softening the virgin binder to a PG binder grade of 58-28 or softer will provide similar mixture properties.

4. The HMA mixtures containing only RAP showed parallel results in the dynamic modulus and phase angle as the virgin binder was changed. This indicates a high probability that an asphalt mixture with high RAP content and soft binder could be equivalent to an asphalt mixture with low RAP and stiff binder.

5. When RAS was used in the HMA mixtures, the dynamic modulus was less susceptible to changed in frequency and the phase angle was reduced. This indicates that there is a high probability that incorporating RAS in asphalt will increase rut resistance for the asphalt mixture. However, cracking susceptibility may be compromised by somewhat higher stiffness at high stiffness conditions. Since the master curves of the RAP only specimens are not parallel with the RAP/RAS

specimens, it seems that the mixtures with RAS have different performance characteristics than those with RAP only.

6. It was shown that a range of dynamic modulus and phase angles result from mixtures using different amounts of recycled materials and three different binders. With continued experience it should be feasible to develop criteria for maximum and minimum values.

7. The master curves, phase angles, and flow number test results measure the properties of the material and do not directly measure or predict the service life of the pavement. Further analysis is required using the MEPDG and the results from dynamic modulus testing to evaluate the performance of typical pavements with respect to traffic loading and environmental factors.

7.0 RECOMMENDATIONS

Based on the conclusions from this research, the following recommendations are suggested:

1. It is recommended softer virgin binder grade (than the typically used PG 64-22) is selected when using more than 30% RAP in HMA mixtures. It is also recommended to compare the results of this research to other current studies focusing on the effects of High RAP content in asphalt. Analyzing data from other studies will assist in developing guidelines for maximum amount of recycled material that can be incorporated in asphalt.

2. The majority (95%) of RAS available in the U.S. for pavement construction is roof tear off and the rest is factory waste. However, current practice is to use a 2:1 blend of the two sources. It is likely that higher percentages of tear off RAS will be used in the future. This research could be used as a comparison to data collected on the effects of using a higher concentration of RAS, particularly if the percentage of tear off used in the future is increased.

3. It may be beneficial to investigate the effects of rejuvenators on asphalt with RAS and high RAP content. There is evidence that rejuvenators have an impact on the service life of HMA mixtures and assist in reclaiming asphalt binder from both RAP and RAS *(Mogawer et al. 2010)*. Considering that High RAP mixtures are growing in popularity it seems appropriate to compare this data to other strategies that could extend the service life of recycled pavement design.

8.0 FUTURE RESEARCH

This section provides suggestions for future research that could be built from the findings of this project. This research was designed to be further developed depending on the results from this study. The following are suggestions for future research:

1. Conducting a MEPDG study using the results from the dynamic modulus test for each mix design would predict the service life for each recycle content combination and potentially determine how the service life is affected by the recycled material. Such a study would assist in relating material property data to field performance. Such a study should lead to developing criteria for maximum and minimum dynamic modulus values and phase angles for high and low stiffness conditions.

2. This study tested a limited range of mixtures. The addition of more combinations of RAP and RAS would be helpful in a future study, including 20% RAP, 8% RAP & 3% RAS, and, possibly mixtures with more than 5% RAS. This would provide additional data points that could be used to better predict the effects of the recycled binder. In addition, it would be beneficial to use the PG Binder grades 64-22, 58-28, and 58-34 for all chosen recycled material combinations including the ones selected for this research. This will help determine if the effects of changing the binder grade are influenced by the chosen recycled material and quantity. It is estimated that such a study could be completed in a 12 month period.

3. A thorough comparison of the results from this study should be made with the results of a recently completed NCAT study *(Taylor 2015)*.

4. Field trials should be conducted using mixtures with 40% binder replacement.

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APPENDIX A

SCOPE MODIFICATIONS AND AIR CONTENT

APPENDIX A: SCOPE MODIFICATION AND AIR CONTENT

Initially, the scope of this research included measuring the effects of changing the virgin aggregate source while keeping the binder supplier and binder grade constant. Each aggregate source was going to be tested with seven different recycled binder combinations. However, during the summer of 2013, it was decided by the technical advisory committee to redesign the study to isolate the effects of the virgin binder instead of the aggregate source. After this decision, the following changes were made:

- One constant aggregate source (West River Bend Sand & Gravel)
- One Binder supplier with three different binder grades (64-22, 58-28, and either 74-22 or 58-34)
- Seven different RAP/RAS combinations

o Recycled Asphalt Pavement	o Recycled Asphalt Shingles
o 20%	o 0%
o 30%	o 0%
o 40%	o 0%
o 0%	o 5%
o 8%	o 3%
o 17%	o 3%
o 19%	o 5%

- AMPT and Overlay Test with a possible Flow Test

This change of scope made it very difficult to keep the research on schedule and required multiple testing practices to be re-evaluated. During the re-evaluation, multiple quality control tests and adjustments to current testing practices were incorporated in the testing process to limit variability between specimens. The following list contains the quality control checks added to the specimen preparation and adjustments to current testing practices.

Test Procedures	Current Practice	Required adjustments to current practices	Material/actions required to accomplish adjustments
AASHTO T 209-10 (Gmm)	Inability to control air pressure	Target (25 to 30mmHg) Install manometer and pressure valve to control the air pressure	Manometer, pressure valve
AASHTO T 166-10 Gmb	Poor temperature control, large water basket, no overflow.	Implement aquarium temperature control and thermometer. Smaller basket, add overflow	Water heater, water thermometer, custom specimen holder (waterproof), overflow drain.
AASHTO PP 60-12	No pre-cored tests. No air content uniformity test. Air content target=4%	Add pre-cored test, add air content uniformity test, air content target=7%	Training in testing procedures. Development of air content curves.
Batching Aggregate	Use scale with 5 gram accuracy	Use scale with .1 gram accuracy	Purchase of new scale
HMA Lab Mixing	No material thermometers used on material in ovens	Measure temperature of aggregate, RAP/RAS, and binder	Purchase of more probe thermometers
Gyratory Compaction	Poor cleaning of molds, allowing residue to build	Use a grease cutter to clean molds after each use to prevent residue build up	Cleaning supplies
Batching RAP/RAS	Scoop material directly from bag, no drying, no splitting.	Dry material before use. Use mechanical splitter to batch out material	Training in splitting recycling material and drying recycled material.

These adjustments to the testing procedure were not considered in the initial scheduling for the research leading to major time constraints for the progress of the research. Furthermore, it was discovered that the specimen preparation process required significantly more time than anticipated. After re-evaluation of the schedule with this information, it was decided by the TAC and the Graduate Research Student to adjust the scope to fit the time constraints.

The most demanding quality control measure was achieving the target air content for the specimens. Below is example calculations used to measure the air content for each specimen. A complete set of data is available on request.

Table A1. Example Calculations to Determine Air Content of Specimens

VBG	64-22
Spec. #	1
RAP	40
Mdry	2865.5
Mssd	2868.7
Mh20	1626
Bulk Sd	2.305866
Gmm	2.432
Volume	1239.5
Air	64.28568
Void	5.18642
Absorp	0.257504

VBG	64-22
Spec. #	2
RAP	40
Mdry	2780
Mssd	2873.1
Mh20	1578
Bulk Sd	2.146552
Gmm	2.432
Volume	1202
Air	141.0806
Void	11.73716
Absorp	7.188634

VBG	64-22
Spec. #	3
RAP	40
Mdry	2801.1
Mssd	2803.4
Mh20	1581.7
Bulk Sd	2.292789
Gmm	2.432
Volume	1219.4
Air	69.80025
Void	5.724147
Absorp	0.188262

VBG	64-22
Spec. #	4
RAP	40
Mdry	2861
Mssd	2863.6
Mh20	1616.3
Bulk Sd	2.29375
Gmm	2.432
Volume	1244.7
Air	70.7542
Void	5.68444
Absorp	0.20845

VBG	64-22
Spec. #	5.1
RAP	40
Mdry	2816.5
Mssd	2824.1
Mh20	1585.4
Bulk Sd	2.273755
Gmm	2.432
Volume	1231.1
Air	80.10515
Void	6.506795
Absorp	0.613546

VBG	64-22
Spec. #	5.2
RAP	40
Mdry	2796.4
Mssd	2805.9
Mh20	1564
Bulk Sd	2.251711
Gmm	2.432
Volume	1232.4
Air	91.36022
Void	7.413195
Absorp	0.764957

APPENDIX B:

AGGREGATE SPECIFIC GRAVITY

APPENDIX B: AGGREGATE SPECIFIC GRAVITY

The following data sheet contains the aggregate specific gravities design summary data sheet provided by APAO. This information was used to calculate the VMA, VFA, and VTM used in creating the dynamic modulus master curves. A complete set of data is available on request.

APAO

INDIVIDUAL STOCKPILE AGGREGATE SPECIFIC GRAVITIES

DESIGN SUMMARY

Click to Reset this SHEET

Project name:	CMDT Class Design 2009		**Contract No:**	CMDT				
Mix Type:	l 3, 1/2 " Dense-Graded w/25%		**Date:**	11/29/2009				
Separated Size:	1/2" - No.4	1/2" - No.4	1/2" - No.4	No.4 - 0	No.4 - 0	No.4 - 0	RAP	RAP
Laboratory:	ODOT	Class	APAO	ODOT	Class	APAO	Class	APAO
Date:	10/10/2007	12/3/2007	11/27/2007	10/10/2007	12/3/2007	11/27/2007	12/3/2007	11/27/2007
AASHTO T 85 - Sp Gr. and Absorption of Coarse Aggregate								
G_{sb}:	2.653		2.643	2.658		2.634		2.639
G_{sa}:	2.787		2.797	2.798		2.803		
% Absorption:	1.80		2.10	1.90		2.30		
AASHTO T 84 - Sp Gr. and Absorption of Fine Aggregate								
G_{sb}:	n/a			2.604		2.599		
G_{sa}:	n/a			2.786		2.797		
% Absorption:	n/a			2.50		2.70		
Combined Specific Gravity and Absorption								
QL Mean PNo. 4	**1.0**		**2.0**	**65.0**		**58.1**		
G_{sb}:	2.653		2.643			2.613		
G_{sa}:	2.787		2.797			2.800		

DESIGN VALUES SELECTED

Separated Size:	G_{sb}	G_{sa}	**Justification:**
1/2" - No. 4	**2.659**	**2.797**	Karl: I threw the dice....
No. 4 - No. 8	**2.605**	**2.803**	
No. 8 - 0	**2.461**	**2.666**	
n/a	**0.100**	**0.100**	
RAP	2.615	2.771	
Lime	0.100	0.100	

APPENDIX C:

AGGREGATE BLENDING

AND

BATCHING CALCULATIONS

EXAMPLE

APPENDIX C: AGGREGATE BLENDING AND BATCHING CALCULATIONS

Example:

The following example is representative of the calculations used to determine material quantities for each mixture prepared. All stockpile gradations were provided by APAO and ODOT. This example is for the 30% RAP design. A complete set of data is available on request.

