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16. ABSTRACT

Including some reclaimed asphalt in new asphalt concrete mixes used on pavements has attracted considerable interest from departments of transportation and other agencies mainly because of the cost savings and environmental benefits associated with substituting reclaimed binder for some virgin binder. However, the laboratory testing in this study, which was all undertaken on unaged asphalt specimens, has clearly shown that although adding reclaimed asphalt to new mixes is likely to increase mix stiffness, which in most instances is likely to improve its rutting resistance, the cracking resistance properties could be diminished. Preliminary findings from this study indicate that:

- The asphalt binder in reclaimed asphalt shingles (RAS) may not effectively mobilize and blend with virgin asphalt. If used as a binder replacement, this recycled asphalt could reduce the actual effective binder content in the mix, which could in turn lead to early cracking and raveling.
- The results of tests on the properties of blended virgin and reclaimed asphalt binders can be influenced by the chemistry of the solvent used to extract and recover the binders. Fine aggregate matrix (FAM) mix testing was found to be a potentially appropriate alternative procedure for evaluating the properties of blended asphalt binder in mixes containing relatively high quantities of reclaimed asphalt.
- Although considerable laboratory testing has been undertaken to evaluate the performance of mixes in which reclaimed/recycled asphalt binders are a partial replacement of virgin binders, only limited longer-term, full-scale field testing has been undertaken. Consequently, any potential effects of accelerated aging of these mixes caused by the presence of the aged reclaimed binder and its effects on long-term performance are not fully understood.
- Reclaimed/recycled binder cannot be considered as a generic material with consistent properties, and some form of mix performance testing (FAM or full-grading) needs to be undertaken to assess the influence of the reclaimed/ recycled binder replacement on longer-term performance.
- The known benefits of adding polymer to asphalt binders may be compromised if some of the virgin binder is replaced with binder from RAP or RAS.
- The use of a softer virgin binder to compensate for the stiffening effect of high RAP/RAS binder replacement rates (i.e., above 25 percent) appears to be justified.

It is recommended that the benefits and risks of using reclaimed asphalt binders in pavement mixes be further quantified in additional laboratory testing on appropriately aged specimens, and in controlled full-scale field studies with associated laboratory testing. Accelerated loading tests are recommended as part of this research.

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Investigation of the Effect of Reclaimed Asphalt Pavement and Reclaimed Asphalt Shingles on the Performance Properties of Asphalt Binders: Phase 1 Laboratory Testing

Authors:
M.Z. Alavi, D. Jones, Y. He, P. Chavez and Y. Liang

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D. Jones **FIRST AUTHOR**	J.T. Harvey **TECHNICAL REVIEW**	D. Spinner **EDITOR**	J.T. Harvey **PRINCIPAL INVESTIGATOR**	A. Vasquez **CALTRANS TECH. LEADS**	T.J. Holland **CALTRANS CONTRACT MANAGER**

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PROJECT OBJECTIVES

This study is a continuation of PPRC Project 4.46 (Effect of RAP on PG Grading). The objective of this project is to develop guidelines for minimizing the risk of using high RAP and/or RAS contents in asphalt concrete mixes. This will be achieved in two phases. Phase 1, and the focus of this report, includes the following tasks.

1. A literature review on research related to the topic, with special emphasis on the work of Federal Highway Administration (FHWA) and recent National Cooperative Highway Research Program (NCHRP) projects.
2. Development of a testing matrix followed by a preliminary evaluation of the rheological and engineering properties of a range of asphalt binders, asphalt mastics, and asphalt mixes (carried out in conjunction with ongoing projects undertaken by the University of California Pavement Research Center [UCPRC] for the Federal Aviation Administration [FAA]).
3. Development of an experimental plan for additional laboratory testing if required, and full-scale field testing, accelerated wheel load testing (if deemed appropriate), and associated laboratory testing.
4. Preparation of a summary report detailing the study.

This report covers all tasks.

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Dr. Richard Willis from the National Center for Asphalt Technology in Auburn, Alabama, and Dr. Nima Roohi from C.A.C Industries/Green Asphalt in Long Island City, New York, are acknowledged for processing and supplying reclaimed asphalt pavement materials from out-of-state for the study. The Federal Aviation Administration (FAA) and the National Center for Sustainable Transportation (NCST) are acknowledged for funding additional research into the use of reclaimed asphalt pavement in new asphalt mixes and for allowing use of the results in this study. The staff from the University of California Pavement Research Center (UCPRC) laboratory is acknowledged for assisting with the laboratory testing component of this study.

EXECUTIVE SUMMARY

Road agencies are increasingly allowing the use of reclaimed asphalt pavement (RAP) and reclaimed asphalt shingles (RAS) in new mixes placed on highways. This report describes a study that investigated the potential implications of using relatively high reclaimed asphalt contents (up to 40 percent virgin binder replacement) in new asphalt concrete. The study included a literature review, preliminary testing to develop alternative methods for assessing the properties of virgin binders blended with RAP, the development of mix designs for mixes containing varying reclaimed asphalt contents, and the testing of the properties of the blended binders, fine aggregate matrix mixes, and full-graded mixes.

Key points from the literature review include the following:

- The asphalt binder in RAP and RAS can blend appreciably with virgin binder in new mixes. The level of blending between the aged and new binders depends on numerous factors including the chemical composition of the individual binders. To ensure the optimal performance of asphalt mixes containing high proportions of reclaimed asphalt, the compatibility of reclaimed and virgin asphalt binders from different sources and with different performance grades (PG) needs to be well understood.
- Appropriate methods for extracting aged binder from reclaimed asphalt materials are still being developed; these development efforts are focused on reducing the effects of extraction solvents on the properties of recovered binders. The solvents in current use are considered to be aggressive enough to fully blend the binders extracted from new mixes containing aged and virgin binders, and thereby provide potentially misleading binder replacement values and nonrepresentative performance gradings of the blended binders. Alternative methods to the use of extraction and recovery are also being explored to better characterize the performance properties of blended virgin and RAP and/or RAS binders. Tests on mortar and FAM mixes warrant further investigation in this regard.
- Adding RAP to a new asphalt mix can alter the volumetrics and performance of the mix. However, volumetric requirements can still be met with relatively high RAP contents (i.e., up to 25 percent). Compared to equivalent mixes without RAP, rutting performance was generally improved by the addition of RAP, but cracking performance was generally worse. Conflicting results with regard to laboratory test performance were reported.
- Given that the use of RAP as binder replacement and not just as aggregate replacement is a relatively new practice, there is limited knowledge on the long-term field performance of mixes containing high RAP contents (i.e., above 25 percent binder replacement), specifically with regard to the rate of binder aging and its effect on stiffness and susceptibility to cracking. Conventional laboratory aging procedures have not been verified for high RAP mixes.

Preliminary laboratory testing to investigate the properties of binders recovered from RAP and RAS samples and simulated RAP binders prepared in the laboratory revealed the following:

- Asphalt binder extracted and recovered from RAS could not be tested due to its very high stiffness. The RAS binder was not sufficiently workable to mold samples for testing in a dynamic shear rheometer (DSR) or bending beam rheometer (BBR).
- The guidelines recommended in NCHRP 9-12 for determining the performance grade of binders recovered from RAP samples were considered to be appropriate for this UCPRC study. Recovered binders from three different RAP sources were tested according to these guidelines.
- Initial attempts to synthesize a simulated RAP binder with performance properties comparable to recovered binders provided mixed results. Various pressure aging vessel (PAV) test scenarios were considered, but only the high critical temperature of the simulated binder was similar to the recovered binders. The low critical temperatures were significantly different. It is not clear whether this was attributable to the aging procedure or to the effect of the extraction chemicals.

Preliminary laboratory testing to investigate the properties of asphalt mortars prepared in the laboratory revealed the following:

- Mortar samples with binder replacement rates of up to 25 percent were sufficiently workable to fabricate specimens that could be tested in a DSR. Samples with binder replacement rates greater than 25 percent were generally unworkable and specimens could not be fabricated satisfactorily.
- Although the mortar test deserves further investigation, it may not be appropriate for testing samples with high binder replacement rates (i.e., >25 percent). Given that this UCPRC study focused on investigating the influence of binder replacement rates of up to 40 percent on the performance properties of the blended binders, the use of mortar testing was not considered for the remainder of the study.

Supplementary laboratory testing to investigate the blending between virgin and RAP binders revealed the following:

- The wafer composite-binder testing method using a DSR was shown to be an effective approach for examining the level of blending between new and age-hardened binders. The sample preparation and test procedure is straightforward and applicable for both practitioners and researchers.
- The diffusion mechanism in the blending process was shown to be temperature and time dependent:
  + The 153 minutes for the hot mix asphalt (HMA) time-temperature path resulted in nearly complete blending of the new and simulated RAP binders.
  + The 153 minutes for the warm mix asphalt (WMA) time-temperature path resulted in only partial blending.
  + The diffusion coefficient increased with temperature.
- The representative constant diffusivity for wafer composite specimens under a hot mix asphalt production temperature path can be successfully estimated using a finite control volume approach to numerically solve Fick's law of diffusion.
- The predicted complex modulus values of the wafer specimens following a warm mix asphalt production path for longer than 63 minutes conditioning time were found to be higher than the actual measured values and were close to the values corresponding to the fully blended binder specimen.

Key observations and findings from preliminary testing on fine aggregate matrix (FAM) mixes include the following:

- Asphalt binder extracted and recovered from RAS could not be tested due to its very high stiffness. The RAS binder was not sufficiently workable to mold specimens for testing in a DSR or in a BBR.
- Preliminary testing of FAM mixes (prepared with materials passing the 2.36 mm [#8] sieve) indicated that this approach appears to be repeatable (consistent results on multiple specimens by the same operator) and reproducible (consistent results by different operators), and produces representative results for characterizing the performance-related properties of composite binder at binder replacement rates up to 40 percent and possibly higher.
- The effect of RAP in increasing the stiffness of blended binders was dependent primarily on the asphalt binder grade and, to a lesser extent, on the source of the asphalt binder.
- The FAM mixes containing RAS showed similar stiffnesses to the corresponding control mixes (i.e., containing no reclaimed materials), suggesting that the RAS binder did not effectively blend with the virgin binder at the temperatures and mixing durations used in this study. Based on these results, RAS was not included in further phases of this UCPRC study.
- The influence of rejuvenating agent on reducing the blended binder and FAM mix stiffnesses was evident. Additional testing (beyond the scope of this study) is required to evaluate the long-term behavior of mixes produced with rejuvenating agents to determine whether the benefits are limited to production and early life, or whether they extend through the design life of the layer.
- Reasonable correlations were observed between the stiffness of asphalt binder and the stiffness of FAM mixes. Discrepancies between the two measured stiffnesses may indicate that complete blending of the virgin and reclaimed asphalt binders was not achieved in the FAM mix, but was forced during the chemical extraction and recovery. The specific chemical solvent used in the extraction process also may have influenced the RAP binder properties. These factors warrant further investigation.

Key observations from the mix design phase of the study include the following:

- Grading and volumetric property specification requirements were difficult to meet when RAP binder replacement rates exceeded 25 percent.
- RAP source had a notable influence on the volumetric properties, which implies that RAP cannot be considered as a generic material with consistent properties, even when only using the fine fractions (i.e., material passing the 4.75 mm [#4] sieve).

Key observations from the binder and FAM mix testing phase of the study include the following:

- The degree of change in PG grade after the addition of RAP binder varied depending on the virgin binder grade and the RAP source. This was attributed to various factors including but not limited to the degree of aging of the RAP binder, the original PG grade of the RAP binder, and the extent of the "dilution" of the polymer in virgin polymer-modified binders.
- Using RAP binder to replace a portion of the virgin binder always increased the stiffness of the binder, but the degree of increase was dependent on the RAP source.
- Results from FAM mix testing were consistent with the results from binder testing. Differences were attributed to the differences in the degree of blending during preparation of the binders (stirred

with a glass rod in a glass beaker) and preparation of the FAM mixes (standard laboratory mixing process), and to possible effects of the chemical solvent on the properties of the extracted and recovered binder.

- The FAM mix test results further supported the use of this testing approach as an appropriate procedure for evaluating the properties of blended asphalt binder in mixes containing relatively high quantities of RAP.

Key observations from testing on full-graded mixes include the following:

- The test methods used in this phase of the study were sufficiently sensitive to distinguish the behavior of the different mixes and to consistently distinguish the differences in performance between the mixes containing no RAP (i.e., control mixes) and mixes containing RAP. However, all testing was undertaken on newly prepared laboratory specimens, and consequently do not necessarily reflect long-term performance of the mixes or the longer-term effects of the RAP binder on the rate of aging of the virgin binder.
- Adding RAP increased the stiffness of the mixes, which in most instances improved the mixes' rutting resistance properties, but it had differing impacts on their cracking resistance properties. The addition of RAP clearly influenced the results for beam fatigue tests. However, when considered in a mechanistic analysis, the results indicated potentially better performance than the control mixes, although it is not clear if these results are indicative of long-term performance since the flexural modulus and beam fatigue tests were undertaken on newly prepared and compacted specimens.
- The degree of change in rutting and cracking resistance was dependent on the RAP source, with test results for each source ranking consistently across the different tests (i.e., the RAP from the New York source consistently had the least effect on mix performance, while the RAP from the California and Alabama sources both consistently had the largest effects). Given that the mixes had the same gradation and binder content and similar volumetric properties, the results support an earlier observation that RAP cannot be considered as a generic material with consistent properties.
- Adding RAP to mixes with polymer-modified binders appears to have limited effect in terms of improving rutting performance but a significant effect in terms of reducing fatigue life. This implies that the known benefits of adding polymer to asphalt binders may be compromised by replacing some of the virgin binder with binder from RAP.
- The use of a softer binder to compensate for the stiffening effect of high RAP binder replacement rates (i.e., above 25 percent) appears to be justified.