Stockpile	1/2" - #4	#4 - #8	#8 - 0	RAP Aggr.	RAS Aggr.	Comparison: Combined vs. Target					
Stockpile Percentage, P_{sj}	27.0	24.0	19.0	30.0	0.0						
Check ΣP_{sj}	100.0					Combined Aggregate			Target		
Sieve Size	Percent Passing					%Ret., P_i	Cum. %Ret.	%Pass	%Pass	Diff	Diff^2
3/4"	100	100	100	100	100	0.0	0.0	100	100	0.0	0.0
1/2"	94.94	100	100	98.5	99.7	1.8	1.8	98.2	98	-0.2	0.0
3/8"	53.5	99.1	100	88.5	99.4	14.4	16.2	83.8	83	-0.8	0.6
1/4"	16	65	100	70.2	99	23.8	40.0	60.0	59	-1.0	1.0
#4	9	43	99.68	60.2	97.3	10.2	50.3	49.7	49	-0.7	0.6
#8	2.5	12.5	81.12	42.5	94.4	17.9	68.2	31.8	31	-0.8	0.7
#16	2	10	55.82	30.2	77.3	9.2	77.4	22.6	22	-0.6	0.4
#30	2	8	38.06	23	59.1	6.0	83.4	16.6	16	-0.6	0.3
#50	0.96	2.78	28	17.1	51.4	5.2	88.6	11.4	11	-0.4	0.1
#100	0.92	2.24	19	12.8	43.4	3.1	91.8	8.2	8	-0.2	0.1
#200	0.79	2.05	15	8.7	35.4	2.1	93.8	6.2	6.3	0.1	0.0
Pan	0	0	0	0	0	6.2	100	0.0	0	0.0	0.0
Binder Content, %	---	---	---	6	18.2	0.5875	<--- Root Mean Square Error				

Stockpile	1/2" - #4	#4 - #8	#8 - 0	RAP Aggr.	RAS Aggr.	Check			
Stockpile Percentage, P_{sj}	27.0	24.0	19.0	30.0	0.0				
100	100.0					Combined Aggregate			Target
Sieve Size, i	Percent Retained, p_{ij}					%Ret., P_i	Cum. %Ret.	%Pass	%Pass
3/4"	0	0	0	0	0	0.0	0.0	100	100
1/2"	5.06	0	0	2	0.3	1.8	1.8	98.2	98
3/8"	41.44	0.9	0	10	0.3	14.4	16.2	83.8	83
1/4"	37.5	34.1	0	18.3	0.4	23.8	40.0	60.0	59
#4	7	22	0.32	10	1.7	10.2	50.3	49.7	49
#8	6.5	30.5	18.56	17.7	2.9	17.9	68.2	31.8	31
#16	0.5	2.5	25.3	12.3	17.1	9.2	77.4	22.6	22
#30	0	2	17.76	7.2	18.2	6.0	83.4	16.6	16
#50	1.04	5.22	10.06	5.9	7.7	5.2	88.6	11.4	11
#100	0.04	0.54	9	4.3	8	3.1	91.8	8.2	8
#200	0.13	0.19	4	4.1	8	2.1	93.8	6.2	6.3
Pan	0.79	2.05	15	8.7	35.4	6.2	100.0	0.0	---

Mixture Binder Content, P_b, %	6.0
Mixture Batch Mass, M_T, grams	7000
Aggregate Batch Mass, grams	6580

Stockpile	1/2" - #4	#4 - #8	#8 - 0	RAP Aggr.	RAS Aggr.
Stockpile Percentage, P_{sj}	27.0	24.0	19.0	30.0	0.0
Sieve Size, i	Batch Mass*, m_{ij}, grams				
3/4"	0.0	0.0	0.0	0.0	0.0
1/2"	89.9	0.0	0.0	29.6	0.0
3/8"	736.2	14.2	0.0	197.4	0.0
1/4"	666.2	538.5	0.0	361.2	0.0
#4	124.4	347.4	4.0	197.4	0.0
#8	115.5	481.7	232.0	349.4	0.0
#16	8.9	39.5	316.3	242.8	0.0
#30	0.0	31.6	222.0	142.1	0.0
#50	18.5	82.4	125.8	116.5	0.0
#100	0.7	8.5	112.5	84.9	0.0
#200	2.3	3.0	50.0	80.9	0.0
Pan	14.0	32.4	187.5	171.7	0.0
Check — Mass, g	1776.6	1579.2	1250.1	1973.9	0.0
Check — Percent	27.0	24.0	19.0	30.0	0.0
Check — Total Mass	6579.8				

*Excludes mass of binder on the reclaimed materials

RAP Binder Content, $(P_b)_{RAP}$	6.0
RAS Binder Content, $(P_b)_{RAS}$	18.2

Stockpile	1/2" - #4	#4 - #8	#8 - 0	RAP	RAS
Stockpile Percentage, P_{sj}	27.0	24.0	19.0	30.0	0.0
Sieve Size, i	Batch Mass*, m_{ij}, grams				
3/4"	0.0	0.0	0.0	0.0	0.0
1/2"	89.9	0.0	0.0	31.5	0.0
3/8"	736.2	14.2	0.0	210.0	0.0
1/4"	666.2	538.5	0.0	384.3	0.0
#4	124.4	347.4	4.0	210.0	0.0
#8	115.5	481.7	232.0	371.7	0.0
#16	8.9	39.5	316.3	258.3	0.0
#30	0.0	31.6	222.0	151.2	0.0
#50	18.5	82.4	125.8	123.9	0.0
#100	0.7	8.5	112.5	90.3	0.0
#200	2.3	3.0	50.0	86.1	0.0
Pan	14.0	32.4	187.5	182.7	0.0
Totals	1776.6	1579.2	1250.1	2099.9	0.0
	6705.8				
RAP Binder	Mass (grams) =	126.0	$(P_{br})_{RAP}$ =	1.80	
RAS Binder	Mass (grams) =	0.0	$(P_{br})_{RAS}$ =	0.00	
Total Reclaimed Binder	Mass (grams) =	126.0	P_{br} =	1.80	
Virgin Binder	Mass (grams) =	294.0	P_{virgin} =	4.2	
Mixture	Mass (grams) =	6999.8	P_b =	6.0	
Percent of virgin binder replaced by RAP binder					30.0
Percent of virgin binder replaced by RAS binder					0.0
Percent of virgin binder replaced by RAM binder					30.0

*Includes mass of binder on the reclaimed materials

Stockpile	1/2" - #4	#4 - #8	#8 - 0	RAP	RAS
Batch Mass, grams	1776.6	1579.2	1250.1	2099.9	0.0
Virgin Binder, grams	294.0				

APPENDIX D:

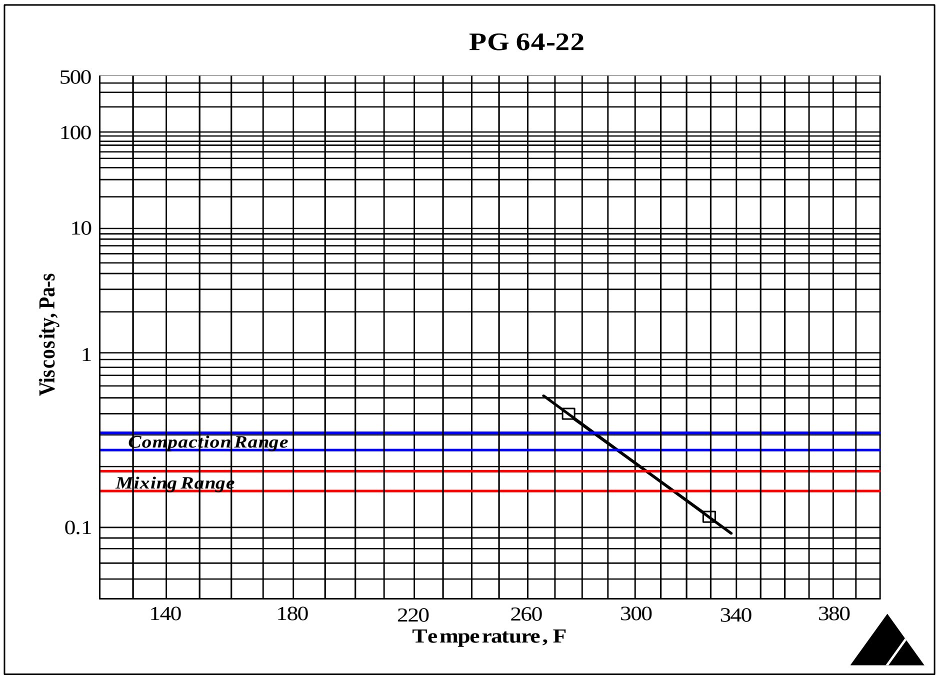
ASPHALT BINDER TEMPERATURE CURVE

APPENDIX D: ASPHALT BINDER TEMPERATURE CURVE

The data below represents one of the three binder temperature curves used for this research. All temperature curves were provided by McCall Oil. This example is the data for the PG Binder Grade 64-22. A complete set of data is available on request.

Binder	**PG 64-22**				
Temp (F)	Viscosity (cp)	Mixing Temperature Range, F	305	-	315
275	**400**	Compaction Temperature Range, F	285	-	293
329	**113**				

Specific Gravity@60F	**1.0295**



APPENDIX E:

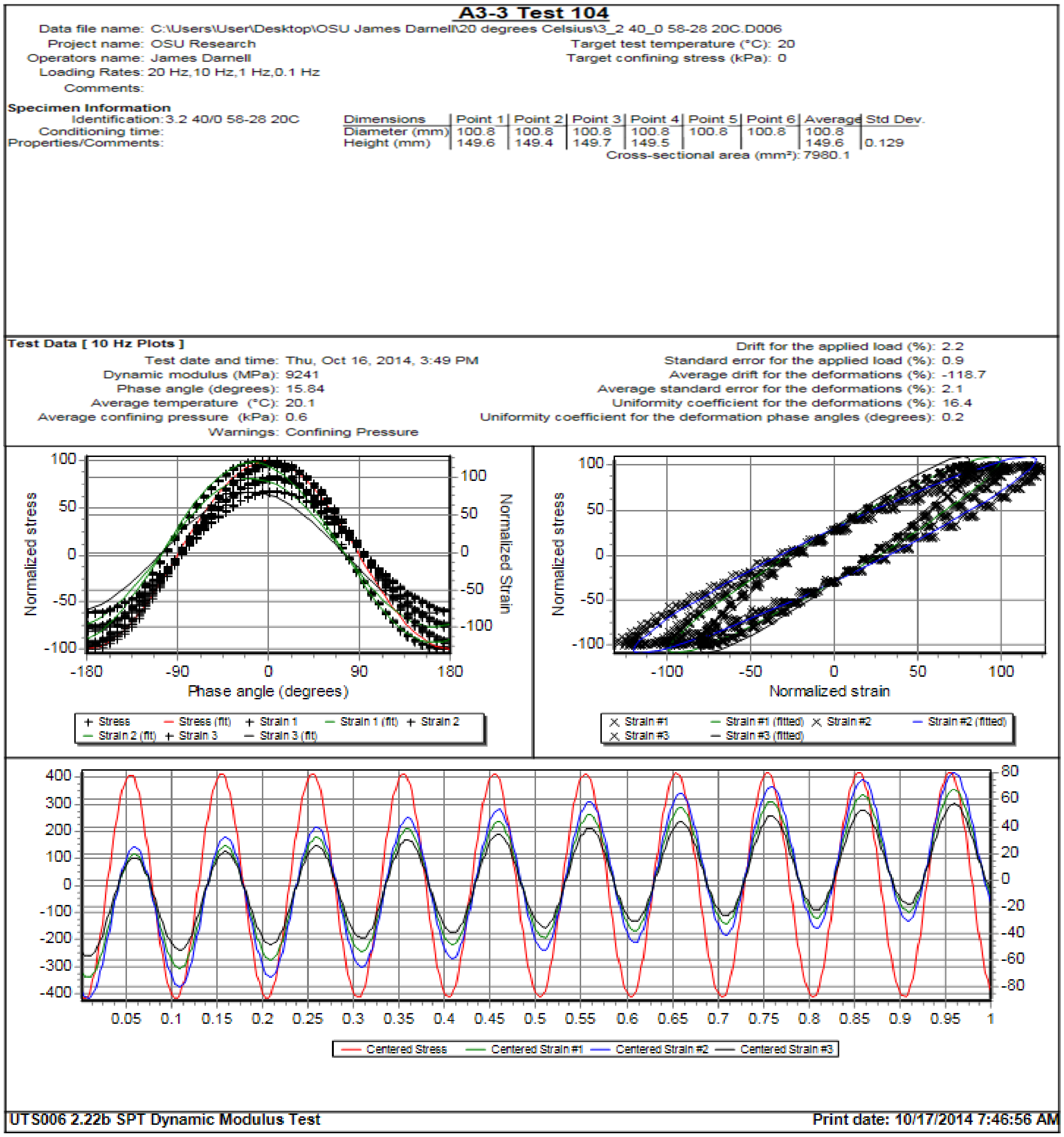
EXAMPLES OF AMPT TEST RESULTS

AND

MASTER CURVE DATA AND PLOTS

APPENDIX E: EXAMPLES OF AMPT TEST RESULTS AND MASTER CURVE DATA AND PLOTS

The following is an example of the data produced by the AMPT dynamic modulus test. This data was used to generate the master curves and phase angles in this study. A complete set of data is available on request.



The tables and figures below are an example of the data used to generate the dynamic modulus and phase angle master curves that are included in Chapter 5 of the report. A complete set of data is available on request.

The following is a raw data table for replicate specimens:

Project:	OSU Recycle Increase				
Mix Identification:	1/2 inch Level 3				
Date:	10/30/14				
Technician:	James Darnell				
Sample Description:	PG64-22 with 19% RAP5%RAS				
Notes:	Specimen 3 is average of 1 and 2				
		Specimen 1	Specimen 2	Specimen 3	Average
VMA	Volume, %	18.6	19.2	18.9	18.9
VFA	Volume, %	65.7	63.4	64.6	64.6
Reference Temp	20	C			

Conditions		Samp 2.1		Samp 3.1		Specimen		Average	Modulus	Average	Std
Temperatur	Frequency	Modulus	Phase	Modulus	Phase	Modulus	Phase	Modulus	CV	Phase	Phase
C	Hz	Ksi	Degree	Ksi	Degree	Ksi	Degree	Ksi	%	Deg	Deg
4	0.1	1399.3	10.2	1307.8	11.0	1353.6	10.6	1353.6	3.4	10	0.4
4	1	1747.1	7.9	1650.2	8.5	1698.7	8.2	1698.7	2.9	8.2	0.3
4	10	2075.5	6.4	1857.4	8.3	1966.4	7.3	1966.4	5.5	7.3	0.9
20	0.1	527.2	21.9	502.6	22.0	514.9	21.9	514.9	2.4	21	0.1
20	1	826.9	17.3	805.0	17.3	815.9	17.3	815.9	1.3	17	0.0
20	10	1163.9	13.3	1168.0	13.5	1166.0	13.4	1166.0	0.2	13	0.1
40	0.01	52.5	30.5	53.0	28.8	52.7	29.7	52.7	0.5	29	0.8
40	0.1	108.6	31.8	122.7	30.9	115.6	31.3	115.6	6.1	31	0.5
40	1	229.4	29.5	254.3	28.6	241.9	29.0	241.9	5.1	29	0.5
40	10	449.0	25.3	481.7	24.2	465.4	24.8	465.4	3.5	24	0.6

The data on the next page is the "FIT", i.e for establishing the best fit curve and shift factors to create the Master Curves.

			Pc	E*, ksi	logE*
Maximum Modulus			0.85393844	3122.674	3.49452668
		Initial Values			
Log (Min)	-0.13998	0.5	Copy Cells C4:C7 to B4:B7 using Copy/Paste Values		
Beta	-1.69513	-1			
Gamma	-0.38243	-0.5			
EA	202299.6	200000			
Reference Temp	20				

R2	0.996944	0.999899
Se	0.02043	

Temperature C	Frequency Hz	Average Modulus Ksi	Average Phase Ang Degree	Log Average Modulus	Predicted	Error	Error^2	loga(t)	log (wr)	wr
4	0.1	1353.6	10.6	3.1314789	3.100882	0.030597	0.000936	2.079954	1.079954	12.02138
4	1	1698.7	8.2	3.23011197	3.216409	0.013703	0.000188	2.079954	2.079954	120.2138
4	10	1966.4	7.3	3.29367653	3.300066	-0.00639	4.08E-05	2.079954	3.079954	1202.138
20	0.1	514.9	21.9	2.71170926	2.723883	-0.01217	0.000148	0	-1	0.1
20	1	815.9	17.3	2.91164203	2.930808	-0.01917	0.000367	0	0	1
20	10	1166.0	13.4	3.06668293	3.090019	-0.02334	0.000545	0	1	10
40	0.01	52.7	29.7	1.7221645	1.722923	-0.00076	5.75E-07	-2.3011	-4.3011	5E-05
40	0.1	115.6	31.3	2.0631299	2.064401	-0.00127	1.61E-06	-2.3011	-3.3011	0.0005
40	1	241.9	29.0	2.38354675	2.379456	0.004091	1.67E-05	-2.3011	-2.3011	0.004999
40	10	465.4	24.8	2.66778295	2.651644	0.016139	0.00026	-2.3011	-1.3011	0.049992
			Sy	0.52267125			0.002504	Use Solver on this Cell		

wr	log E*	E*, ksi
1000000	3.428493	2682.214
100000	3.398544	2503.481
10000	3.355541	2267.468
1000	3.294361	1969.522
100	3.208454	1616.046
10	3.090019	1230.324
1	2.930808	852.7231
0.1	2.723883	529.521
0.01	2.466432	292.7064
0.001	2.162963	145.5336
0.0001	1.827219	67.17679
0.00001	1.480842	30.25813
0.000001	1.148329	14.07111

The data on the next two pages constitutes the "REPORT" generated for the replicate specimens.

Note that the Shift Factors and equation for the Master Curve are included, as well as a coefficient of variation for each combination of temperature and frequency.

The plots show the Master Curves for dynamic modulus and phase angle. The same shift factors established for the dynamic modulus master curve are used for the phase angle mastercurve.

Project:	OSU Recycle Increase							
Mix Identification:	1/2 inch Level 3							
Date:	12/9/2014							
Technician:	James Darnell							
Sample Description:	PG64-22 with 19% RAP5%RAS							
Notes:	Specimen 3 is average of 1 and 2							
Shift Factors:	Arrhenius log10 (a(T)) = EA/19.147143*(1/T - 1/Tr)							
Master Curve Model:	log(E*) = logMin) + (log(Max) - log(Min)) / (1+EXP (Beta + Gamma* log (wr)))							
Reference Temperature:	20	C						

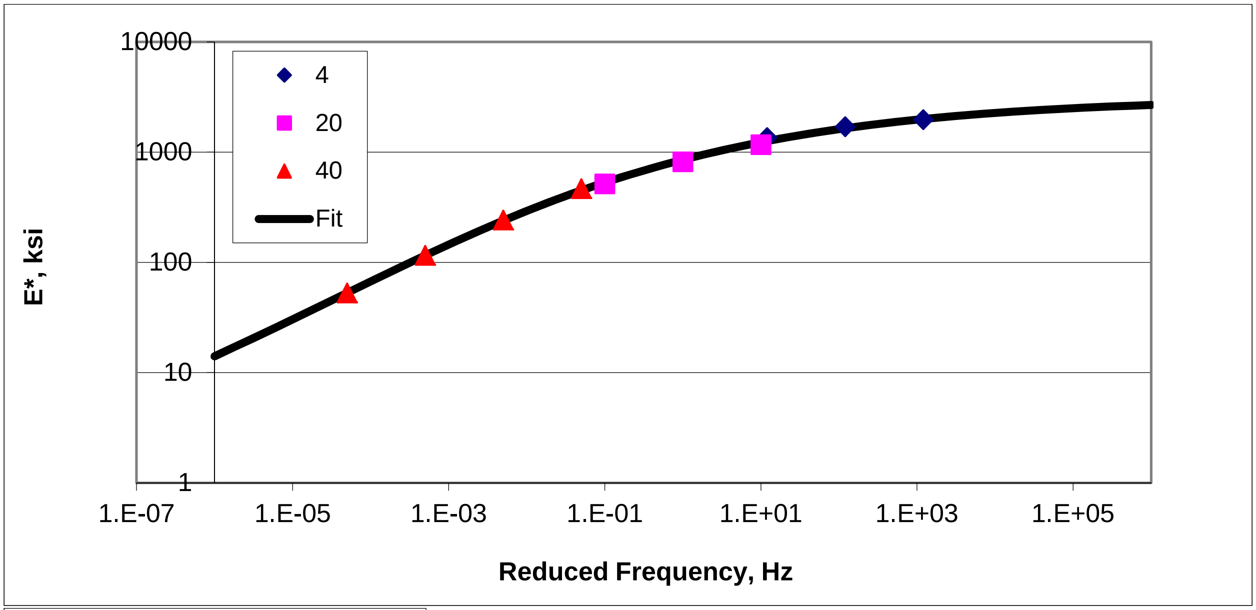
Data:

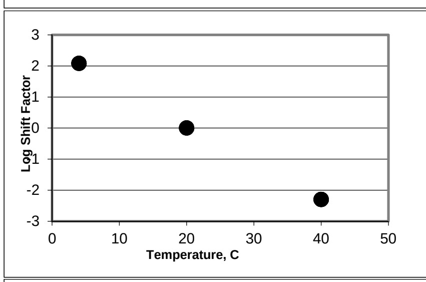
VMA:	18.9	%
VFA:	64.6	%

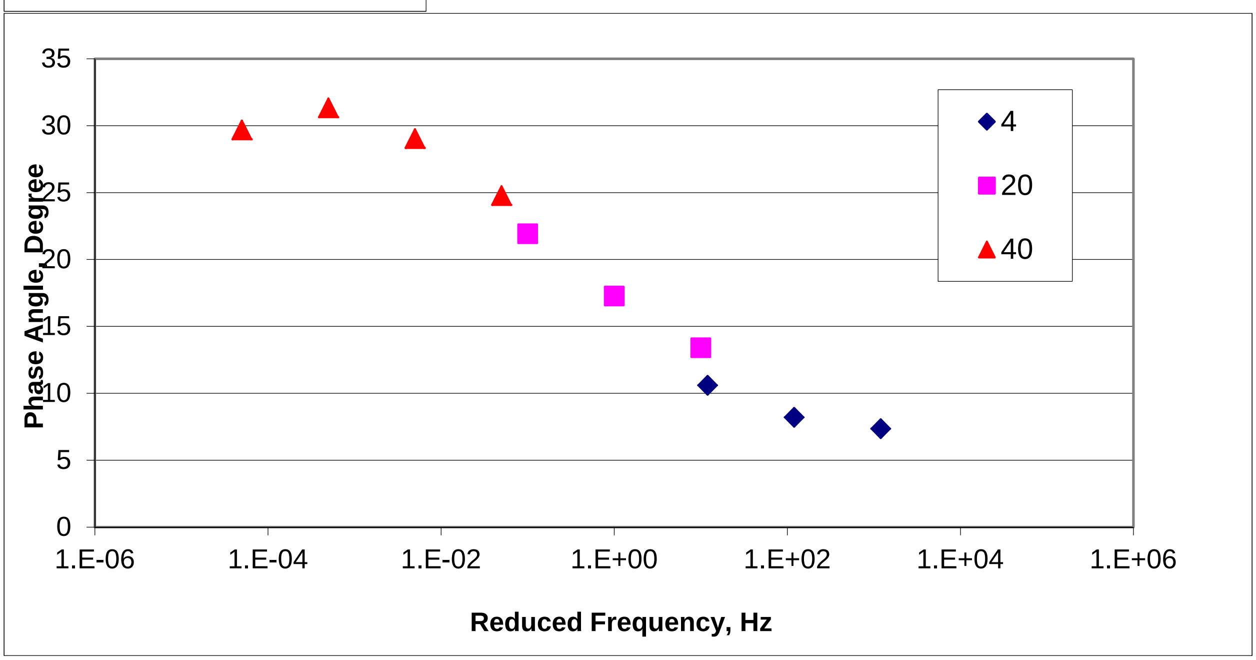
		Samp 2.1 19%5%		Samp 3.1 19%5%		Specimen 3		Average	Modulus	Average	Std Dev	Fitted
Temp	Frequ	Modulus	Phase	Modulus	Phase	Modulus	Phase	Modulus	CV	Phase	Phase	Modulus
C	Hz	ksi	Degree	ksi	Degree	ksi	Degree	ksi	%	Deg	Deg	ksi
4	0.1	1399.3	10.	1307.8	11.	1353.6	10.	1353.6	3.4	10	0.4	1261.
4	1	1747.1	7.	1650.2	8.	1698.7	8.	1698.7	2.9	8.2	0.3	1645.
4	10	2075.5	6.	1857.4	8.	1966.4	7.	1966.4	5.5	7.3	0.9	1995.
20	0.1	527.2	21.	502.6	22.	514.9	21.	514.9	2.4	21	0.1	529.
20	1	826.9	17.	805.0	17.	815.9	17.	815.9	1.3	17	0.0	852.
20	10	1163.9	13.	1168.0	13.	1166.0	13.	1166.0	0.2	13	0.1	1230.
40		52.5	30.	53.0	28.	52.7	29.	52.7	0.5	29	0.8	52.
40	0.1	108.6	31.	122.7	30.	115.6	31.	115.6	6.1	31	0.5	116.
40	1	229.4	17.	254.3	28.	241.9	29.	241.9	5.1	25	6.7	239.
40	10	449.0	25.	481.7	24.	465.4	24.	465.4	3.5	24	0.6	448.