Conclusions

The following conclusions are made based on the test results summarized above:

- There is considerable interest in the use of reclaimed asphalt in new asphalt concrete mixes, primarily due to the cost savings and environmental benefits associated with substituting some of the virgin binder with the binder from the reclaimed asphalt. However, the laboratory testing in this study, which was all undertaken on unaged specimens, has clearly shown that although adding reclaimed asphalt (from RAP) to new mixes is likely to increase the stiffness of the mix, which in most instances will potentially improve the rutting resistance properties of the mix, the cracking resistance properties could be worse. Therefore, before use of reclaimed asphalt in new mixes is

implemented, further testing on appropriately aged specimens is proposed to better understand the implications of using this process.
- Preliminary findings from this study indicate that the asphalt binder in reclaimed asphalt shingles may not effectively mobilize and blend with virgin asphalt. Using this reclaimed asphalt as a binder replacement could reduce the actual effective binder content in the mix, which could in turn lead to early cracking and raveling.
- Test results collected on the properties of blended virgin and reclaimed asphalt binders can be influenced by the chemistry of the solvents used to extract and recover the binders. Fine aggregate matrix (FAM) mix testing is considered to be a potentially appropriate alternative procedure for evaluating the properties of blended asphalt binder in mixes containing relatively high quantities of reclaimed asphalt.
- Although considerable laboratory testing has been undertaken to evaluate the performance of mixes in which reclaimed asphalt binders are a partial replacement for virgin binders, only limited longer-term full-scale field testing, with associated laboratory testing, has been undertaken. Consequently, any potential effects of accelerated aging of these mixes caused by the presence of the aged RAP binder are not fully understood.
- RAP, and the binder in it, cannot be considered as a generic material with consistent properties, and some form of mix performance testing (FAM or full-grading) will need to be undertaken as part of the project mix design process to assess the influence of the RAP binder replacement on longer-term performance.
- The known benefits of adding polymer to asphalt binders may be compromised by replacing some of the virgin binder with binder from RAP.
- The use of a softer virgin binder to compensate for the stiffening effect of high RAP binder replacement rates (i.e., above 25 percent) appears to be justified. For example, in an area where PG 64-22 binders are typically used, a PG 58-28 mix with 40 percent RAP would probably have generally similar performance to a PG 64-22 mix with 25 percent RAP. Performance properties will always need to be confirmed, however.

Recommendations

The following recommendations are made based on the findings from this study:

- Given the interest in using reclaimed asphalt for partial binder replacement in new mixes, the benefits and risks of the process should be further quantified in additional laboratory testing on appropriately aged specimens, and in controlled full-scale field studies with associated laboratory testing. Accelerated loading tests are proposed as part of this research.
- Any future research phases should also include assessments of the following:
  + The effects of reclaimed asphalt on the aging properties of the mix over time, and the effects of this on cracking performance over time.
  + The effects of reclaimed asphalt on the low-temperature properties of the mix.
  + The influence of different rejuvenating agents on mix properties and on short-, medium-, and long-term performance.
  + The influence of warm mix additives and the implications of producing mixes containing RAP at warm mix temperatures.

- Given the interest in using RAS in conjunction with RAP, further studies on the effective blending of virgin and RAS binders during mix production, transport, and placement, and the effect of RAS binders on long-term mix performance is warranted. Studying only binders chemically extracted from mixes is not recommended given that forced blending between virgin and reclaimed binders during the extraction process is likely.

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LIST OF ABBREVIATIONS

AASHTO	American Association of State Highway and Transportation Officials
AMPT	Asphalt mixture performance tester
ANOVA	Analysis of variance
APA	Asphalt Pavement Analyzer
ASTM	American Society for Testing and Materials
ATR	Attenuated total reflectance
BBR	Bending beam rheometer
Caltrans	California Department of Transportation
DCT	Disc-shaped compact tension test
DMA	Dynamic mechanical analyzer
DP	Dust proportion
DSR	Dynamic shear rheometer
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
FAM	Fine aggregate matrix
FHWA	Federal Highway Administration
FTIR	Fourier transform infrared spectroscopy
GmB	Bulk specific gravity
Gmm	Theoretical maximum specific gravity
HMA	Hot mix asphalt
ITS	Indirect tensile strength
LVE	Linear viscoelastic
NAPMRC	National Airport Pavement and Materials Research Center
NCHRP	National Cooperative Highway Research Program
NCST	National Center for Sustainable Transport
PAV	Pressure aging vessel
PDE	Partial differential equation
PG	Performance Grading
PM	Polymer-modified
RA	Rejuvenating agent
RAP	Reclaimed asphalt pavement
RAS	Reclaimed asphalt shingles
RTFO	Rolling thin-film oven
SARA	Saturates, aromatics, resins, and asphaltenes
SHRP	Strategic Highway Research Program
SSD	Saturated surface-dry
Superpave	Superior Performing Asphalt Pavement
TCE	Trichloroethylene
TSR	Tensile strength retained
UCPRC	University of California Pavement Research Center
VFA	Voids filled with asphalt
VMA	Voids in mineral aggregate
WMA	Warm mix asphalt

TEST METHODS CITED IN THE TEXT

AASHTO M 320	Standard Specification for Performance-Graded Asphalt Binder
AASHTO M 323	Standard Specification for Superpave Volumetric Mix Design
AASHTO R 30	Standard Practice for Mixture Conditioning of Hot-Mix Asphalt (HMA)
AASHTO R 35	Standard Practice for Superpave Volumetric Design for Asphalt Mixtures
AASHTO TP 79	Standard Method of Test for Determining the Dynamic Modulus and Flow Number for Asphalt Mixtures Using the Asphalt Mixture Performance Tester (AMPT)
AASHTO T 30	Standard Method of Test for Mechanical Analysis of Extracted Aggregate
AASHTO T 84	Standard Method of Test for Specific Gravity and Absorption of Fine Aggregate
AASHTO T 85	Standard Method of Test for Specific Gravity and Absorption of Coarse Aggregate
AASHTO T 164	Standard Method of Test for Quantitative Extraction of Asphalt Binder from Hot-Mix Asphalt
AASHTO T 166	Standard Method of Test for Bulk Specific Gravity (Gmb) of Compacted Hot Mix Asphalt (HMA) Using Saturated Surface-Dry Specimens
AASHTO T 209	Standard Method of Test for Theoretical Maximum Specific Gravity (Gmm) and Density of Hot-Mix Asphalt
AASHTO T 240	Standard Method of Test for Effect of Heat and Air on a Moving Film of Asphalt Binder (Rolling Thin-Film Oven Test)
AASHTO T 248	Standard Method of Test for Reducing Samples of Aggregate to Testing Size
AASHTO T 269	Standard Method of Test for Percent Air-voids in Compacted Dense and Open Asphalt Mixtures
AASHTO T 283	Standard Method of Test for Resistance of Compacted Asphalt Mixtures to Moisture-Induced Damage
AASHTO T 308	Standard Method of Test for Determining the Asphalt Binder Content of Hot Mix Asphalt (HMA) by the Ignition Method
AASHTO T 312	Standard Method of Test for Preparing and Determining the Density of Asphalt Mix Specimens by Means of the Superpave Gyratory Compactor
AASHTO T 313	Standard Method of Test for Determining the Flexural Creep Stiffness of Asphalt Binder Using the Bending Beam Rheometer
AASHTO T 315	Standard Method of Test for Determining the Rheological Properties of Asphalt Binder Using a Dynamic Shear Rheometer

AASHTO T 321	Standard Method of Test for Determining the Fatigue Life of Compacted Asphalt Mixtures Subjected to Repeated Flexural Bending
AASHTO T 324	Standard Method of Test for Hamburg Wheel-Track Testing of Compacted Hot Mix Asphalt
AASHTO T 340	Standard Method of Test for Determining the Rutting Susceptibility of Hot Mix Asphalt Using the Asphalt Pavement Analyzer (APA)
ASTM D 1856	Standard Test Method for Recovery of Asphalt from Solution by Abson Method

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CONVERSION FACTORS

SI* (MODERN METRIC) CONVERSION FACTORS				
APPROXIMATE CONVERSIONS TO SI UNITS				
Symbol	**When You Know**	**Multiply By**	**To Find**	**Symbol**
		LENGTH		
in	in.	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 in.	645.2	Square millimeters	mm^2
ft^2	square feet	0.093	Square meters	m^2
yd^2	square yard	0.836	Square meters	m^2
ac	acres	0.405	Hectares	ha
mi^2	square miles	2.59	Square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	Milliliters	mL
gal	gallons	3.785	Liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	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 (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	Lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	Newtons	N
lbf/in^2	poundforce per square inch	6.89	Kilopascals	kPa
APPROXIMATE CONVERSIONS FROM SI UNITS				
Symbol	**When You Know**	**Multiply By**	**To Find**	**Symbol**
		LENGTH		
mm	millimeters	0.039	In.	in
m	meters	3.28	Feet	ft
m	meters	1.09	Yards	yd
km	kilometers	0.621	Miles	mi
		AREA		
mm^2	square millimeters	0.0016	square in.	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	Hectares	2.47	Acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	Milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	Gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	Ounces	oz
kg	kilograms	2.202	Pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	Newtons	0.225	Poundforce	lbf
kPa	Kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380 (Revised March 2003)

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1. INTRODUCTION

1.1 Background

Approximately 84 percent of the highway pavements and 85 percent of the airfield pavements in the United States tracked by the Federal Highway Administration (FHWA) and the Federal Aviation Administration (FAA), respectively, are paved with asphalt concrete *(1)*. To perform effectively under heavy repetitive wheel loads and severe environmental conditions, these pavements require regular maintenance and periodic rehabilitation, processes that require continuous supplies of aggregate and asphalt binder, both of which are becoming increasingly scarce and more expensive. As a consequence, there is growing interest in the use of reclaimed asphalt pavement (RAP) and reclaimed asphalt shingle (RAS) materials in the production of new asphalt mixes to reduce costs and preserve nonrenewable resources.

Considerable research has been conducted on the use of RAP in highway pavements, and a number of state departments of transportation now allow between 15 percent and 25 percent (either by weight of total mix or by binder replacement) RAP in new mixes. The use of RAP and/or RAS in new asphalt mixes offers several potential environmental benefits as well as production and construction cost savings. It reduces the amount of emissions during production, preserves nonrenewable natural resources, and reduces the amount of material dumped in landfills. Further, replacing a portion of the virgin aggregate and binder by incorporating RAP and/or RAS into new asphalt mixes reduces the costs associated with acquiring raw materials. Studies and short-term field observations on highway pavements where RAP has been added to the mix indicate that to date these pavements have performance equal to or better than conventional mixes with no reclaimed materials. However, considerable uncertainty still exists with respect to these pavements' longer-term performance, especially with regard to the possible effects of the aged RAP binder on cracking.

1.2 Problem Statements

The following concerns need to be addressed to better understand the longer-term effects of using RAP and/or RAS in new asphalt mixes that are placed on highways pavements in California:

- The degree of blending between reclaimed and virgin binders and the factors that influence it are not fully understood. Consequently, accurate determination of the effective asphalt binder replacement from the reclaimed material is difficult.
- The short- and long-term effects of RAP and RAS binders on the performance grade of the composite binder (i.e., virgin binder blended with binder from RAP or RAS) are unknown and need to be addressed.

- The performance of asphalt mixtures containing RAP and/or RAS is dependent on the properties of their constitutive components, which change during service after short- and long-term aging and as the new and aged binders diffuse over time. A simplified procedure using current Superpave equipment is needed to simulate field conditions in the laboratory and to characterize the rheological properties of the blended binder with respect to rutting and cracking performance at high, intermediate, and low temperatures, and without the need to chemically extract the binder from the mix.
- Potential problems that arise due to the incompatibilities of different virgin binders and different RAP or RAS binders have not been investigated, either in terms of the properties of the blended binder, or in terms of short- and long-term performance of the mix.
- The relationship between the long-term field performance of high RAP or RAS content mixes under heavy highway traffic and how they perform in laboratory mix design and performance testing is not fully understood.
- The effects of the use of different warm mix asphalt technologies and the effects of producing RAP and/or RAS mixes at a range of temperatures below conventional temperatures, specifically with respect to blending of the aged and virgin binder, is unknown.
- The effects of the use of rejuvenating agents on the properties and degree of blending of aged and virgin binder have not been quantified.

1.3 Study Objectives/Goals

This study, PPRC Project 4.51a, is a continuation of PPRC Project 4.46 (Effect of RAP on PG Grading). The objective of this project is to develop guidelines for minimizing the risk of using high RAP and/or RAS contents in asphalt concrete mixes. This will be achieved in two phases. Phase 1, and the focus of this report, included the following tasks.

1. A literature review on research related to the topic, with special emphasis on the work of FHWA and recent National Cooperative Highway Research Program (NCHRP) projects.
2. Development of a testing matrix followed by a preliminary evaluation of the rheological and engineering properties of a range of asphalt binders, asphalt mastics, and asphalt mixes (carried out in conjunction with ongoing projects undertaken by the University of California Pavement Research Center [UCPRC] for the FAA).
3. Development of an experimental plan for Phase 2 detailing additional laboratory testing if required, and full-scale field testing, and Phase 3 detailing accelerated load testing (if deemed appropriate) with associated laboratory testing.
4. Preparation of a summary report detailing the study.

The expected results from this study will provide the following, at minimum:

- Recommendations for workplans that will accommodate an appropriate range of field and associated laboratory tests, the results from which will provide a satisfactory level of information and confidence to make informed decisions about the use of RAP and/or RAS in asphalt mixes used on highway pavements.