Final Parameters:	Max	3122.7	ksi	**Goodness of Fit:**	R^2	0.9969
	Min	0.7	ksi		Se/Sy	0.04
	Beta	-1.69513				
	Gamma	-0.38243				
	EA	202300				

Master Curves for Dynamic Modulus and Phase Angle:







Data in the format required for the MEPDG:

Project:	OSU Recycle Increase
Mix Identification:	1/2 inch Level 3
Date:	10/30/14
Technician:	James Darnell
Sample Description:	PG64-22 with 19% RAP5%RAS
Notes:	Specimen 3 is average of 1 and 2
Shift Factors:	Arrhenius log10 (a(T)) = EA/19.147143*(1/T - 1/Tr)
Master Curve Model:	log(E*) = logMin) + (log(Max) - log(Min)) / (1+EXP (Beta + Gamma* log (wr)))
Reference Temperature:	20 C

Temp C	Temp F	Frequency Hz	Shift Factor	Reduced Frequency	E* ksi	E* MPa
-10.0	14	25	4.107356	320107.9	2600.4	17935.0
-10.0	14	10	4.107356	128043.1	2525.3	17416.8
-10.0	14	5	4.107356	64021.57	2462.5	16983.8
-10.0	14	1	4.107356	12804.31	2295.8	15833.9
-10.0	14	0.5	4.107356	6402.157	2214.6	15274.1
-10.0	14	0.1	4.107356	1280.431	2004.4	13824.4
4.4	40	25	2.018941	2611.444	2101.2	14491.8
4.4	40	10	2.018941	1044.577	1975.7	13626.6
4.4	40	5	2.018941	522.2887	1874.8	12930.3
4.4	40	1	2.018941	104.4577	1623.1	11194.8
4.4	40	0.5	2.018941	52.22887	1509.0	10407.8
4.4	40	0.1	2.018941	10.44577	1237.7	8536.4
21.1	70	25	-0.13604	18.27665	1332.4	9189.8
21.1	70	10	-0.13604	7.310658	1177.4	8120.7
21.1	70	5	-0.13604	3.655329	1061.5	7321.1
21.1	70	1	-0.13604	0.731066	804.6	5549.3
21.1	70	0.5	-0.13604	0.365533	702.3	4843.9
21.1	70	0.1	-0.13604	0.073107	491.8	3392.2
37.8	100	25	-2.06004	0.217722	630.1	4346.1
37.8	100	10	-2.06004	0.087089	512.7	3536.0
37.8	100	5	-2.06004	0.043544	433.2	2987.9
37.8	100	1	-2.06004	0.008709	281.5	1941.2
37.8	100	0.5	-2.06004	0.004354	230.0	1586.0
37.8	100	0.1	-2.06004	0.000871	139.2	959.8
54.4	130	25	-3.78829	0.004071	225.4	1554.4
54.4	130	10	-3.78829	0.001628	170.0	1172.6
54.4	130	5	-3.78829	0.000814	136.1	939.0
54.4	130	1	-3.78829	0.000163	79.4	547.9
54.4	130	0.5	-3.78829	8.14E-05	62.6	431.5
54.4	130	0.1	-3.78829	1.63E-05	35.8	246.9

APPENDIX F:

PLOTS OF MODULUS AND PHASE ANGLE

VS

FREQUENCY OF LOADING AT 4, 20 AND 40ºC

F1. PLOTS OF MODULUS VS FREQUENCY OF LOADING AT 4, 20 AND 40ºC

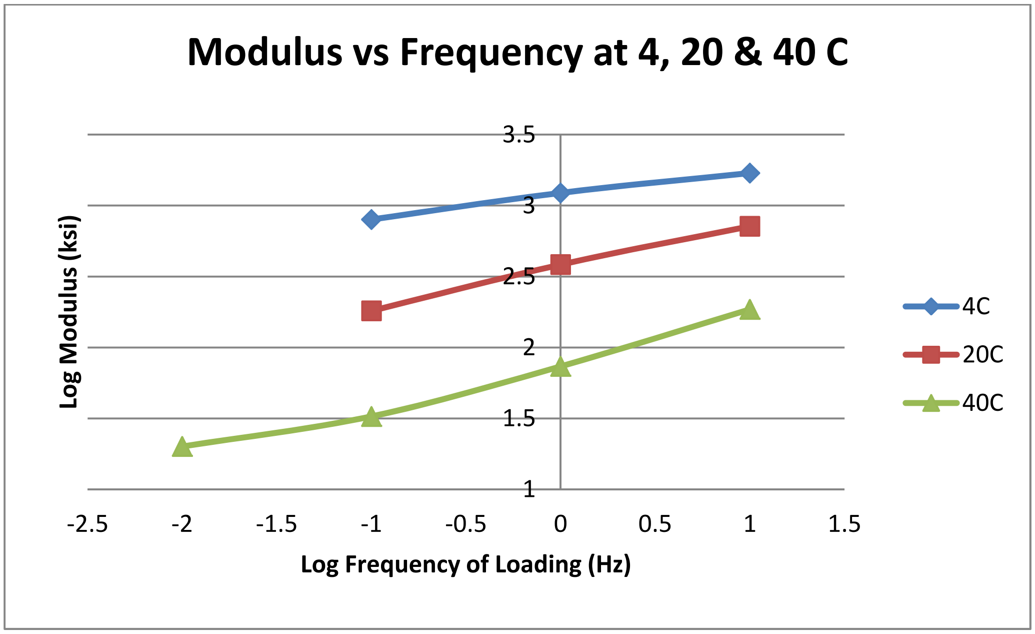


Figure F.1: Dynamic Modulus Data for 0% RAP, 5% RAS with PG 58-28 Binder

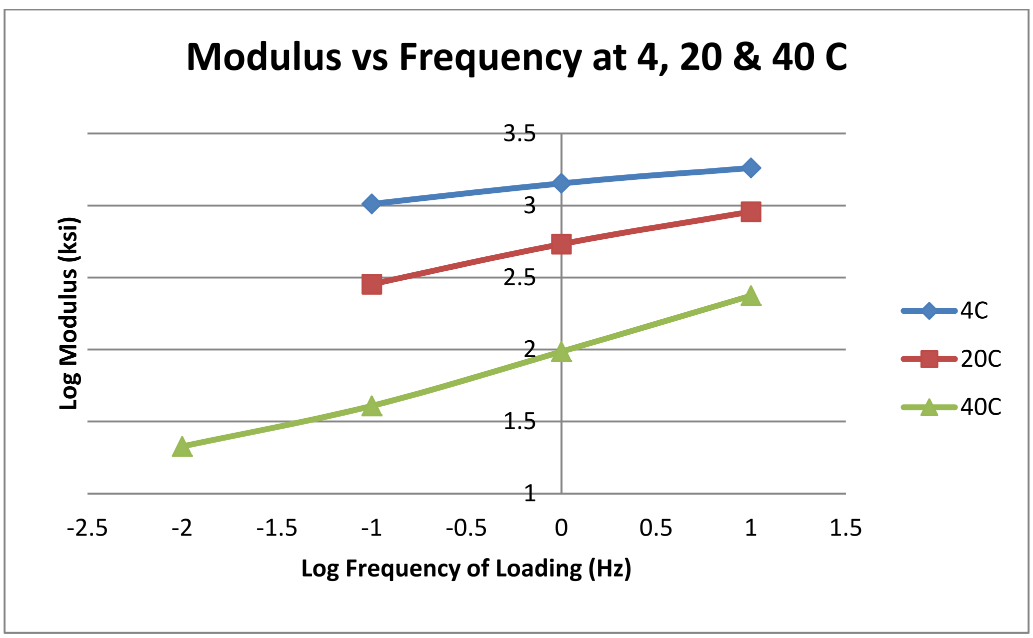


Figure F.2: Dynamic Modulus Data for 0% RAP, 5% RAS with PG 64-22 Binder

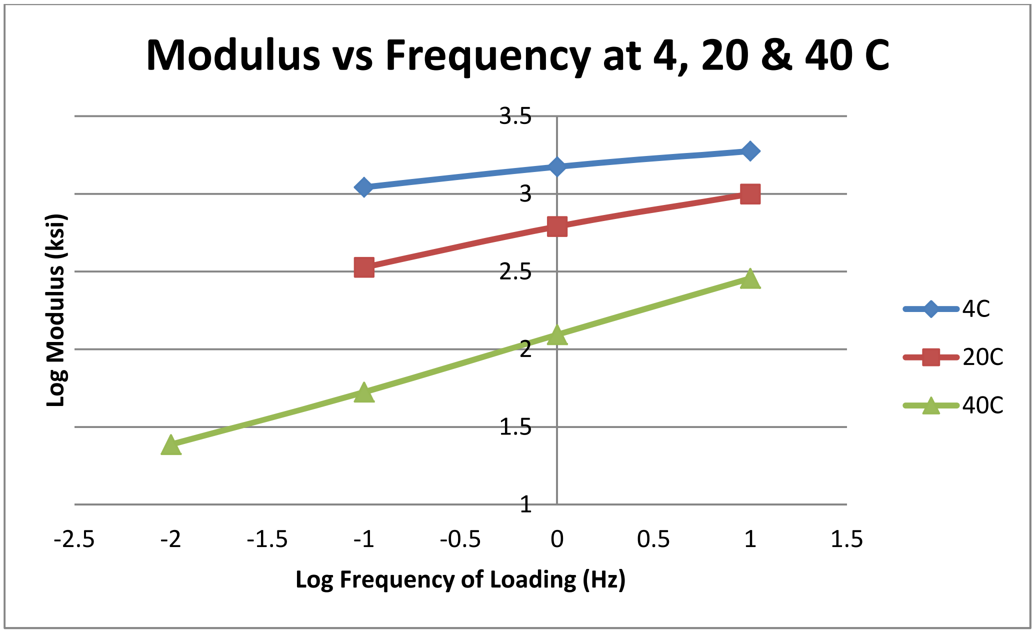


Figure F.3: Dynamic Modulus Data for 17% RAP, 3% RAS with PG 58-28 Binder

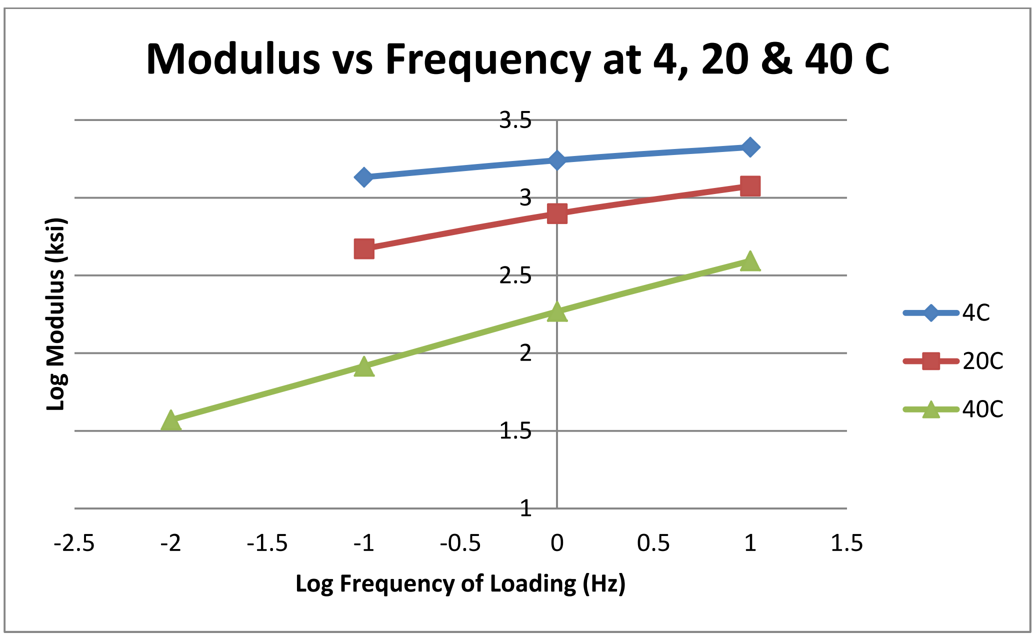


Figure F.4: Dynamic Modulus Data for 17% RAP, 3% RAS with PG 64-22 Binder

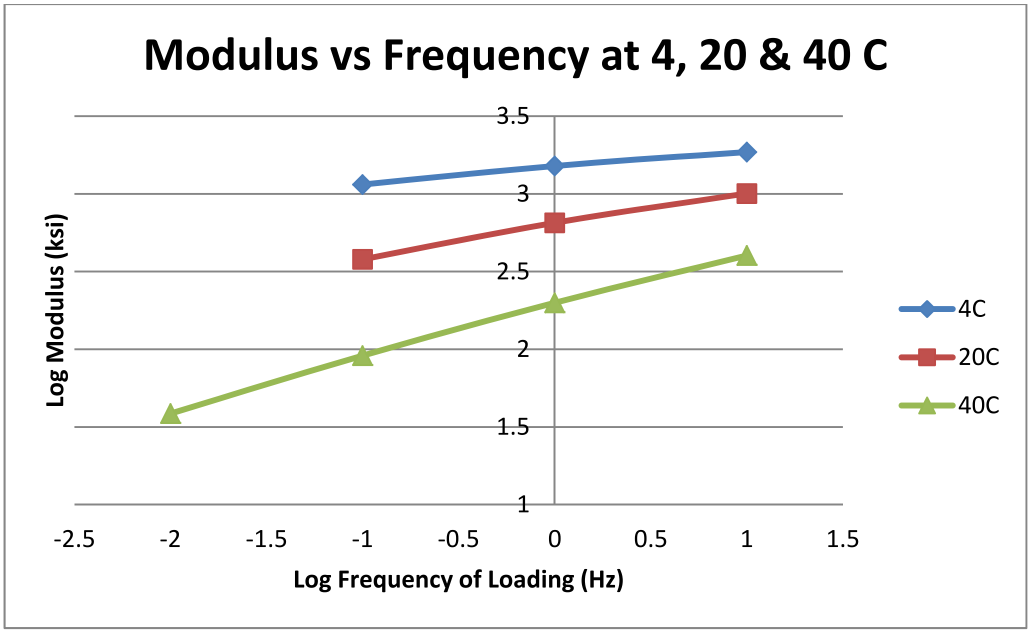


Figure F.5: Dynamic Modulus Data for 19% RAP, 5% RAS with PG 58-28 Binder

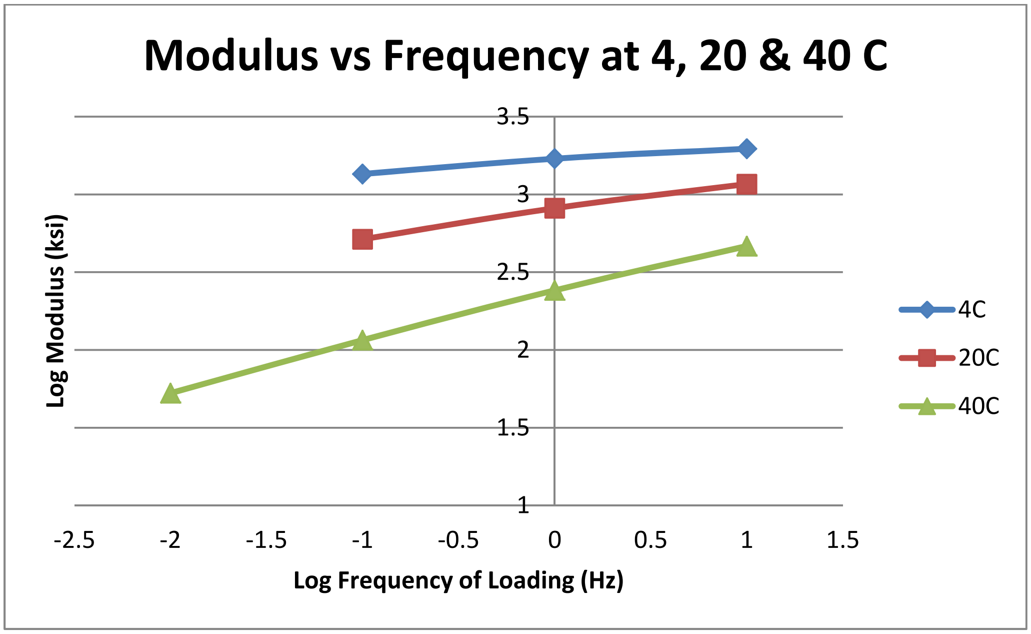


Figure F.6: Dynamic Modulus Data for 19% RAP, 5% RAS with PG 64-22 Binder

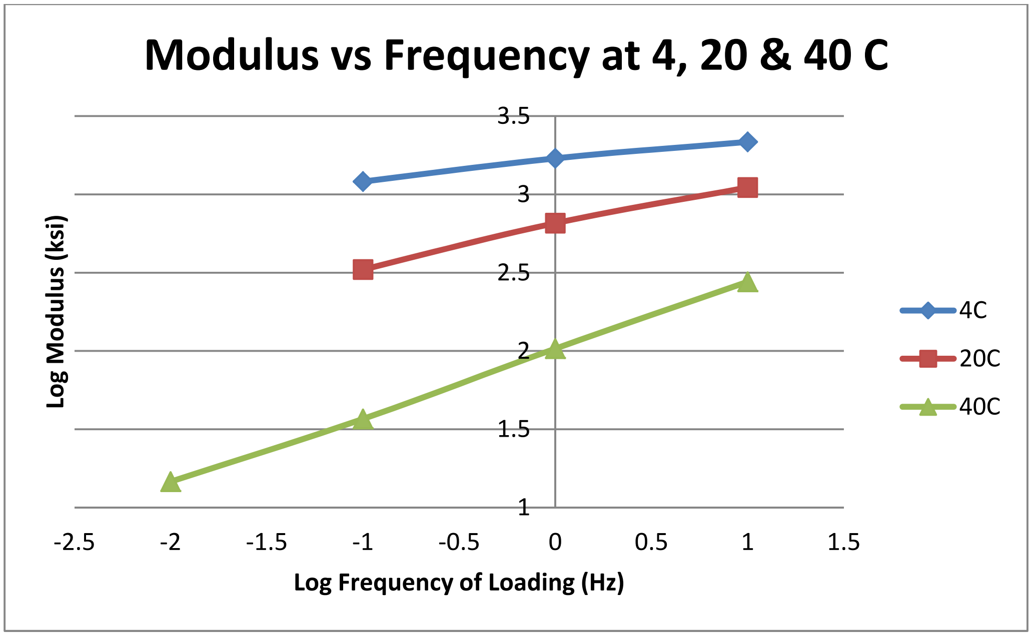


Figure F.7: Dynamic Modulus Data for 30% RAP, 0% RAS with PG 58-28 Binder

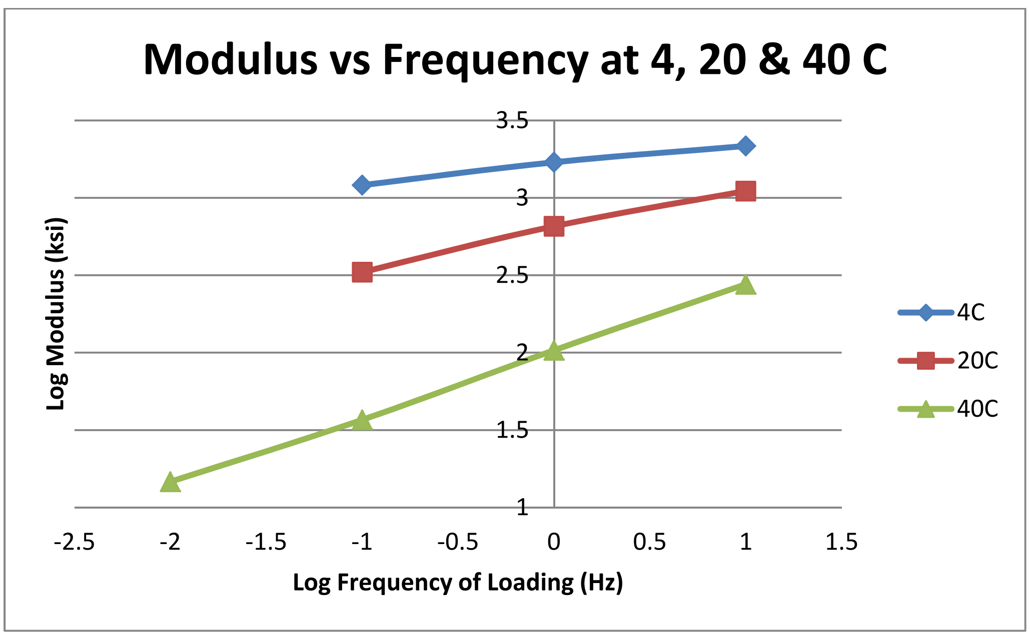


Figure F.8: Dynamic Modulus Data for 30% RAP, 0% RAS with PG 58-34 Binder

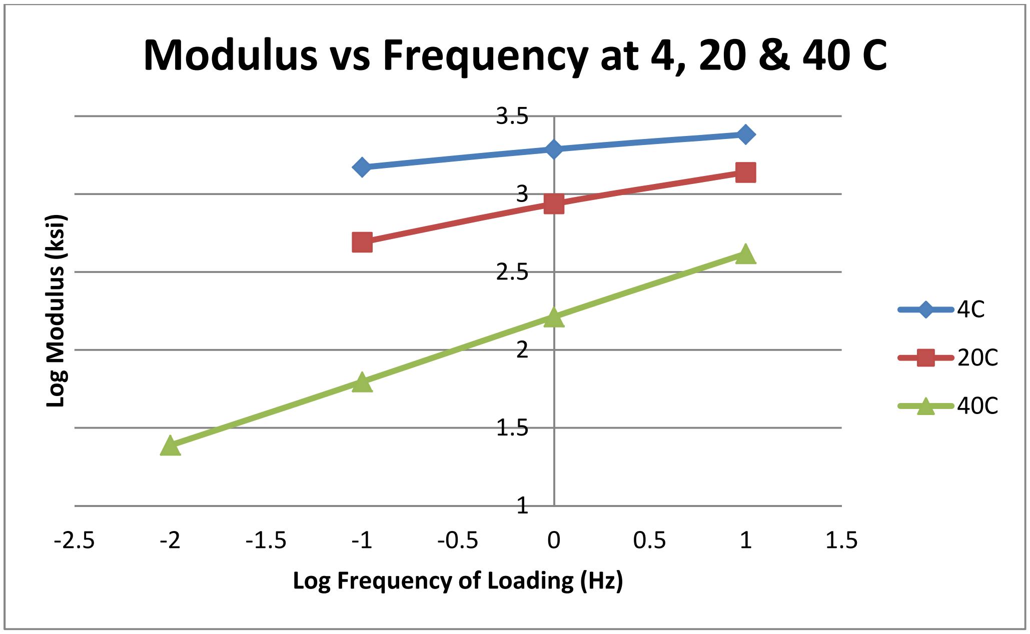