- Development and validation of a simple procedure to assess the contribution of RAP and/or RAS on the final composite binder properties, using standard Superpave laboratory testing equipment only and without the need for binder extraction.
- Evaluation of the sensitivity of individual RAP and RAS sources to a specific binder grade and multiple RAP and RAS sources to a specific binder grade.
- Evaluation of the high-, intermediate- and low-temperature properties of binders containing RAP and/or RAS blends.
- Evaluation of performance-related properties of mixes containing RAP and/or RAS in terms of resistance to permanent deformation (or rutting), fatigue cracking, and moisture damage.

This report documents the work completed on all tasks in Phase 1. It should be noted that this project was carried out as part of a larger comprehensive research study on using higher quantities of RAP and RAS in new asphalt mixes in road pavements (funded by the FAA and the National Center for Sustainable Transportation [NCST]).

1.4 Report Layout

This research report presents an overview of the work carried out in meeting the objectives of the study, and is organized as follows:

- Chapter 2 provides an overview of the literature related to the topic.
- Chapter 3 summarizes the experimental plan and the materials and testing methodologies followed.
- Chapter 4 discusses preliminary testing of virgin asphalt binders blended with binders chemically extracted from RAP and RAS (Phase 1a).
- Chapter 5 summarizes additional binder testing undertaken to better understand the mechanisms influencing the blending of aged and virgin binders, with a focus on the effects of diffusion and temperature (Phase 1b).
- Chapter 6 describes the development of a procedure for characterizing the rheological properties of blended binders using a mortar of asphalt binder and fines without the need to chemically extract the binders from the mix (Phase 1c).
- Chapter 7 describes the development of a procedure for characterizing the rheological properties of blended binders using a fine aggregate matrix (FAM) mixed with asphalt binder, also without needing to chemically extract the binders from the mix (Phase 1d).
- Chapter 8 summarizes the Superpave volumetric mix design procedure followed to prepare mixes for laboratory performance testing (Phase 1e).
- Chapter 9 presents results and analysis of binder rheology and FAM mix tests (Phase 1f).
- Chapter 10 presents results and analysis of full-graded mix performance tests (Phase 1g).
- Chapter 11 provides a project summary, conclusions, and preliminary recommendations.
- Chapter 12 summarizes the proposed Phase 2 experimental plan.

1.5 Measurement Units

Although Caltrans recently returned to the use of U.S. standard measurement units, the Superpave Performance Grading (PG) System is a metric standard and uses metric units. In this research report, both English and metric units (provided in parentheses after the English units) are provided in the general discussion. Metric units are used in the reporting of PG test results. A conversion table is provided on page xxi at the beginning of this report.

2. LITERATURE REVIEW

The literature relevant to the use of reclaimed asphalt pavement (RAP) and/or reclaimed asphalt shingles (RAS) in highway pavements is discussed under the following headings:

- Reclaimed asphalt materials
- Asphalt binder chemistry
- Asphalt binder extraction
- Characterization of blended virgin and reclaimed binders
- Quantifying the level of diffusion and blending between virgin and reclaimed asphalt binders
- Selection of virgin binder for RAP and RAS mixes
- Properties of asphalt mixes containing RAP and RAS
- Airfield pavement Superpave mix designs incorporating RAP

2.1 Reclaimed Asphalt Materials

Reclaimed asphalt pavement is defined as "removed and/or reprocessed pavement materials containing asphalt binder and aggregates" *(3)*. As noted, it is mostly obtained by milling off aged or distressed pavement surface layers and is usually crushed and processed at an asphalt plant to produce well-graded aggregates, many still coated with asphalt binder. This processed material can then be incorporated into new mixes at varying percentages as a replacement for virgin aggregates and binders. RAP is by far the most recyclable material according to a survey conducted in the early 1990s by the Federal Highway Administration (FHWA) and the U.S. Environmental Protection Agency (EPA), which stated that of the more than 90 million tons of RAP produced every year in the United States, at least 80 percent of it could be recycled into new pavement construction projects *(3)*.

Reclaimed asphalt shingles (RAS) are another potentially valuable source of asphalt binder for use in pavement construction since shingles contain between 20 and 35 percent asphalt binder by weight of the shingle (other constituents include fine aggregates [20 to 38 percent], fillers [8 to 40 percent], and fiberglass and cellulosic fibers [2 to 15 percent]) *(4)*. The majority of RAS produced in the United States (approximately 10 million tons per year) is obtained from used roof shingles (i.e., tear-offs), with about 1 million tons obtained from production rejects. During asphalt shingle production, the binder is heavily oxidized during an air-blowing process. Additional aging occurs over time as the shingles are exposed to the sun and precipitation and subjected to daily and seasonal temperature extremes. Consequently, the binder is highly aged by the time that it is used in new pavement mixes, and although the binder contents in the shingles are high, the properties of the binder are very different from those recovered from RAP, particularly for the more heavily aged tear-off shingles.

RAP materials have been used in small quantities in new highway mixes for many years. However, in the past this material has been considered only as a replacement for virgin aggregate (i.e., "black rock") and not as a part replacement for virgin asphalt binder. Consequently the potential binder replacement and properties of the aged RAP binder were not taken into account in new mix designs. This generally did not result in any problems as long as the percentage of RAP was kept below approximately 15 percent. Recent studies and field observations *(3,5-7)* have demonstrated that the aged binder in reclaimed materials can blend appreciably with virgin binder, allowing for binder replacement to be considered if RAP and RAS are added to the mix. However, the properties of the virgin binder will be altered by the aged RAP and RAS binders, which could in turn influence the performance of a mix in terms of rutting, cracking, raveling, and/or moisture sensitivity.

2.2 Asphalt Binder Chemistry

Asphalt binder is obtained from the distillation of crude oil and is a blend of complex hydrocarbons containing thousands of different molecules *(8)*. More than 90 percent of asphalt binder consists of carbon and hydrogen with the remainder consisting of heteroatoms (sulfur, hydrogen, and nitrogen) and a few metallic elements (e.g., vanadium, nickel, and iron). The polar molecules of asphalt binder can be categorized into four main fractions, namely saturates, aromatics, resins, and asphaltenes (i.e., SARA fractions). The chemical composition and proportions of the SARA fractions are dependent on the source of the crude oil and on the refining process used to produce the binder *(8,9)*.

Asphaltenes have the highest polarity and molecular weight, followed by resins, aromatics, and saturates *(8)*. These four main compounds can be assembled in a colloidal structure to model the properties and performance of asphalt binder. Asphaltene forms the core, which is covered by resins that are bridged to aromatics and dispersed in saturates, as shown in Figure 2.1 *(9)*.

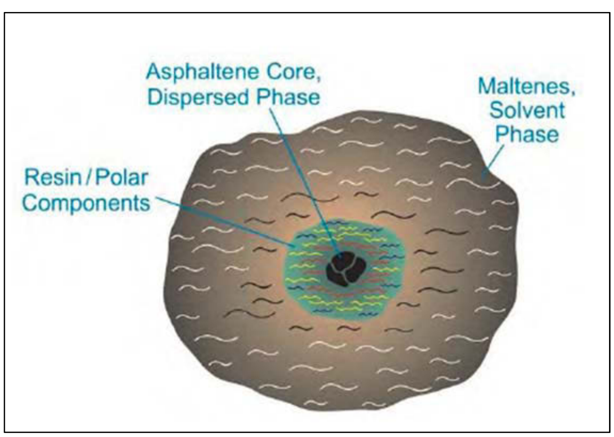

Figure 2.1: Asphalt binder colloidal structure *(9)*.

The stiffness and strength properties of asphalt binders are generally related to the asphaltenes and resins, while its viscous and plasticizing properties are generally related to the aromatics and saturates *(10)*. The rheological and desired performance properties of asphalt binder are therefore dependent on the properties of the individual fractions and their proportions, which change over the life of a pavement due to oxidation, volatilization, and other weathering mechanisms.

2.3 Asphalt Binder Extraction from Mixes Containing Reclaimed Asphalt

A number of studies have been conducted to evaluate different solvents and methods for the extraction and recovery of asphalt binder from mixes *(7,11-14)*. Petersen et al. *(15)* evaluated different solvent types (trichloroethylene [TCE], toluene/ethanol, and a proprietary product known as *EnSolve*) and three combinations of extraction and recovery methods (centrifuge-Abson, centrifuge-Rotavapor, and SHRP [Strategic Highway Research Program] method-Rotavapor), and found there was no significant difference between solvent type or method when determining the asphalt binder content and rheological properties of the recovered binder. Another study using the reflux–Rotovapor recovery method also demonstrated that binder extracted using either TCE or *EnSolve* had relatively similar properties *(13)*. A study by Stroup-Gardiner et al. *(16)* found that using normal propyl bromide rather than TCE as a chemical solvent could reduce the amount of aging of the asphalt binder during extraction and recovery. The study also found that the binder content determined was not influenced by solvent type. However, incompatibilities between various types of propyl bromide and polymer-modified binders were recognized.

2.4 Characterization of Blended Virgin and Reclaimed Asphalt Binders

The following methods for characterizing the properties of blended binders in mixes containing RAP and/or RAS have been investigated in the literature and are discussed below under the following headings:

- Backcalculation of blended binder properties
- Testing extracted and recovered binder
- Testing simulated RAP binder
- Testing asphalt mortar
- Testing fine aggregate matrix mixes

2.4.1 Backcalculation of Blended Binder Properties

Asphalt binder shear modulus can be predicted from the measured asphalt mix dynamic modulus using the Hirsch model *(17,18*). The Hirsch model represents the stiffness of an asphalt mix as a function of the asphalt binder shear modulus and the mix volumetric properties, including voids in mineral aggregate (VMA) and voids filled with asphalt (VFA). This approach has been used to evaluate the level of blending between aged and reclaimed binders and to predict the performance grade of blended binders. Hajj et al. *(11)* predicted asphalt binder modulus from mix modulus using the modified Huet-Sayegh model. Zofka et al. *(19)* used creep stiffness measurements at low temperatures, obtained from the inverse of creep compliance, with the Hirsch model to predict asphalt binder properties at low temperatures.

The Hirsch model can be used to predict the shear modulus, but it cannot be used to predict the phase angle. Both parameters are needed to understand the full viscoelastic behavior of asphalt binder. Phase angle is also a key parameter for determining the performance grade of asphalt binders. Typically it is difficult, if not impossible; to do routine tests on asphalt mixes at the high and low performance grade temperature limits of the asphalt binder. Therefore, the measured modulus of the asphalt mix has to be shifted, using time-temperature superposition, to predict the asphalt binder moduli at the desired performance grade temperatures. Recent work by Bennert and Dongre *(18)* used analytical approaches developed by Bonaquist *(17)* and Rowe *(20)* to estimate the shear modulus and phase angle of asphalt binders from the properties of asphalt mixes. Mixes with zero, 10, and 25 percent RAP were assessed and the results indicated that the measured shear modulus and phase angle of the recovered binders were comparable to the predicted values.

2.4.2 Testing Extracted and Recovered Binders

To date, the majority of studies on the characterization and design of asphalt mixes containing RAP and/or RAS involve extraction and recovery of asphalt binder from the mix using chemical solvents *(3,5,7,21-30)*. The extraction and recovery method has long been criticized for being labor intensive, for its potential to alter binder chemistry and rheology, and for creating hazardous chemical disposal issues. Studies have also demonstrated that some of the aged binder may still remain on the aggregate after extraction, and thus the measured properties from the extracted and recovered binder may not completely represent the actual properties of the binder in the mix *(5,15)*. After extraction, asphalt binder can also stiffen due to potential reactions between the binder compounds and the solvent *(31)*. Typically, the extraction process also blends aged and virgin binders into a homogenous composite binder that may not be truly representative of the actual composite binder in the mix after production.

Three alternative methods to solvent extraction and recovery have been investigated for characterizing the properties of blended binders, namely producing and testing simulated RAP binders, testing the asphalt mortar of mixes containing both RAP and virgin binders, and testing only the fine aggregate matrix (FAM) of those mixes.

2.4.3 Testing Simulated RAP Binders

RAP and RAS stockpiles are typically highly variable because they contain materials reclaimed from numerous different projects in different locations. The asphalt binders in these materials may have different binder grades, may have been originally refined from various crude oil sources, and may contain different modifiers including recycled tire rubber or polymers. Chemical extraction of these binders for use in research-based laboratory testing, with limited or no knowledge of their original grade, source, added modifiers, and properties, could lead to unexplained variability in the results.

Simulated RAP binders can be produced under controlled mixing and aging conditions and then blended with virgin binders as a means of providing some level of consistency to better understand key aspects of the testing and performance of composite binders *(32,33)*. Aging is carried out in single or multiple cycles in a pressure aging vessel (PAV). Changes in the properties of the binder during the course of the aging process are assessed by standard rheology tests with a dynamic shear rheometer (DSR) and bending beam rheometer (BBR).

2.4.4 Testing Asphalt Mortar

Asphalt mortar tests are conducted using two mortar samples: one containing virgin binder plus fine RAP (passing the #50 [300 µm] and retained on the #100 [150 µm] sieves), and one containing virgin binder plus the fine aggregates obtained from processing RAP in an ignition oven (i.e., the RAP binder is burned off in the ignition oven). Conceptually, if the total binder contents and aggregate gradations are exactly the same for both samples, the differences between the rheological and performance properties of the two samples can be attributed to the RAP binder *(34-36)*. A number of studies have been conducted using this approach with DSR and BBR testing to assess the stiffness of the samples at high and low temperatures, respectively *(34-36)*. Ma et al. (*34*) developed a BBR testing procedure for asphalt mortar specimens made with single size RAP material (100 percent passing the #50 sieve [300 µm] and retained on the #100 sieve [150 µm]). Based on the relationship between the asphalt binder and asphalt mortar properties, the low PG grade of the RAP binder could be estimated without the need for extraction and recovery of the binder. The asphalt mortar samples evaluated in that study had a maximum of 25 percent binder replacement from the RAP. Swierz et al. *(35)* continued this work and found that the BBR test on asphalt mortar was sufficiently sensitive to distinguish between different RAP sources and contents in blended binders up to 25 percent binder replacement. Asphalt mortar samples containing only RAS (up to 40 percent binder replacement) and a combination of RAP and RAS were also evaluated in the study. The work culminated in the development of a blending chart that estimates the PG grade of the blended binder in a mix based on the respective RAP and RAS percentages.

Hajj et al. *(11)* compared the performance grade properties of blended binder by using DSR and BBR testing of both recovered binder and asphalt mortar. The results were found to be dependent on the amount of RAP in the mix, and although the results of mixes with up to 50 percent RAP showed similar trends, the measured high, intermediate, and low performance-grade (PG) temperatures of the mortar were lower than those measured on the extracted binder. The differences in results increased with increasing RAP content. The reasons for the differences were not forensically investigated, but were attributed in part to the influence of the extraction chemistry on full blending of the binders and possibly to the effect of the chemistry on additional hardening of the binders.

2.4.5 Testing Fine Aggregate Matrix Mixes

Testing fine aggregate matrix (FAM) mixes as an alternative to testing asphalt mortar has also been investigated *(12-14)*. FAM mixes are a homogenous blend of asphalt binder and fine aggregates (i.e., passing a #4, #8, or #16 [4.75 mm, 2.36 mm, or 1.18 mm] sieve). The asphalt binder content and the gradation of the FAM must be representative of the binder content and gradation of the fine portion of a full-graded asphalt mix. Small FAM mix cylindrical or prismatic bars can be tested with a solid torsion bar fixture in a DSR (known as a dynamic mechanical analyzer [DMA]). This testing approach is similar to that used for asphalt mortars in that two samples are tested, one containing virgin binder plus RAP and/or RAS, and the second containing virgin binder plus the aggregates obtained from processing RAP or RAS in an ignition oven. Any differences in the results can then be attributed to the RAP/RAS component of the FAM mix. Kanaan *(36)* evaluated the viscoelastic, strength, and fatigue cracking properties of FAM mix specimens with different quantities of RAS. The results showed that FAM mix testing detected differences in the properties evaluated among the various mixes, and specifically that the stiffness and strength of the asphalt mixes increased with increasing RAS content. Under strain-control mode, the fatigue life of the FAM mix specimens decreased with increasing RAS content, while under stress-control mode, an opposite trend was observed.

2.5 Quantifying Diffusion and Blending between Virgin and Reclaimed Binders

A number of studies have been undertaken recently to better understand the diffusion and blending of aged and virgin binders.

The diffusion process involves transferring new binder molecules from regions of higher concentration to regions of lower concentration, without requiring bulk motion. In this process, the new binder acts like a rejuvenator as it diffuses into the RAP binder *(26)*. The concentration of new binder in the RAP binder film around the aggregate increases as a function of time until equilibrium is achieved.

Karlsson and Isacsson *(37-40)* used the Fourier transformed infrared spectroscopy (FTIR) technique to investigate important diffusion parameters, including aging, temperature, binder film thickness, viscosity of the diffusion medium and chemical properties of the binders. They compared the diffusion coefficient calculated by Fick's second law and Stoke-Einstein's equation with values obtained using FTIR attenuated total reflectance (ATR) and discovered that diffusion rates detected by the DSR were somewhat higher than those obtained using FTIR-ATR.

McDaniel et al. *(7)* investigated whether RAP acts like a "black rock" or if there is some level of blending occurring between the age-hardened binder in RAP and virgin binder. Asphalt mixes were prepared with 10 and 30 percent RAP content using RAP materials collected from three different locations (Arizona, Connecticut, and Florida) and two grades of virgin binder. The mixes were fabricated to simulate actual asphalt plant conditions, zero binder blending, and full blending conditions. Statistical differences between the properties of the asphalt mixes fabricated at three blending conditions were only measured on the mix with 30 percent RAP. Based on these results, the investigators concluded that RAP should therefore not be considered as black rock and that significant blending does occur.

Bonaquist *(17)* evaluated the level of blending between reclaimed and virgin binder in mixes containing RAP and RAS. The shear modulus of the blended binder was predicted with the Hirsch model and then compared with the measured shear modulus of the recovered binder from the mixes. The results indicated that full blending occurred in an asphalt mix containing 35 percent RAP, but that only limited blending occurred between the virgin and RAS binder in a mix containing 5 percent RAS. The approach proposed by Bonaquist was used in other studies *(20,25,26,41)* to evaluate the level of blending between RAP and virgin binder in asphalt mixes containing RAP. Results from these studies indicated that complete blending occurred in most cases. Mogawer et al. *(42)* also evaluated the degree of blending between the aged and virgin binders by comparing the ratio of the measured mix dynamic modulus to the recovered binder modulus for the control and corresponding RAP mix. The study concluded that sufficient blending of the RAP and the virgin binders in the RAP mix were achieved.

Hung et al. *(43)* used extraction and recovery to investigate how aged RAP binder blended with virgin binder under normal mixing conditions. One source of RAP was mixed with virgin binder at different percentages. The results indicated that only a small percentage of the RAP blended with the virgin binder, with the remaining RAP binder forming a stiff coating around the RAP aggregate, thereby creating a "composite black rock." The investigators recommended further analysis to investigate a larger range of RAP sources and virgin binders under various mix conditions.

Yar et al. *(33)* evaluated and quantified the effects of time and temperature on diffusion rate and the ultimate blending of the aged and virgin binders through an experimental-based approach validated with analytical modeling of diffusion. The changes in the stiffness of a composite two-layer asphalt binder specimen (also known as a wafer specimen) were monitored in DSR tests. The wafer specimen was composed of two 1 mm-thick asphalt disks made with simulated RAP binder and virgin binder, respectively. This study revealed that the diffusion coefficient between two binders in contact can be estimated from DSR test results and that the diffusion mechanism can be modeled (i.e., Fick's second law of diffusion). The diffusion rate was found to increase with temperature, but the rate was influenced by binder chemistry. Only limited diffusion and blending occurred at temperatures below 100°C. Consequently, production temperatures and times would need to be appropriately selected at asphalt plants to ensure sufficient blending between the virgin binder and aged RAP binder. Rad *(44, 45)* and Kriz et al. *(46)* completed similar studies by testing two-layer binder specimens in a DSR and using the results to model diffusion. The results indicated that complete binder blending occurred within minutes after mixing in both hot mix and warm mix asphalt samples, that diffusion rates increased with increasing temperature, but that the rates were influenced by binder chemistry. Only limited diffusion and blending occur at temperatures below 100°C. Further simulations with the results indicated that binder film thickness in mixes could have a significant impact on the degree of blending and that further research was necessary to understand this.

Zhou et al. *(4,48)* characterized tear-off asphalt shingles and manufacturer waste asphalt shingles from various sources and the blending of extracted binders with virgin binder and RAP binder using DSR and BBR tests. The results showed that the binder extracted from tear-off shingles had distinguishably different properties than the binder from manufacturer waste shingles, and the study concluded that RAS source needed to be considered in any mix design if use of RAS was planned. Changes in the high and low performance-related temperatures were generally linear up to 30 percent RAS content and nonlinear thereafter. Zhao et al. *(49)* and Zhou et al. *(50)* also quantified the rate at which reclaimed binder was mobilized to blend with virgin binder in mixes containing up to 80 percent RAP and up to 10 percent RAS. This was achieved by measuring the large molecular size percentage using gel permeation chromatography. The results showed that the asphalt binder mobilization rate decreased with increasing RAP content. The rate of binder mobilization was 100 percent for 10 to 20 percent RAP content, 73 percent for 30 percent RAP content, and 24 percent for 80 percent RAP content. In the mixes containing RAS, the maximum mobilization rate peaked at up to 5 percent RAS content and then decreased with increasing RAS content thereafter.

Falchetto et al. *(51)* compared backcalculated asphalt binder creep stiffnesses, determined from the properties of asphalt mixes containing RAP or RAS, to the measured creep stiffness values of the binder chemically extracted from those mixes. The measured creep stiffness values were higher than the backcalculated stiffness values. The difference was attributed to forced blending between the virgin and age-hardened RAP or RAS binders during the solvent extraction process.

Arnold et al. *(52)* noted that small amounts of RAS can increase asphalt mix embrittlement temperatures resulting in poorer mix performance at low temperatures. The study found that incorporation of 2.5 percent RAS by total weight of mix resulted in an increase in the embrittlement temperature of about 10°C, which was attributed to partial blending between the RAS binder and the virgin binder. Mix performance improved when production temperatures were increased. The higher production temperatures would have increased the rate of blending between the RAS binder and the virgin binder, resulting in some reduction in the embrittlement temperature.

2.6 Selection of Virgin Binder for RAP/RAS Mixes

Current practice (AASHTO M 323) specifies using one-grade softer virgin binder than specified for the pavement location when 15 to 25 percent RAP is used in the mix. This is intended to compensate for the stiffening effect of the aged reclaimed binder. For higher amounts of RAP, the performance grade of the virgin binder must be determined from a blending chart, which requires testing of extracted and recovered reclaimed binder *(3,7)*.

Mogawer et al. *(21)* studied the performance data from a plant-produced asphalt mix with no RAP, and two asphalt mixes with 10 and 30 percent RAP. A PG 64-28 virgin binder was used in the control mix and in the mix with 10 percent RAP. A softer PG 58-28 was used for the mix with 30 percent RAP to compensate for the stiffer, aged RAP binder. The mix with 30 percent RAP did not pass the Hamburg Wheel-Track Test requirement for moisture susceptibility. This observation raised a concern that the selection of virgin binder grade should be based on the desired performance of the mix rather than only on a change in binder grade according to the proposed RAP content.

Abbas et al. *(24)* evaluated the effect of different quantities of RAS (5, 7, and 10 percent) on the physical and chemical properties of a PG 58-28 unmodified binder. Incorporation of RAS binder improved the rutting resistance properties of the asphalt binder, but increased the thermal cracking susceptibility. RAS binder did not appear to influence binder fatigue performance. This finding differed from other studies in which fatigue life of mixes was reduced by adding RAS. Chemical analyses of original, RTFO-aged, and

PAV-aged blended binders conducted by Abbas et al. found that the addition of RAS binder can increase the asphalt binder aging potential in the long-term.

Swiertz et al. *(35)* evaluated the influence of RAP and RAS binder on the low-temperature grade of blended binder using a BBR test on asphalt mortar specimens (no solvent extraction and recovery of aged binder). The study found that the influence of the RAP and the influence of the RAS on the virgin binder properties can be combined into a single factor. Accordingly a chart was developed to estimate the virgin binder low PG grade required in mixes containing both RAP and RAS.

Kriz et al. *(46)* found that the current AASHTO M 323 specification recommendation for using a one-grade softer asphalt binder in mixes with 15 to 25 percent RAP may not be justified, as test results demonstrated that a binder grade change was not necessary for up to 25 percent RAP binder replacement for most of the blends investigated.

Sabouri et al *(53)* investigated how incorporation of RAP changes the binder grade. Testing was performed on both PG 64-28 and PG 58-28 binders and at zero, 20, and 40 percent RAP binder replacement. Results showed that mixes with the softer binder (PG 58-28) had better fatigue resistance properties. The study suggested the use of a soft binder while maintaining the optimum binder content or increasing the asphalt layer thickness when incorporating high quantities of RAP in mixes.

2.7 Properties of Asphalt Mixes Containing Reclaimed Asphalt

The effects of RAP and RAS on the volumetric properties of new asphalt mix, blending between new and aged binders in asphalt mixes containing RAP and/or RAS, and the influence of RAP and RAS on mix performance are reviewed below under the following headings:

- Effect of reclaimed asphalt on mix volumetric properties
- Effect of reclaimed asphalt on mix performance properties

2.7.1 Effect of Reclaimed Asphalt on Mix Volumetric Properties

Most of the literature reviewed recommended that the same volumetric criteria specified for conventional asphalt mixes (including VMA, VFA, and dust proportion [DP]) should be followed for asphalt mixes containing RAP and/or RAS. However, studies have shown that mix volumetric properties can be altered by the addition of RAP and RAS.

Swamy et al. *(54)* found negligible changes in volumetric properties when up to 10 percent RAP was used in a mix and that the effects of higher percentages of RAP (20 and 30 percent) on volumetric properties were inconsistent. Daniel and Lachance *(55)* observed increases in VMA and VFA values with increasing RAP up to 40 percent. The preheating of RAP materials was also found to influence volumetric properties. Studies in Minnesota *(56)* found that the volumetric properties of conventional mixes and mixes with 15, 25, and 30 percent RAP, mixes with 3 and 5 percent RAS, and mixes with combinations of RAP and RAS (10/5, 15/5, 25/5, 15/3, 25/3 percent) were similar and that all mixes satisfied the Minnesota Department of Transportation volumetric requirements.

Aurangzeb et al. *(57)* investigated the use of high percentages of RAP (30, 40, and 50 percent) in asphalt mixes to obtain desired volumetric and performance properties. The results showed that all of the mixes with RAP performed equally or better than the mixes prepared using virgin aggregate. Given that consistent and similar volumetric properties were achieved for all mixes, the researchers concluded that the performance properties of the tested mixes were a function of only their mechanical properties. Appropriate processing and fractioning of the RAP was recommended for high RAP mixes to ensure consistent quality.

Rubino *(58)* found that addition of 5 percent RAS by total weight of mix reduced the VMA slightly but marginally increased the VFA. The optimum virgin binder content reduced with the addition of RAS, but not by the amount of theoretically available RAS binder. Rubino concluded that it was possible to design high-quality asphalt mixes with high quantities of RAP and small quantities of RAS that met the designed volumetric properties.