Figure F.9: Dynamic Modulus Data for 30% RAP, 0% RAS with PG 64-22 Binder

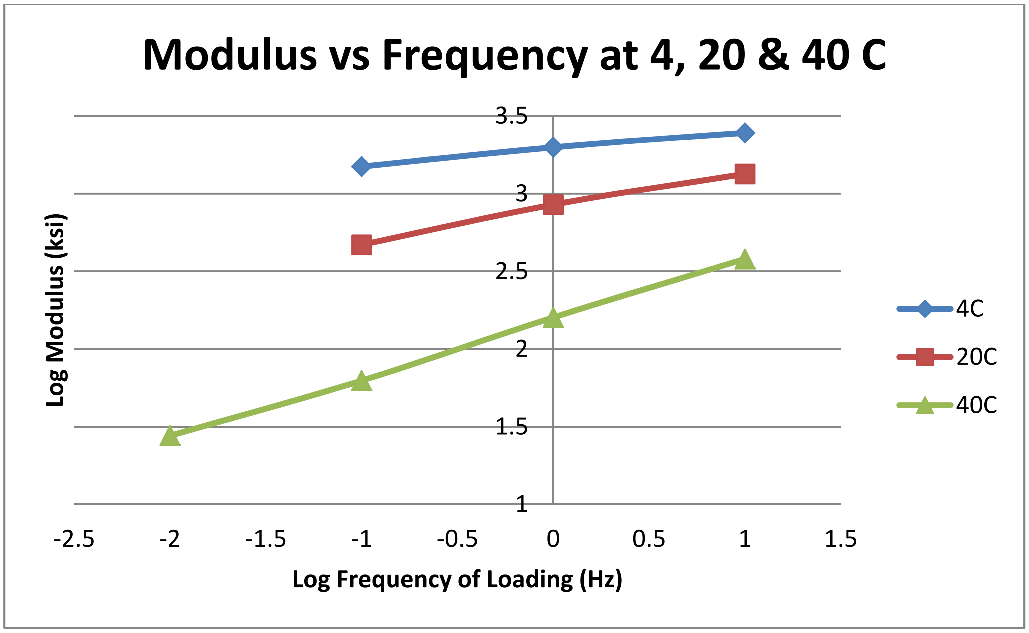


Figure F.10: Dynamic Modulus Data for 40% RAP, 0% RAS with PG 58-28 Binder

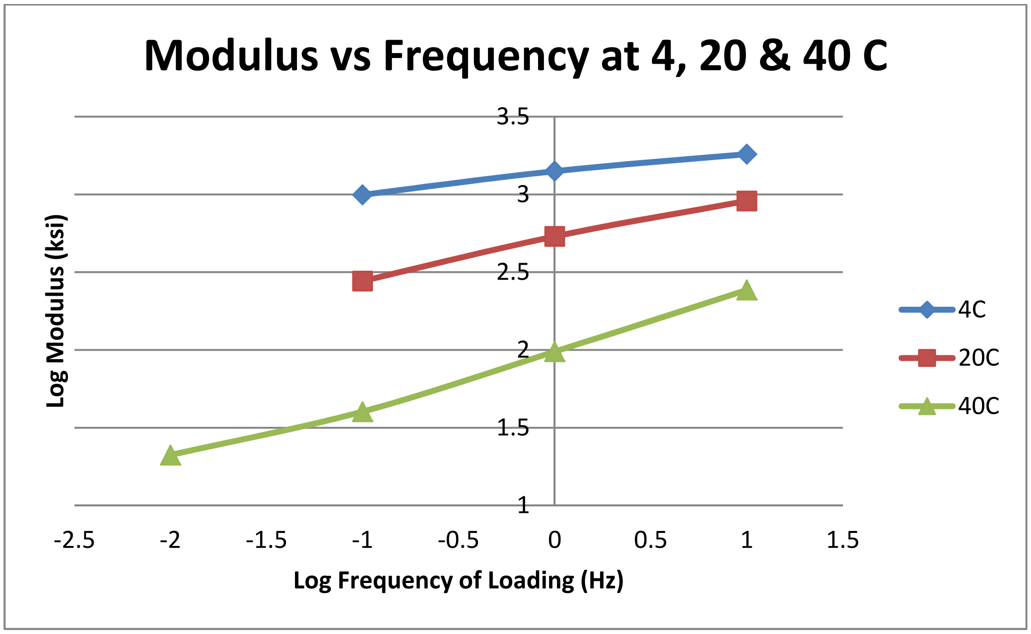


Figure F.11: Dynamic Modulus Data for 40% RAP, 0% RAS with PG 58-34 Binder

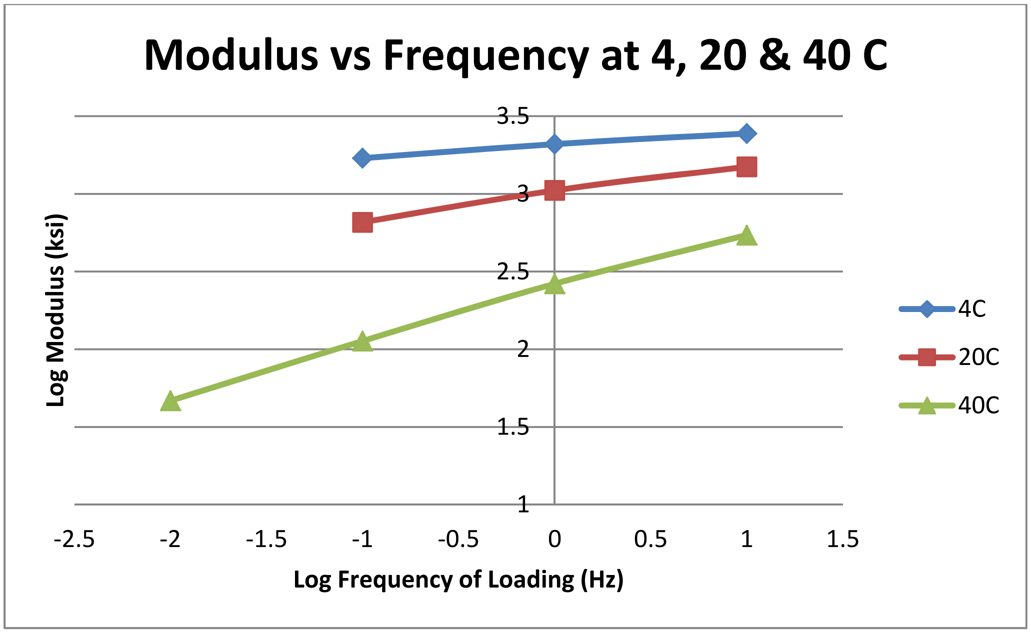


Figure F.12: Dynamic Modulus Data for 40% RAP, 0% RAS with PG 64-22 Binder

F2. PLOTS OF PHASE ANGLE VS FREQUENCY OF LOADING AT 4, 20 AND 40°C

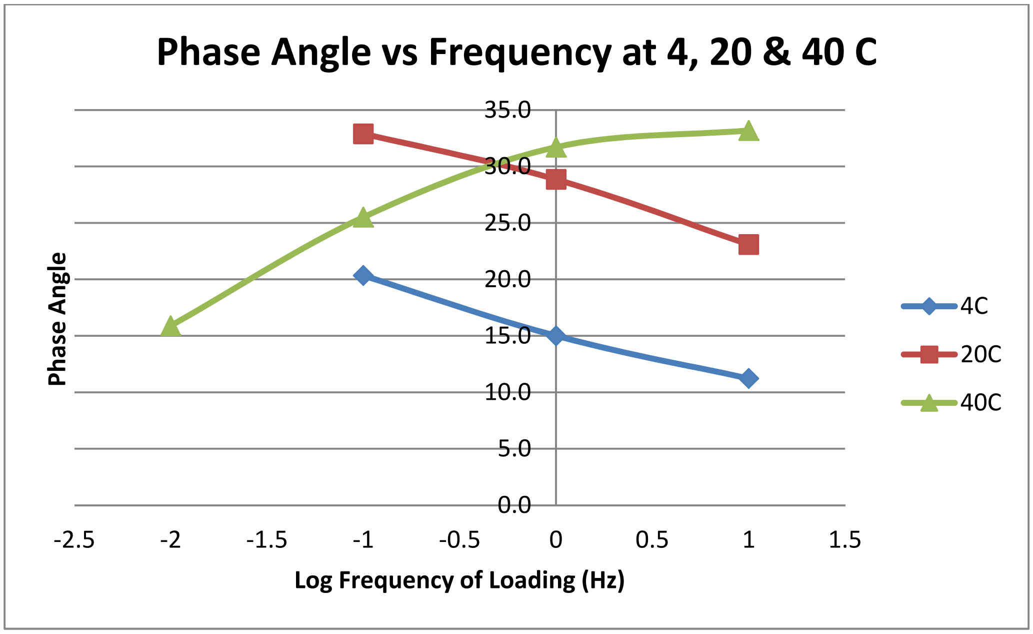


Figure F.13: Phase Angle Data for 0% RAP, 5% RAS with PG 58-28 Binder

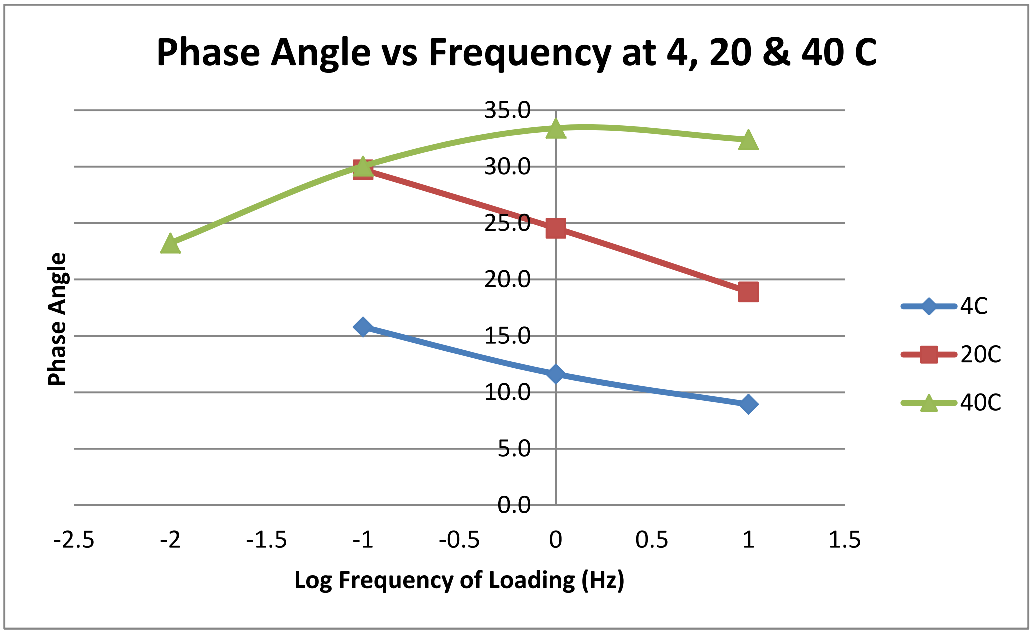


Figure F.14: Phase Angle Data for 0% RAP, 5% RAS with PG 64-22 Binder

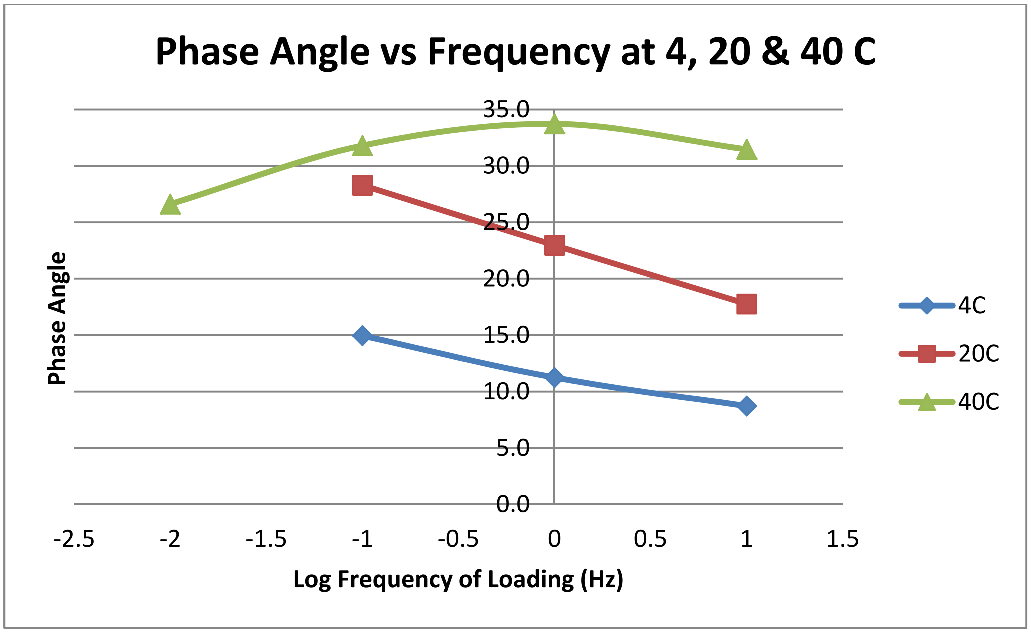


Figure F.15: Phase Angle Data for 17% RAP, 3% RAS with PG 58-28 Binder

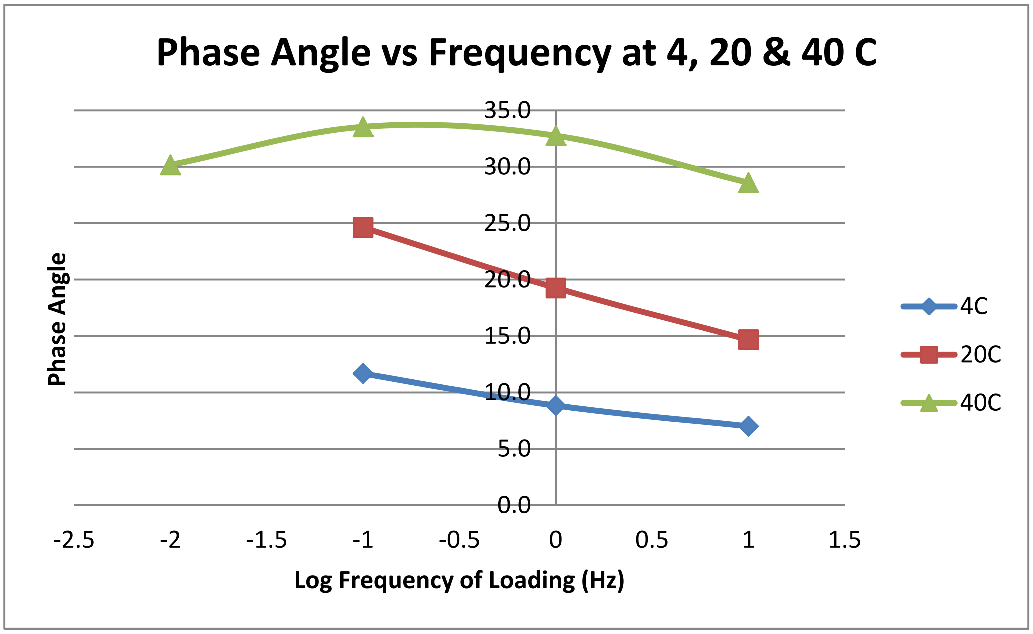


Figure F.16: Phase Angle Data for 17% RAP, 3% RAS with PG 64-22 Binder

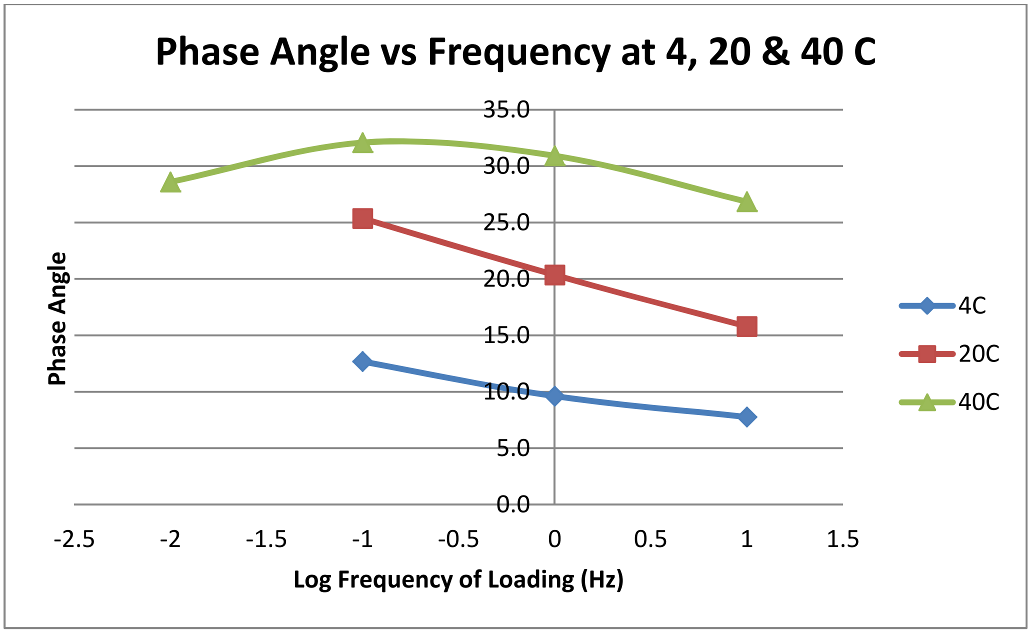


Figure F.17: Phase Angle Data for 19% RAP, 5% RAS with PG 58-28 Binder

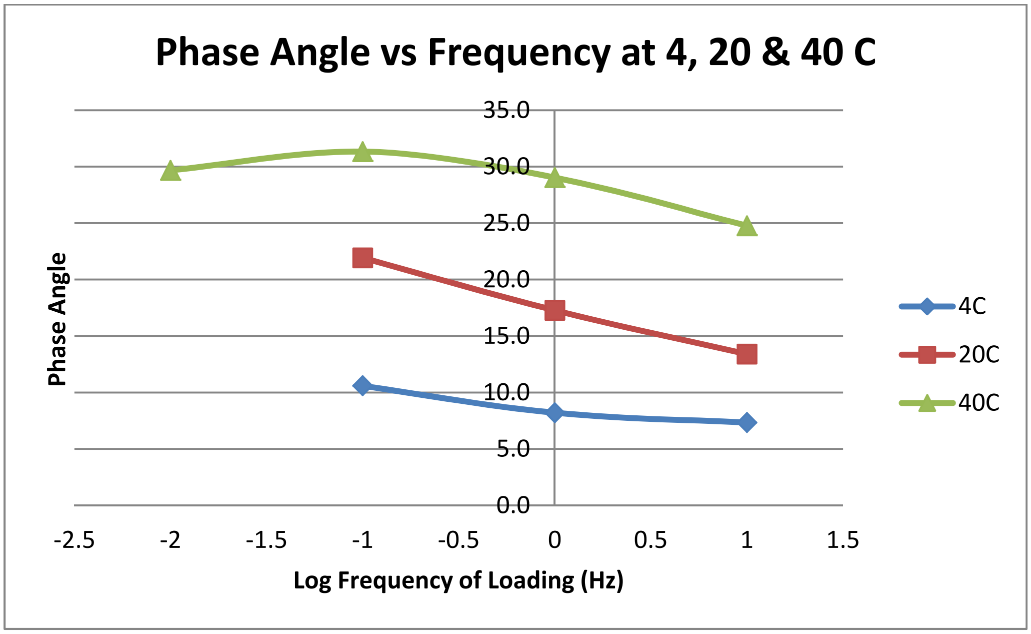


Figure F.18: Phase Angle Data for 19% RAP, 5% RAS with PG 64-22 Binder