Kvasnak et al. *(59)* investigated the best method of determining the bulk specific gravity of RAP aggregates, which is used for determining the VMA. Asphalt mixes with known aggregate properties were produced and aged, after which the aggregates were recovered for further analysis. The maximum theoretical specific gravity was determined for each mix and then used to estimate the bulk specific gravity of the aggregates. The study concluded that the bulk specific gravity of aggregates can be successfully estimated from the measured maximum theoretical specific gravity of the mix and then used to determine the VMA of the mix when a regional absorption value is known.

A joint study conducted by the National Center for Asphalt Technology and the University of Nevada-Reno *(60,61)* investigated three methods for characterizing RAP for binder content and aggregate properties, namely the ignition method, centrifuge extraction, and reflux extraction. Laboratory-produced RAP materials were prepared with aggregates from four different sources. Trichloroethylene was used as the solvent in both extraction methods. The properties of the virgin aggregates were compared to those of the recovered aggregates, with the results indicating that the asphalt binder content was best determined using the ignition oven method and that centrifuge extraction had the least effect on the gradation of the material recovered *(60)*. The combined bulk specific gravity of the aggregate recovered using the ignition method was the closest to the true values, except for the limestone aggregates *(61)*. The study found that solvent extraction was the most appropriate method for determining the gradation and specific gravity of the coarse and fine aggregates in mixes with RAP contents higher than 25 percent. However, the study concluded that any method used to recover RAP will cause some error in the determination of bulk specific gravity, especially if the degree of asphalt absorption is not known. Mixes containing up to 50 percent RAP had variances in VMA of up to ± 0.5 percent.

Mangiafico et al. *(62)* conducted a statistical analysis on how different variables influence the volumetric properties of mixes containing RAP. The selected variables included aggregate properties, gradation, filler properties, binder content, and binder properties. All mix design parameters were found to be statistically significant with respect to the complex modulus of a mix. When assessing fatigue resistance, the aggregate properties, aggregate gradation, and interaction of the binder content and binder properties were found to be the most significant.

Stroup-Gardiner and Wagner *(63)* investigated the used of RAP in Superpave designed mixes. Splitting the RAP stockpile into fine and course fractions increased the potential for maximizing RAP binder replacement to meet Superpave aggregate gradation requirements.

2.7.2 Effect of Reclaimed Asphalt on Mix Performance Properties

The Virginia Department of Transportation evaluated the effect of higher RAP percentages (20 to 30 percent) on performance properties and the relative cost for specific paving projects in 2007 *(64)*. The predicted performance of the control and high RAP mixes were found to be equal based on the results of rutting, fatigue, and moisture susceptibility testing. The addition of RAP did increase the high-temperature performance grade of the virgin binder by one or two grades and in some cases it increased the low-temperature grade by one (from -22°C to -16°C). No construction problems were observed with the high RAP mixes and adding RAP to the mix did not increase production or construction costs.

The constructability and accelerated field performance of RAP mixes were evaluated at the NCAT test track *(65,66)*. Mixes with 20 percent RAP content were more easily compacted than mixes with 45 percent RAP content. Mixes with 45 percent RAP and a softer binder (PG 58-28) required less compaction effort than the same mix with stiffer binder (PG 76-22 polymer-modified). A warm mix additive did not improve compaction. All the mixes evaluated showed acceptable rutting performance, but some low-severity longitudinal cracking, attributed to reflection cracks and/or construction defects was observed. Laboratory rut testing (Asphalt Pavement Analyzer [APA]) on specimens sampled from the track showed that the use of RAP reduced the rutting potential. Specimens from the section with 45 percent RAP content and softer binder (PG 58-22) had a lower dynamic modulus than the mix with a stiffer binder, which could adversely affect mix durability at high-strain conditions. The mixes with 45 percent RAP had shorter fatigue life than the mixes with 20 percent RAP and the control mixes with no RAP. However, in these tests fatigue life did not appear to be influenced by the stiffness of the virgin binder.

Shah et al. *(67)* performed complex dynamic modulus and complex shear modulus tests on virgin binder and binder recovered from mixes with 15, 25, and 40 percent RAP. The results showed no statistical difference between the control binder and binder from the mixes with 15 and 25 percent RAP. Some differences were observed in the dynamic modulus of the control binder and the binder extracted from the mix with 40 percent RAP. Stiffening of the mix with increasing RAP content did not occur as expected.

Li et al *(56)* evaluated the stiffness and low-temperature fracture properties of asphalt mixes containing zero, 20, and 40 percent RAP from two sources and with two grades of base binder (PG 58-28 and PG 58-34). The results indicated that the mix stiffness (dynamic modulus) increased with increasing RAP content. Using a softer virgin binder reduced the stiffness of the control and RAP mixes. The fracture energy of the mixes at low temperatures decreased with increasing RAP content. The source of the RAP did not influence performance at low temperatures, but was found to be significant in influencing stiffness at higher temperatures.

Mogawer et al. *(42)* evaluated how the stiffness and performance of plant-produced RAP are affected by plant type and production parameters. Tests included dynamic modulus, moisture susceptibility, Hamburg Wheel-Track, cracking, and workability. The results indicated that mixes with up to 30 percent RAP showed moisture damage susceptibility and rutting and low-temperature cracking performance that were similar to the control mixes. Workability was found to be a potential construction issue because mix workability decreased with an increase in RAP content. The results also showed that selection of the virgin binder grade for mixes with high RAP content should be based on the desired performance, given that notable differences were observed in performance between similar mixes with different virgin binder PG grades. In another study, Mogawer et al. *(21)* investigated the performance characteristics of plant-produced mixes with up to 40 percent RAP. The results showed improved rutting and moisture damage resistance with increasing RAP content, but reduced cracking resistance, compared to the control with no RAP.

Anderson et al. *(68)* compared the long-term field performance of mixes with no RAP and mixes containing up to 25 percent RAP. Based on the available performance data, the study found that pavement sections with RAP had better rutting resistance than the control sections, but exhibited a lower ride quality and more cracking.

Kim et al. *(69)* investigated the effects of using polymer-modified binder in mixes with zero, 15, 25, and 35 percent RAP on laboratory rutting (Asphalt Pavement Analyzer) and cracking (indirect tensile strength) tests. No significant differences were noticed in the results between the different mixes.

Tarbox and Daniel *(70,71)* investigated the effect of long-term aging on asphalt mixes containing RAP. Mixes with zero, 20, 30, and 40 percent RAP were compacted and then aged in an oven for two, four, or eight days at 185°F (85°C) before testing. A comparison of dynamic modulus test results showed that the susceptibility of mixes to aging-related stiffness increases reduced with increasing RAP content. Similar results were obtained in a similar study completed by Singh et al. *(72)*.

Watson et al. *(73)* monitored the performance of pavement test sections in Georgia constructed with mixes containing five percent asphalt shingles (manufacturer waste). Similar performance to the control sections with no RAS was observed after 2.5 years of trafficking.

Ozer et al. *(74)* evaluated laboratory performance-related properties of mixes containing up to 7.5 percent RAS by total weight of the mix. Permanent deformation resistance improved with incorporation of RAS, but fatigue resistance was reduced. No significant difference in the fracture properties of the mixes containing different RAS contents was observed when tested under monotonic loading at low temperatures. Improvements in fatigue resistance and fracture properties of high RAS content mixes were observed when a softer grade virgin binder (PG 46-34 instead of PG 58-28) was used. Similar results were obtained in a similar study by Cooper et al. *(75)*.

Research by Williams et al. *(76)* studied the influence of adding five percent RAS to mixes containing between 25 and 50 percent fractionated RAP. Laboratory- and plant-produced samples from a field demonstration project on the Illinois Tollway were compacted in a laboratory and then evaluated in terms of dynamic modulus, flow number, tensile strength ratio (TSR), beam fatigue, and disc-shaped compact tension (DCT) tests. Stiffening of the mix caused by incorporation of RAS was more noticeable at lower RAP contents. Mixes with RAS also had higher rutting resistance than the mixes with no RAS. No moisture damage problems were observed in any of the mixes. However, cracking resistance decreased in mixes with increasing RAS content and in mixes with both RAP and RAS when the reclaimed material content exceeded 40 percent. Mixes with 35 percent RAP and five percent RAS and a softer PG 58-22 virgin binder had acceptable cracking performance. In another related study, Williams et al. *(77)* compared the performance of mixes with and without RAS by testing cores sampled from highway test sections. Test results, together with pavement condition survey data indicated that mixes containing up to five percent RAS had similar performance to control sections with no RAS in terms of rutting, fatigue cracking, and low-temperature cracking resistance.

2.8 Literature Review Summary

Key points from the literature review relevant to this UCPRC study include the following:

- The asphalt binder in RAP and RAS can blend appreciably with virgin binder in new mixes. The level of blending between the aged and new binders depends on the chemical composition of the individual binders. To ensure the optimal performance of mixes containing high quantities of reclaimed asphalt, the compatibility of reclaimed and virgin asphalt binders from different sources and with different performance grades must be well understood.
- Appropriate methods for extracting aged binder from reclaimed asphalt materials are still being developed and are focusing on the effects of extraction solvents on the properties of recovered binders. The solvents currently being used are considered to be aggressive enough to fully blend the binders extracted from new mixes containing aged and virgin binders, and thereby provide potentially misleading binder replacement values and nonrepresentative PG gradings of the blended binders.
- Alternative methods to the use of extraction and recovery are being explored to better characterize the performance properties of virgin binders blended with the aged binders in RAP and RAS. Tests on mortar and FAM mixes warrant further investigation.
- Adding RAP to a new asphalt mix can alter the volumetrics and performance of the mix. However, volumetric requirements can still be met with relatively high RAP contents. Compared to equivalent mixes without RAP, rutting performance was generally improved by the addition of RAP, but cracking performance was generally lower. Conflicting results with regard to laboratory test performance were reported.
- Given that the use of RAP as binder replacement and not just as aggregate replacement is relatively new, there is limited knowledge on the long-term field performance of mixes containing high RAP contents (i.e., above 25 percent binder replacement), specifically with regard to the rate of binder aging and its effect on stiffness and susceptibility to cracking. Conventional laboratory aging procedures have not been verified for high RAP mixes.

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3. EXPERIMENT DESIGN

This multiphase UCPRC study is focused on evaluating the effect of virgin binder source and performance grade on the performance properties of blended binder in mixes with high quantities of reclaimed asphalt (i.e., ≥ 25 percent) obtained from RAP and/or RAS. Phase 1, documented in this report, focused on assessing different testing methods for characterizing the blended binder in mixes containing high quantities of reclaimed asphalt pavement (RAP) and reclaimed asphalt shingles (RAS) without the need for extraction and recovery of asphalt binders from the mixes. This work was cofunded by the Federal Aviation Administration (FAA) and the National Center for Sustainable Transportation (NCST). Phase 1 was subdivided as follows:

- Phase 1a: Preliminary asphalt binder testing to assess the variability of three California RAP sources and to compare the properties of field-sampled materials with those of a simulated RAP prepared in the laboratory. The rheological properties of the virgin binders, recovered RAP binder, recovered RAS binder, and the blended binders (virgin binder and RAP and/or RAS binder) at various replacement rates were determined. Testing is discussed in Chapter 4 and included:
  + Performance grading
  + Frequency and temperature sweep tests to develop master curves
- Phase 1b: Supplementary testing on aged and virgin binders to assess blending mechanisms, with special focus on the effects of diffusion and temperature. A new test method was developed for this phase. The rheological properties of the virgin and blended simulated RAP binders were determined. Testing is discussed in Chapter 5 and included:
  + Wafer binder testing
  + Determination of the rheological properties of blended binder samples
- Phase 1c: Preliminary testing on mortar samples to determine the rheological properties of asphalt mastics made with virgin binders, virgin fine aggregates, and various quantities of fine RAP. Mortar samples were prepared on a subset of the materials tested in Phase 1a. Testing is discussed in Chapter 6 and included:
  + Binder testing as per Phase 1a
  + Determination of the rheological properties of mortar samples
- Phase 1d: Preliminary testing to determine the rheological properties of fine aggregate matrix (FAM) mix specimens containing different quantities RAP and RAS (by binder replacement rate) and various virgin binders. Testing is discussed in Chapter 6 and included:
  + Development of a mix design procedure for FAM mixes
  + Amplitude sweep strain tests to determine the linear viscoelastic region
  + Frequency sweep tests to develop shear modulus master curves

Phases 1e through 1g focused on evaluating the performance-related properties of asphalt binders, FAM mixes, and asphalt mixes containing high quantities of RAP (25 and 40 percent by binder replacement) as follows:

- Phase 1e: Preparation of a mix design. Testing is discussed in Chapter 8.

- Phase 1f: Characterization of blended binder rheology using conventional testing (DSR on extracted binders) and the FAM mix testing procedures developed in Phase 1d. Testing is discussed in Chapter 9.
- Phase 1g: Full-graded mix performance testing. Testing is discussed in Chapter 10 and included:
  + Frequency sweep tests to evaluate the effect of RAP on mix stiffness and to develop asphalt mix dynamic modulus master curves
  + Flexural beam frequency sweep tests to evaluate the effect of RAP on mix stiffness and to develop flexural stiffness master curves
  + Repeated load triaxial (flow number) and Asphalt Pavement Analyzer (APA) tests to evaluate the effect of RAP on asphalt mix resistance to permanent deformation
  + Hamburg Wheel-Track tests to evaluate the effect of RAP on asphalt mix resistance to rutting, permanent deformation, and moisture damage
  + Flexural beam fatigue tests to evaluate the effect of RAP on asphalt mix resistance to fatigue cracking

Although the effect of RAP on the low-temperature cracking performance of mixes, the effect of producing mixes containing RAP with warm mix additives at warm mix temperatures (i.e., potentially less blending between virgin and RAP binders at lower production temperatures), and the potential role of different rejuvenating agents on the blending of virgin and aged binders were all considered to be important components of the study, no testing was undertaken to assess these variables due to time and budget constraints.