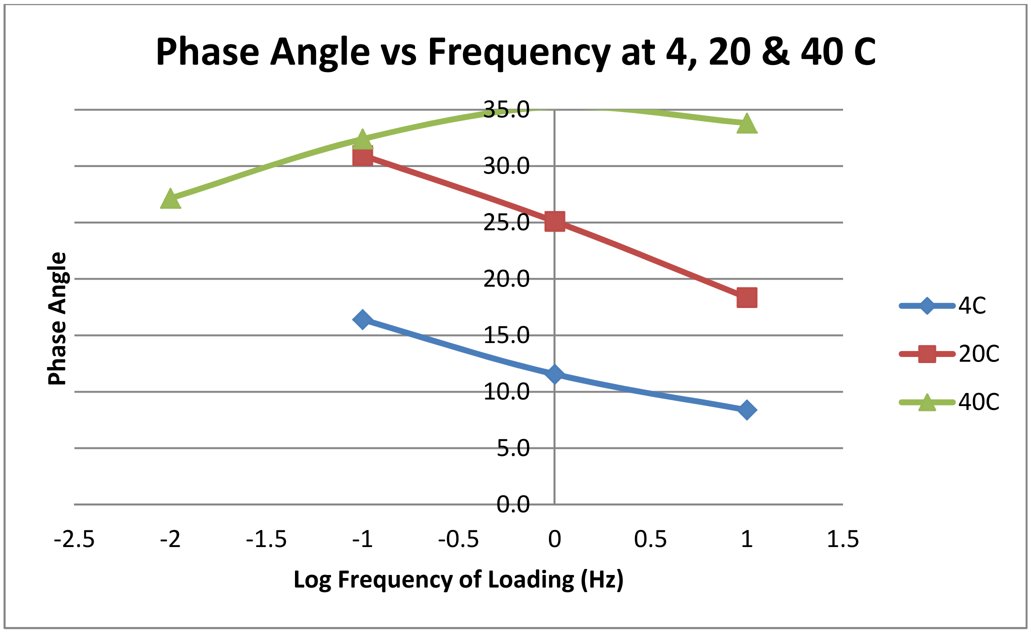


Figure F.19: Phase Angle Data for 30% RAP, 0% RAS with PG 58-28 Binder

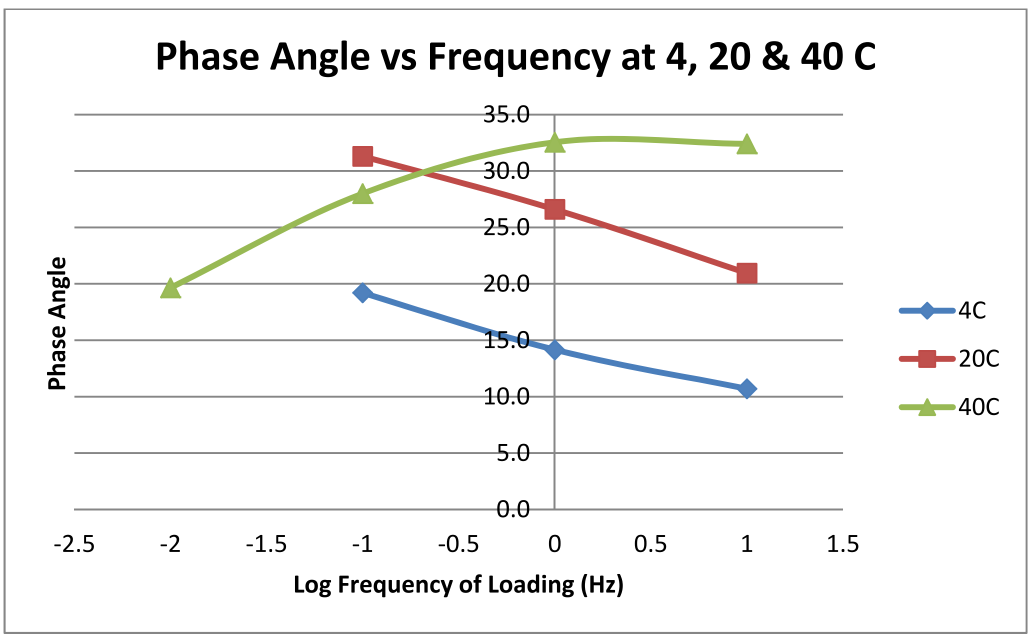


Figure F.20: Phase Angle Data for 30% RAP, 0% RAS with PG 58-34 Binder

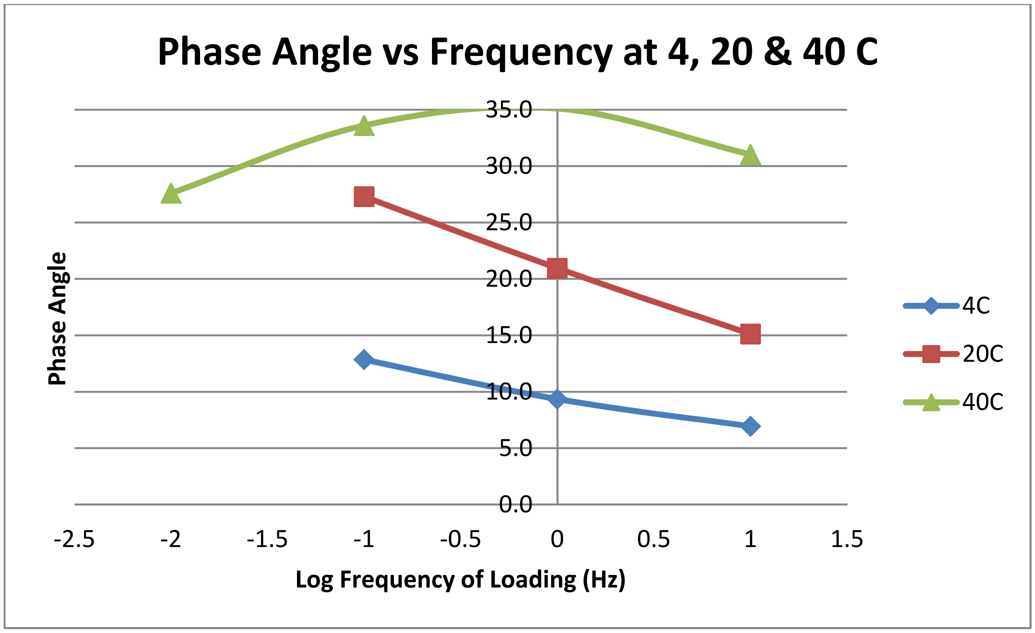


Figure F.21: Phase Angle Data for 30% RAP, 0% RAS with PG 64-22 Binder

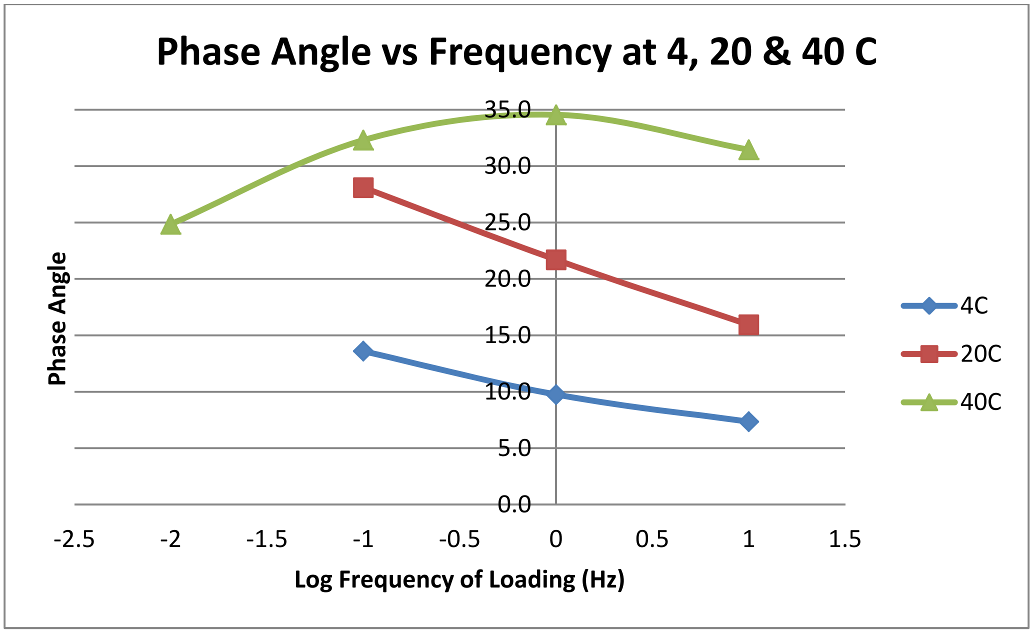


Figure F.22: Phase Angle Data for 40% RAP, 0% RAS with PG 58-28 Binder

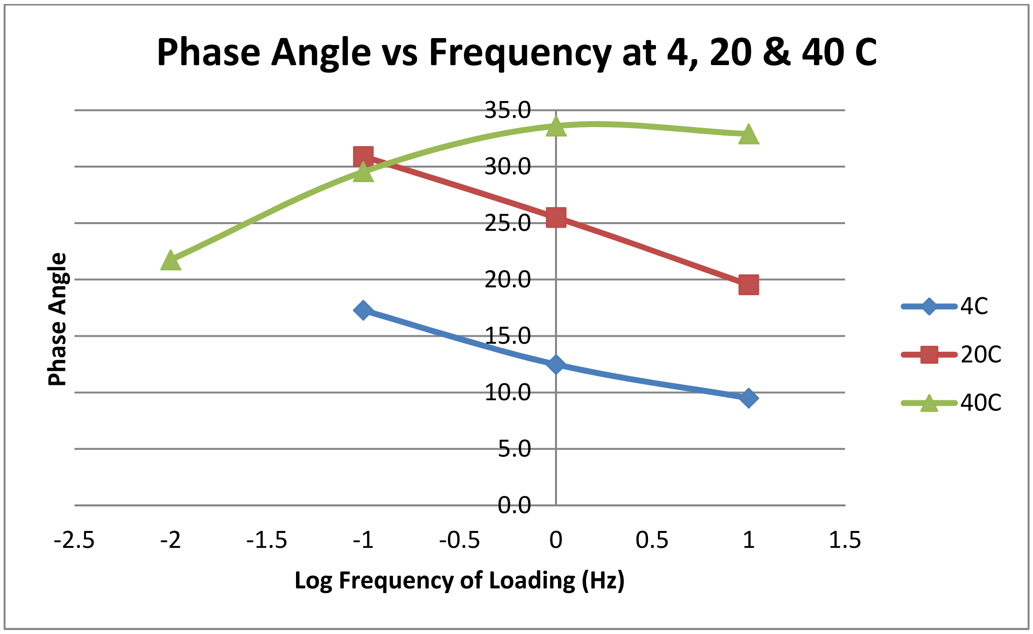


Figure F.23: Phase Angle Data for 40% RAP, 0% RAS with PG 58-34 Binder

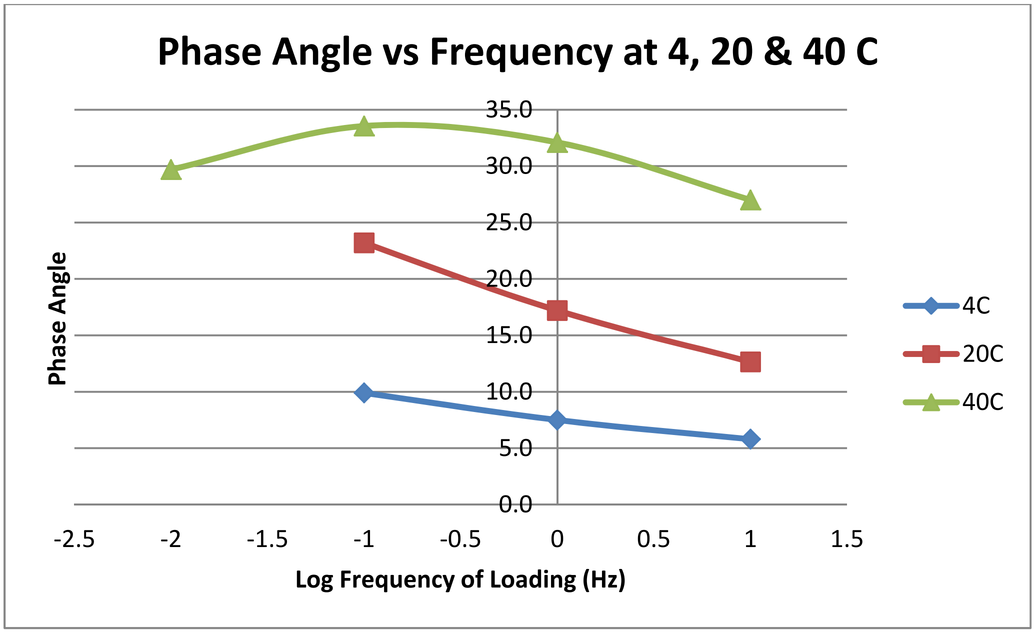


Figure F.24: Phase Angle Data for 40% RAP, 0% RAS with PG 64-22 Binder

APPENDIX G:

FLOW NUMBER TEST RESULTS

APPENDIX G: FLOW NUMBER TEST RESULTS

The following is an example of the data produced by the AMPT Flow Number Tests. This data was used to generate the bar charts to compare the rutting resistance of the asphalt specimens. A complete set of data is available on request.

Simple Performance Flow Number Test

File name: E:\Flows Test for James\5_2 19_5 58-28.D005
Created: 1/6/2015 1:06:56 PM, by software version 1.47