4. PHASE 1a: PRELIMINARY ASPHALT BINDER TESTING

4.1 Introduction

This phase of the study focused on the characterization of extracted and recovered asphalt binder from RAP and RAS materials and reviewing accelerated aging processes for preparing simulated RAP binder. The experimental plan for this part of the study included two main tasks:

- Determine performance grade of the binder and gradation of the aggregates recovered from three different RAP sources and one RAS source.
- Identify an appropriate aging method for virgin binders to produce a simulated RAP binder with properties similar to those of the recovered RAP binders. One PG 64-16 binder was used in this experiment.

4.2 Experiment Design

4.2.1 Material Sampling and Testing Factorial

Table 4.1 summarizes the sampling and testing factorial for the materials assessed in Phase 1a.

Table 4.1: Experimental Design Factors and Factorial Levels for Phase 1a

Factor	Factorial Level	Details
Asphalt binder source and grade	1	PG 64-16 (sourced from Refinery-A)
RAP source	3	RAP-A (Sacramento) RAP-B (San Francisco Bay Area) RAP-C (Southern California)
RAS source	1	Tear-off shingles (Oakland)

4.2.2 Asphalt Binder Testing

Performance Grading of Virgin Asphalt Binder

Performance grading of the virgin asphalt binder was determined in accordance with AASHTO M 320.

Performance Grading of Extracted Asphalt Binder

In 2001, investigators in the NCHRP 9-12 project *(7)* proposed guidelines for the use of RAP in the Superpave mix design method. These proposed guidelines require determination of the performance grade of the RAP binder for mixes containing more than 25 percent RAP to ensure that an appropriate virgin binder performance grade can be accurately selected from a blending chart. The following procedure, proposed in the NCHRP study guidelines, was used for determining the performance grade (PG) of the reclaimed asphalt (RAP or RAS) binders used in the UCPRC study:

- Asphalt binder extraction and recovery
    1. Obtain a representative sample of reclaimed asphalt material (about 1,000 g) that will provide approximately 50 to 60 g of recovered binder (assuming 5 percent RAP binder content).

2. Extract and recover the asphalt binder from the reclaimed asphalt following the AASHTO T 164 procedure. Toluene or n-propyl bromide may be used as the chemical solvent. Document the use of any other solvents on the test sheet. Nitrogen blanketing is recommended to prevent undesired binder oxidation during extraction.

- Asphalt binder performance grading
  1. Determine the performance grade of the extracted reclaimed asphalt binder according to AASHTO M 320. Rotational viscometer, binder flash point, mass loss, and pressure aging vessel (PAV) are not required for reclaimed asphalt binder grading. PAV aging is not necessary given that the reclaimed asphalt binder has already been aged in the pavement (for RAP) or on a roof (for RAS).
  2. Perform a dynamic shear rheometer (DSR) test with 25 mm parallel plate geometry on the recovered reclaimed asphalt binder (AASHTO T 315) to determine the critical high temperature of the binder (temperature at which the complex shear modulus divided by the sine of the phase angle [G*/sin(δ)] is 1.0 kPa).
  3. Age the extracted reclaimed asphalt binder in a rolling thin-film oven (RTFO, AASHTO T 240).
  4. Perform a DSR test with 25 mm parallel plate geometry on the RTFO-aged recovered reclaimed asphalt binder to determine the critical high temperature of the binder after RTFO aging (temperature at which G*/sin(δ) is 2.2 kPa).
  5. Calculate the high PG limit of the recovered reclaimed asphalt binder based on the lowest temperatures obtained in Steps 2 and 4.
  6. Perform a DSR test with 8 mm parallel plate geometry on the RTFO-aged recovered reclaimed asphalt binder to determine the critical intermediate temperature (temperature at which G* x sin(δ) is 5,000 kPa).
  7. Perform a bending beam rheometer (BBR) test (AASHTO T 313) on the RTFO-aged recovered reclaimed asphalt binder to determine the critical low temperatures (temperature at which creep stiffness [S] is equal to 300 MPa and temperature at which m-value is 0.30).
  8. Calculate the low PG limit of the recovered reclaimed asphalt binder based on the highest (least negative) temperatures determined in Step 7.

<u>Frequency Sweep Tests</u>

The RTFO-aged binders (virgin, RAP, and blended) were tested with a DSR using 8 mm parallel plate geometry with a 2 mm plate-to-plate gap setting at 4°C, 20°C, and 40°C at frequencies ranging between 0.1 Hz and 100 Hz at each temperature. The amplitude strain was set at 1.0 percent to ensure the binders behaved in a linear viscoelastic range. The measured complex shear modulus values (G*) were used to construct asphalt binder master curves at the reference temperature (i.e., 20°C) by fitting the data to the sigmoidal function shown in Equation 4.1. The testing frequencies at any testing temperature were converted to the reduced frequency at the reference temperature using a time-temperature superposition principle (Equation 4.2) with the aid of an Arrhenius shift factor (Equation 4.3).

$$log(|G^*(f_r)|) = \delta + \frac{\alpha}{1+e^{\beta+\gamma\times log(f_r)}} \quad \textbf{(4.1)}$$

where: $\delta, \alpha, \beta, and\ \gamma$ are sigmoidal function parameters
f_r is the reduced frequency at reference temperature T_r (°C).

$$log(f_r) = log(a_T(T)) + log(f) \quad \textbf{(4.2)}$$

where: f is the testing frequency at testing temperature T(°C)
f_r is the reduced frequency at reference temperature T_r (°C)

$$log(a_T(T)) = \frac{E_a}{Ln(10)\times R}\left(\frac{1}{T} - \frac{1}{T_r}\right) \quad \textbf{(4.3)}$$

where: $a_T(T)$ is the shift factor value for temperature T (°K)
E_a is an activation energy term (Joules [J]/mol)
R is the universal gas constant (J/(mol·K)
T_r is the reference temperature (°K)

The parameters of the sigmoidal function as well as the activation energy term in the Arrhenius shift factor equation were estimated using the *Solver* feature in *Microsoft Excel*® by minimizing the sum of square error between predicted and measured values. Examples of the measured shear modulus and the corresponding master curve at 20°C for an asphalt binder are shown in Figure 4.1 and Figure 4.2, respectively.

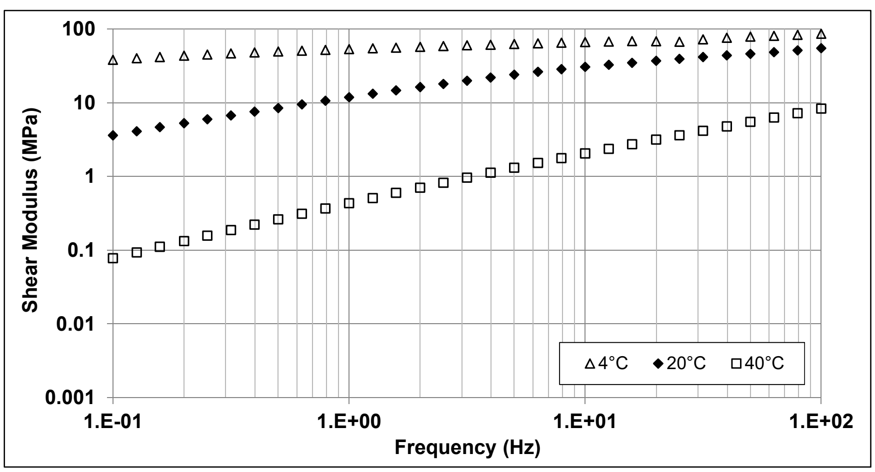

Figure 4.1: Example of measured shear modulus of an asphalt binder at 20°C.

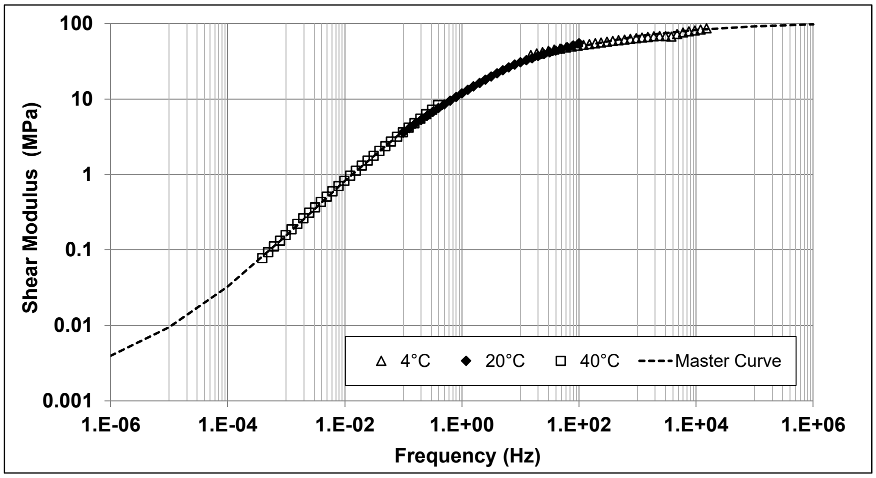

Figure 4.2: Example of a developed master curve for an asphalt binder at 20°C.

4.3 Gradation and Binder Content

Following AASHTO T 248, 5,000 g samples of each RAP and RAS material were sampled and sent to a contracting laboratory for extraction and recovery of the asphalt binder and determination of the RAP and RAS aggregate gradations. The binder was extracted using trichloroethylene (AASHTO T 164) and recovered using the Abson method (ASTM D1856). Gradations were determined in accordance with AASHTO T 30. The results are summarized in Table 4.2.

Table 4.2: Extraction and Recovery Results for RAP and RAS Samples

Gradation (% Passing)					
Sieve Size		RAP-A	RAP-B	RAP-C	RAS
mm	in./mesh				
19.0	3/4	100	100	100	100
12.5	1/2	100	98.5	94.8	100
9.50	3/8	98.8	89.2	87.6	100
4.75	#4	81.2	54.7	66.0	98.9
2.36	#8	59.4	34.3	47.6	96.2
1.19	#16	43.1	24.4	35.8	74.3
0.60	#30	30.4	18.1	26.0	49.7
0.30	#50	19.1	12.5	17.2	42.2
0.15	#100	10.2	6.8	10.0	30.1
0.075	#200	5.8	3.9	6.0	18.8
Binder Content (%)					
Total mix		4.95	4.41	4.94	23.67
Mass of dry aggregate		5.20	4.62	5.20	31.01

4.4 RAP Binder Testing

The critical PG temperatures of the recovered RAP binders, determined according to AASHTO M 320, are provided in Table 4.3 and the PG values are listed in
Table 4.4.

Table 4.3: High, Intermediate, and Low Critical Temperatures of RAP Binders

Critical Temperature (°C)	Test Parameter	RAP-A (°C)		RAP-B (°C)		RAP-C (°C)	
High (Original)	G*/sinδ ≥ 1.00 kPa	92.8		88.0		95.2	
High (RTFO-aged)	G*/sinδ ≥ 2.20 kPa	86.9		83.1		89.0	
Intermediate (RTFO-aged)	G* x sinδ ≤ 5,000 kPa	43.9		41.2		41.3	
Critical Temperature (°C)	**Test Temperature (°C)**	**RAP-A**		**RAP-B**		**RAP-C**	
		S (MPa)	**m**	**S (MPa)**	**m**	**S (MPa)**	**m**
Low (RTFO-aged)	0 6 10	310 NA 127	0.262 NA 0.365	348 163 NA	0.272 0.328 NA	239 NA 89.9	0.258 NA 0.374
Critical Temperature (°C)	**Test Parameter**	**RAP-A (°C)**		**RAP-B (°C)**		**RAP-C (°C)**	
High (unaged) High (aged) Intermediate (aged) Low (aged)	- - - -	92.8 86.8 43.8 -6.3		89.0 88.1 41.2 -7.0		95.2 89.0 41.2 -6.4	

Table 4.4: PG Grades of Extracted and Recovered RAP Binders

Performance Grade	RAP-A (°C)	RAP-B (°C)	RAP-C (°C)
Continuous Full	86.8, -6.3 82, -4	88.1, -7.0 88, -4	89.0, -6.4 88, -4

The results were considered to be reasonably representative of an aged binder. It is not known whether the chemical solvents used in the extraction process influenced the results in any way. Further research (beyond the scope of this study) is required to evaluate the influence of different chemical solvents on the extraction and recovery of binders from RAP materials, including those containing polymer-modified binders and asphalt rubber binders.

4.5 RAS Binder Testing

The binder recovered from the RAS could not be tested according to AASHTO M 320 since it was not sufficiently workable to allow molding of the test specimens after three hours of heating at 190ºC, as shown in Figure 4.3. This observation was consistent with other studies, which reported high PG limits of RAS binder in excess of 120°C and estimated limits to be as high as 240°C *(48,78)*.

Figure 4.3: Recovered RAS binder after three hours of conditioning at 190ºC.

4.6 Evaluation of Properties of Simulated RAP Binders

4.6.1 Background

The testing proposed for the various UCPRC studies investigating the use of reclaimed asphalt in new asphalt concrete mixes required a large quantity of binder. Obtaining this quantity of binder using the AASHTO T 164 process was considered to be inappropriate and impractical given the amount of mix required and a method for producing a simulated RAP binder was instead explored.