Project: I-84 Kamela Interchange
Operator: wayne brown
Comments: Sample conditioned from room temperture for 4 hours to reach 54.7 degrees Celsius. AMPT Research.

Trail Runs before OSU samples

Specimen Information
Identification: 5.2 19/5 58-28
Conditioning: 4 hours @ 55.0C
Remarks:

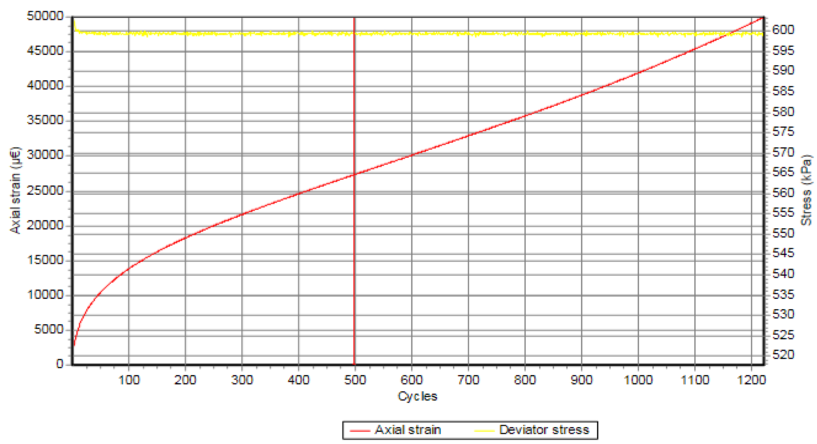
Dimensions	Point 1	Point 2	Point 3	Point 4	Point 5	Point 6	Average	Std Dev.
Diameter (mm)	100.8	100.8	100.8	100.8	100.8	100.8	100.8	
Height (mm)	150.9	151.0	150.7	150.6			150.8	0.2

Cross-sectional area (mm²): 7980.1

Target settings
Test temperature (°C): 54.7
Confining stress (kPa): 0.0
Contact stress (kPa): 30
Deviator stress (kPa): 600

Termination settings
Maximum microstrain: 50000
Test duration (cycles): 10000

Data processing
Sample interval: 1



Test results
Avg test temperature (°C): 54.7
Avg test confining stress (kPa): 0.0
Avg test deviator stress (kPa): 599.4
Axial microstrain at Flow point: 27395
Flow point (cycles): 498

Avg contact stress (kPa): 30.0
Max load Std Error (%): 6.8
Fitted %strain standard deviation: NA
Fitted microstrain at Flow point: NA
Fitted flow point (cycles): NA

Warnings