Different techniques have been used to prepare simulated RAP, but most focus on laboratory aging of loose mix in a forced draft oven *(59,79)*. A number of recent studies have proposed approaches for preparing simulated RAP binder by aging virgin binders in a PAV. Bowers et al. *(32)* recommended two PAV cycles based on the results of chemical analyses of the binders using Fourier transform infrared spectroscopy (FTIR). Other studies by Yar et al. *(33)* and Rad et al *(45)* also recommended two or more PAV cycles, given that each PAV cycle supposedly simulates seven to ten years of field aging.

4.6.2 Preparation of Simulated Binders

Samples of PG 64-16 asphalt binder were aged in a PAV for 40 and 60 hours at 100ºC and under 2.1 MPa of air pressure (per AASHTO R28). The PG grades of these aged binders were then determined following the NCHRP 9-12 guideline for RAP binder grading *(7)*.

4.6.3 Test Results

The results are listed in Table 4.5. A comparison of the high-, intermediate-, and low-temperature properties of the PAV-aged binders with those of the extracted RAP binders (see Table 4.3) indicated that the critical high PG temperature of the 60-hour PAV-aged binder was comparable to the high PG grade of the recovered RAP binders. However, neither of the PAV-aged binders had low-temperature properties that were comparable to the recovered binders. The reason for this is not clear and will be investigated in a separate study. Possible reasons include but are not limited to the influence of the aggregates on the recovered binders, the influence of the extraction chemistry on the binder, or that the PAV does not uniformly age all components of the binder.

Table 4.5: Critical Temperatures for 40 and 60 Hour PAV-Aged Binder

Critical Temperature	Method	Performance Grade (°C)		
		Extracted	At 40 Hours	At 60 Hours
High	Unaged DSR/RTFO DSR	92.8 / 86.9	88.9 / 82.1	93.6 / 86.7
Intermediate	RTFO DSR	43.9	28.7	31.9
Low	RTFO BBR	-6.3	-19.8	-17.2

4.7 Phase 1a Test Summary

Preliminary laboratory testing to investigate the properties of binders recovered from RAP and RAS samples and simulated RAP binders prepared in the laboratory revealed the following:

- Asphalt binder extracted and recovered from RAS could not be tested due to its very high stiffness. The RAS binder was not sufficiently workable to mold samples for testing in a DSR and BBR.
- The guidelines recommended in NCHRP 9-12 for determining the performance grade of binders recovered from RAP samples were considered to be appropriate for this UCPRC study. Recovered binders from three different RAP sources were tested according to these guidelines.
- Initial attempts to produce a simulated RAP binder in the laboratory with performance properties comparable to recovered binders provided mixed results. Various PAV test scenarios were considered, but only the high critical temperature of the simulated binder was similar to the recovered binders. The low critical temperatures were significantly different. It is not clear whether this was attributable to the aging procedure or to the effect of the extraction chemicals.

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5. PHASE 1b: SUPPLEMENTARY ASPHALT BINDER TESTING

5.1 Introduction

This phase of the study focused on understanding the extent of blending between the virgin and RAP binders during mixing and continuing through compaction. The experimental plan for this part of the study included the following four tasks:

- Development of a testing protocol for preparation, conditioning, and testing of wafer composite-binder specimens using a DSR.
- Testing wafer specimens conditioned at different stages over hot mix asphalt (HMA) and warm mix asphalt (WMA) time-temperature paths with a DSR.
- Modeling the blending of new and RAP binders based on Fick's second law of diffusion and considering aging.
- Prediction of representative diffusion and aging coefficients for composite binders based on comparing the estimated and measured values of shear modulus.

5.2 Experiment Design

5.2.1 Material Sampling and Testing Factorial

Table 5.1 summarizes the sampling and testing factorial for the materials assessed in Phase 1b. A PG 58-22 binder was selected as the new binder, consistent with the practice of using a one-grade softer binder when designing mixes with high RAP binder contents to compensate for the stiffening effect of the RAP binder. A PG 64-16 binder was used to produce the simulated age-hardened RAP binder following the process detailed in Section 4.6.

RAP stockpiles are typically highly variable because they contain materials reclaimed from numerous locations. Consequently, obtaining representative RAP binders for research-based laboratory testing using chemical extraction and recovery is not possible. The remaining solvents in recovered binder may also change the chemistry of the binder, which may affect interactions with new binder. Conventional practice for conducting laboratory testing has therefore been to produce simulated asphalt binders under controlled mixing and aging conditions as a way of providing consistency to better understand key aspects of the testing of composite binders *(32,45)*.

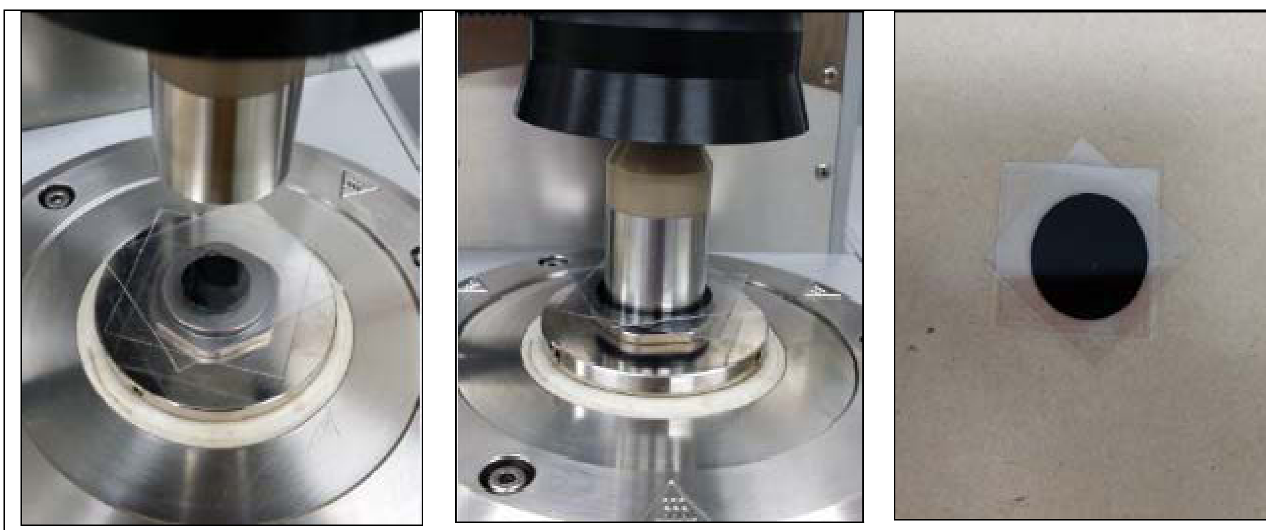
Table 5.1: Experimental Design Factors and Factorial Levels for Phase 1b

Factor	Factorial Level	Details
Asphalt binder source and grade, new	1	PG 58-22 (sourced from Refinery-A)
Asphalt binder source and grade, aged	1	PG 64-16 (sourced from Refinery-A)
New binder/aged binder ratio	1	1:1

5.2.2 Wafer Composite Binder Sample Preparation and Testing

Based on the literature review (Section 2.5) and after a series of trial tests, the following stepwise procedure was developed and adopted for preparing the wafer composite binder specimens:

1. Pour the liquid asphalt binder into a silicon mold and let it cool until the binder solidifies.
2. Place the sample between two 35 mm × 35 mm thermal-resistant transparency sheets.
3. Set up the 25 mm parallel plates on the DSR, set the gap distance to 1.0 mm plus two times the thickness of the transparency sheets, and then set the temperature of the bottom plate to a temperature warm enough for loading the specimen (not more than 64°C).
4. Place the sample covered by the transparency sheet in the middle of the DSR bottom plate (**Figure** [a]). Wait five minutes to warm the binder and then lower the top plate to form a 1 mm-thick disc (**Figure** [b]).
5. Raise the spindle and remove the disc. Carefully place it on a horizontal surface. Keep the top and bottom transparency sheets on to avoid any contamination (**Figure** [c] and [d]).
6. Repeat steps 1 to 5 for the second binder.
7. Place both new and age-hardened binder disc samples into a refrigerator set at 3°C (37°F) for approximately three minutes so that the transparency sheet can be easily removed without damaging the disc.
8. Carefully place the 1 mm new-binder disc on top of the 1 mm aged-binder disc in a silicon conditioning mold (with 28 mm diameter) (**Figure** [e]).
9. Immediately place the conditioning mold into a forced draft oven to condition the wafer composite-binder specimen for the predetermined time and temperature to start the diffusion process.
10. After conditioning, remove the sample from the oven and let it cool until it solidifies (**Figure** [f]).
11. Run the DSR test on the 2 mm-thick wafer composite-binder specimen at the desired temperature to obtain the viscoelastic properties. The gap distance between the parallel plates must be set to 2.0 mm.



a. Binder between two transparency sheets | b. Making binder disc using DSR | c. Binder disc (top view)

Figure 5.1: DSR contact-blending test sample preparation procedure.

d. Binder disc (cross-sectional view)

e. Wafer specimen before oven conditioning

f. Wafer specimen after oven conditioning

Figure 5.1: DSR contact-blending test sample preparation procedure *(continued)*.

5.2.3 Test Method Validation

Validation of the wafer specimen testing procedure was deemed necessary given that no method is specified in AASHTO or ASTM standards. Samples of fully blended new asphalt binders (1:1 ratio) were prepared by mechanical blending using a glass rod at a temperate sufficient for the binders to be stirred. The fully blended specimens were then tested with parallel plate geometry with 1.0 mm gap following AASHTO T 315. Wafer specimens composed of two 1 mm-thick discs of fully blended binder were prepared and tested following the procedure explained above. The results from the two testing approaches are compared in Figure 5.2 and Figure 5.3 (each point on the plots represents one test). Based on these results, wafer specimen testing was considered to provide realistic measurements similar to typical DSR testing specified in AASHTO T 315.

5.2.4 Asphalt Mix Production Time-Temperature Path

Laboratory testing aimed to mimic realistic asphalt mix production temperatures and times. These were determined from the PG 58-22 binder viscosity chart provided by the refinery (145°C to 150°C and 135°C to 139°C, respectively). Temperatures were lowered by 20°C at each stage to simulate WMA production. All samples were conditioned as shown in Table 5.2 to be representative of the different stages of production, shown in Figure 5.4. Two replicate DSR specimens were tested for each condition.

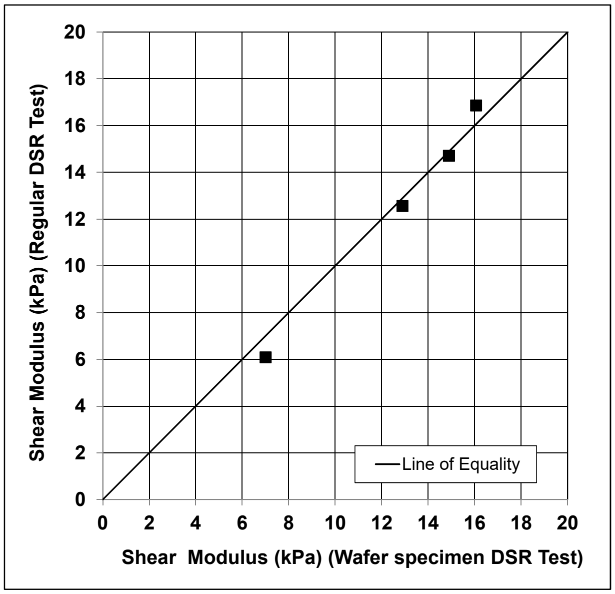


Figure 5.2: Shear modulus (G*) test results for fully blended wafer binder specimen.

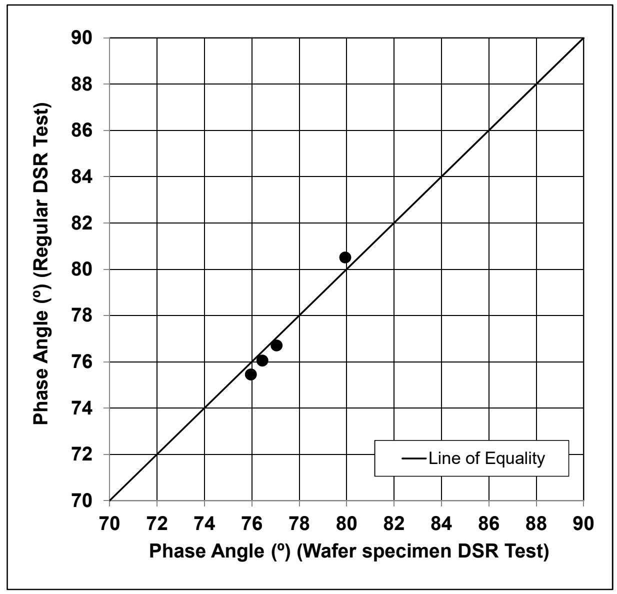


Figure 5.3: Phase angle (δ) test results for fully blended wafer binder specimen.

Table 5.2: Time-Temperature Conditioning of Blended Binder Samples

Phase[1]	Conditioning	
	HMA	WMA
Start Mixing	no conditioning	no conditioning
After Mixing	0.05 hr at 150°C	0.05 hr at 130°C
Silo+Trans_1	0.05 hr at 150°C + 0.5 hr at 140°C	0.05 hr at 130°C + 0.5 hr at 120°C
Silo+Trans_2	0.05 hr at 150°C + 1 hr at 140°C	0.05 hr at 130°C + 1 hr at 120°C
Start Paving	0.05 hr at 150°C + 2 hr at 140°C	0.05 hr at 130°C + 2 hr at 120°C
End Compaction	0.05 hr at 150°C + 2 hr at 140°C + 0.5 hr at 135°C	0.05 hr at 130°C + 2 hr at 120°C + 0.5 hr at 115°C

[1] Silo = silo storage; Trans = transportation to job site

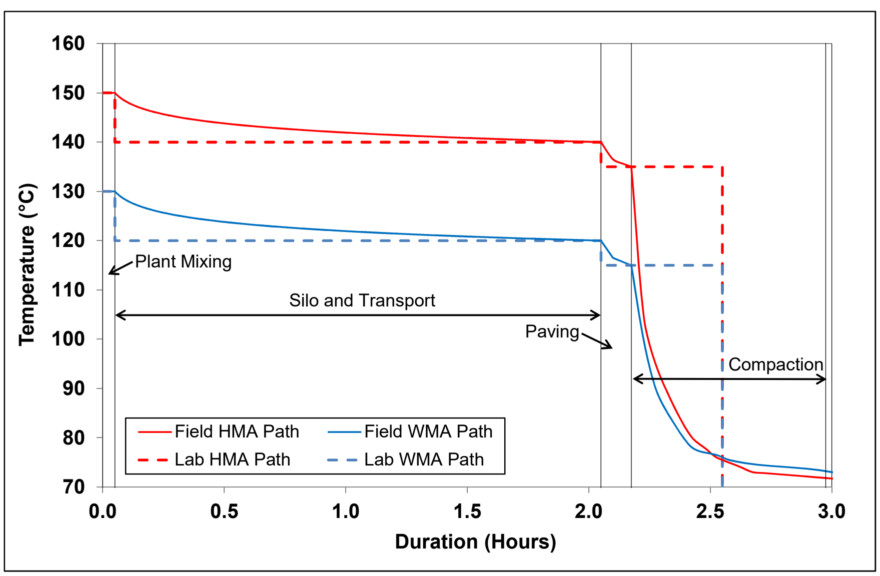


Figure 5.4: Example time-temperature profiles for HMA and WMA from mixing through compaction.

5.3 Test Results

Rheological properties of the fully blended binder and new/RAP contact-blended conditioned specimens are summarized in Table 5.3. Figure 5.5 shows the plots of measured shear modulus values.

Table 5.3: DSR Measurements of Fully Blended Binder and Contact-Blended Binders

Binder Type	Mix Type	Phase[1]	Rheological Property at 64°C		
			$G^*_{full\ Blend}$ (kPa)	δ (°)	$G^*_{full\ Blend}/\sin\delta$ (kPa)
Fully Blended	HMA	Start Mixing	6.08	80.50	6.16
		Silo+Trans_2	9.99	78.25	10.20
		Finish Compaction	14.70	76.05	15.20
	WMA	Start Mixing	6.08	80.50	6.16
		Silo+Trans_2	12.00	76.75	12.35
		Finish Compaction	12.55	76.70	12.90
Binder Type	**Mix Type**	**Phase**	**Rheological Property at 64°C**		
			$G^*_{diffusion}$ (kPa)	δ (°)	$G^*/\sin\delta$ (kPa)
Contact Blended	HMA	Start Mixing	2.55	86.65	2.55
		After Mixing	2.92	85.30	2.93
		Silo+Trans_1	5.07	82.45	5.12
		Silo+Trans_2	8.66	79.30	8.81
		Start Paving	10.80	79.20	10.95
		Finish Compaction	13.85	77.70	14.10
	WMA	Start Mixing	2.55	86.65	2.55
		After Mixing	2.44	86.25	2.45
		Silo+Trans_30 min	4.29	83.45	4.32
		Silo+Trans_60min	5.13	80.95	5.20
		Start Paving	5.43	78.95	8.40
		Finish Compaction	5.95	82.20	6.01

[1] Silo = silo storage   Trans = transportation to job site

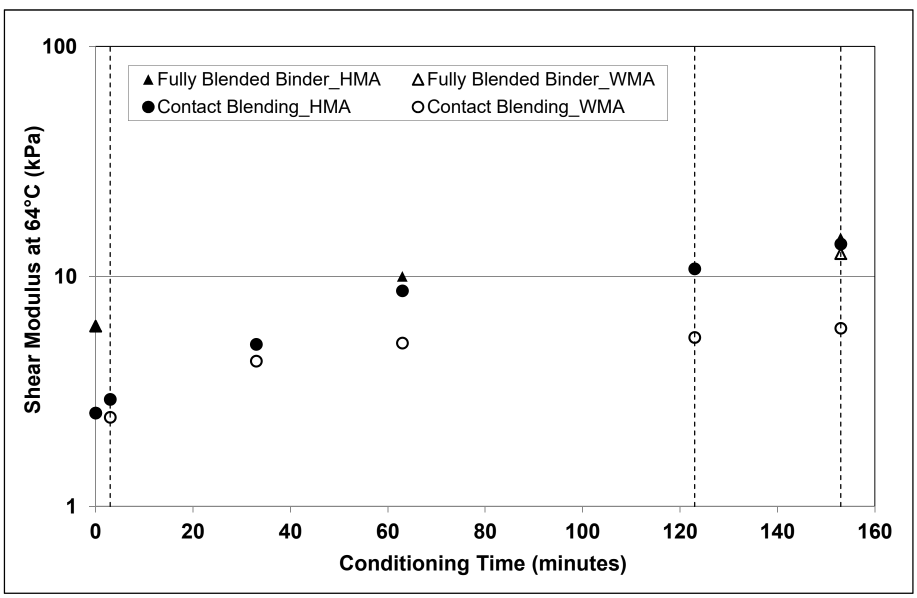


Figure 5.5: Change of complex shear modulus during mix production and placement.

The complex shear modulus of the diffusion specimen ($G^*_{diffusion}$) increased with time, with all measurements on the HMA production temperature path higher than those on the WMA production path, as expected. This implies that the diffusion driven blending process was both temperature and time dependent. The evolution of the complex shear modulus of the fully blended specimen ($G^*_{full\text{-}blend}$) was attributed to aging of the asphalt binder (oxidation and volatilization), whereas the evolution of the modulus of the diffusion specimen was attributed to both diffusion and aging mechanisms.

After 153 minutes on the HMA time-temperature path, $G^*_{diffusion}$ and $G^*_{full\text{-}blend}$ were similar, which implies that the virgin and simulated RAP binders were close to a fully blended condition at this point. It should be noted that the thickness of the new and simulated RAP binders in the wafer composite specimens are not representative of actual binder film thicknesses on the aggregate in a mix (typically between 5 µm and 15 µm). Therefore, it can concluded that full blending between new and RAP binders in a hot mix can have occurred by the time that final compaction is completed.

Conversely, the rate of increase in shear modulus on the WMA time-temperature path was much slower than that for the HMA. After 153 minutes, $G^*_{full\text{-}blend}$ was twice $G^*_{diffusion}$, indicating that only partial blending between the virgin and RAP binders occurred at the lower WMA production temperatures. However, using WMA admixtures and/or rejuvenating agents could potentially improve mobilization of the RAP binder and increase the degree of blending. This was not studied in this project, but warrants further investigation.

5.4 Modeling of Blending Mechanism between New and Aged Binders

The change in the rheological properties of the wafer composite binders can be explained through the diffusion mechanism over time. The virgin and RAP binders are simultaneously aged during conditioning and therefore the blending process can be mathematically modeled using Fick's second law of diffusion with consideration of binder oxidation.

For an isotropic one-dimensional diffusion problem, when diffusivity is independent of concentration (i.e., constant value), Fick's law can be described by the partial differential equation (PDE) shown in Equation 5.1. To solve this equation, one initial condition and two boundary conditions are required *(81,82)*. Figure 5.6 shows the defined boundary conditions for the diffusion specimen. At initial conditions the concentration of new binder is one in the top half of the wafer specimen (z from L to 2L) and zero in the bottom half (z from 0 to L). During the diffusion process there is no transfer of materials to the top (z = 0) and bottom (z = 2L) plates.

$$\frac{\partial C}{\partial t} = D\frac{\partial^2 C}{\partial z^2} \quad (5.1)$$

Where: D is the diffusion coefficient in m^2/sec
C is the concentration in percentage
z is the position in m
t is time in seconds

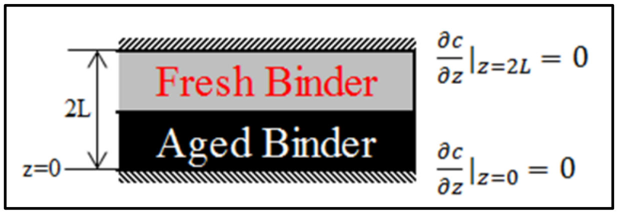


Figure 5.6: Defined boundary conditions of diffusion specimen.

In this study, the PDE of diffusion was solved numerically using a finite control volume approach in a fully explicate time scheme (Equation 5.2 through Equation 5.4) *(83,84)*. Numerical solution of the model considered variations in diffusivity of materials through the thickness of the wafer specimen and over time. However, in this study, the diffusivity coefficient was considered constant with time and depth in specimen thickness. Based on this approach, the wafer specimen thickness was segmented into a number of control elements with a defined thickness (i.e., Δz = 0.01 mm). As a common practice, the top and bottom elements adjacent to the boundaries must have half the thickness of the regular element (i.e., 0.005 mm). The diffusion time was divided into uniform time steps (Δt) with one second duration.

$$C(1,j) = \frac{\Delta t \times D}{(\Delta z)^2} \times [C(2,j-1) - C(1,j-1)] + C(1,j-1) \quad \mathbf{(5.2)}$$

$$C(i,j) = \frac{\Delta t \times D}{(\Delta z)^2} \times [C(i+1,j-1) - 2C(i,j-1) + C(i-1,j-1)] + C(i,j-1) \quad \mathbf{(5.3)}$$

$$C(n-1,j) = \frac{\Delta t \times D}{(\Delta z)^2} \times [C(n-2,j-1) - C(n-1,j-1)] + C(n-1,j-1) \quad \mathbf{(5.4)}$$

Where: i is the distance index changing from 1 to n
j is the time index

The concentration of new binder in the wafer specimen over time for interior elements and elements adjacent to the top and bottom boundaries can be calculated using Equation 5.2 through Equation 5.4. The predicted concentration at any time and depth in the specimen ($C[z,t]$) can be related to its corresponding shear modulus (referred to as $G^*[z,t]$) using the modified Arrhenius mixing rule *(85)*. This rule was validated by Davison et al. *(86)* on asphalt binder using binder viscosity values. In this UCPRC study, the Arrhenius mixing rule was validated using binder shear modulus values. The complex shear modulus at any depth in the specimen thickness and at any given time can be predicted knowing the shear modulus of the virgin and simulated RAP binders as well as the predicted concentration value using Equation 5.5. Virgin and simulated RAP binders were mixed at different ratios and then tested in a DSR with 25 mm parallel plates with a 1.0 mm gap. Figure 5.7 shows the measured and predicted complex shear modulus values at different ratios. The differences between predicted and measured values were considered to be acceptable (i.e., all differences were within 20 percent; 86 percent were within 14 percent).

$$G^* = \frac{{G^*_{simulated\ RAP}}^{C} \times G^*_{New}}{{G^*_{New}}^{C}} \tag{5.5}$$

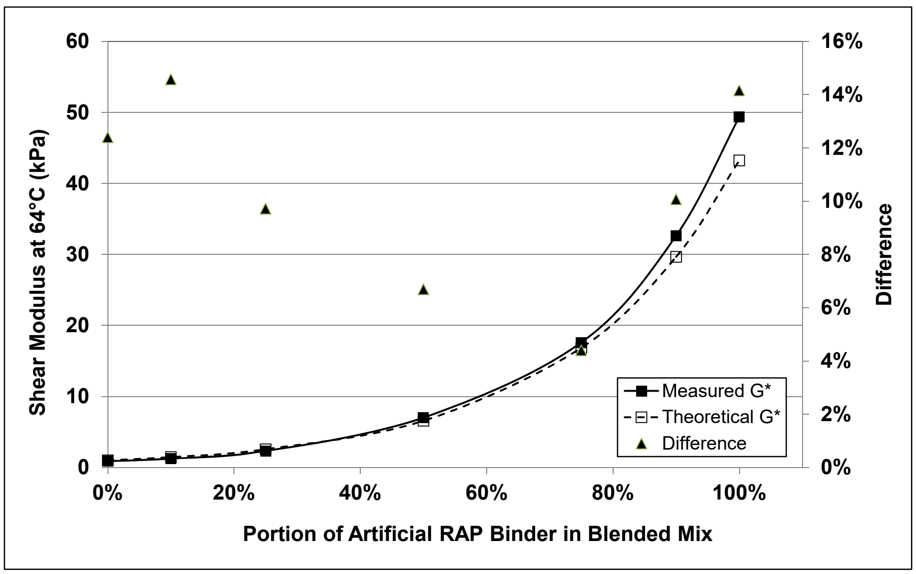


Figure 5.7: Comparison of measured and predicted shear modulus using the Arrhenius rule.

Rad et al. *(45)* introduced a method to estimate the overall complex shear modulus of a wafer specimen with given modulus values at any depth within the thickness of the specimen and at any time (t) using Equation 5.6. The basis of this method is the Reuss model for viscoelastic composites *(87)*.

$$\frac{2L}{G^*_{diffusion}(t)} = \sum_{i=1}^{n} \frac{h_i}{G^*(i,t)} \tag{5.6}$$

Where: $2L$ is the overall thickness of the wafer specimen (2.0 mm in this study)
h_i is the thickness of virgin binder at position i
$G^*_{(i,t)}$ is the corresponding complex shear modulus at position i
n is the number of positions, which depends on the length-step in the model

The effect of aging can be considered using a separated linear function of time. Therefore, the complex shear modulus of the composite binder over time can be predicted using Equation 5.7.

$$G^*_{predicted} = G^*_{diffusion} + C \times t \quad \textbf{(5.7)}$$

Where: C is the aging coefficient
t is the conditioning time

This aging coefficient can be estimated based on the linear regression on the measured complex shear modulus values for the fully blended binder specimens conditioned as detailed in Table 5.2, and is shown in Figure 5.8.

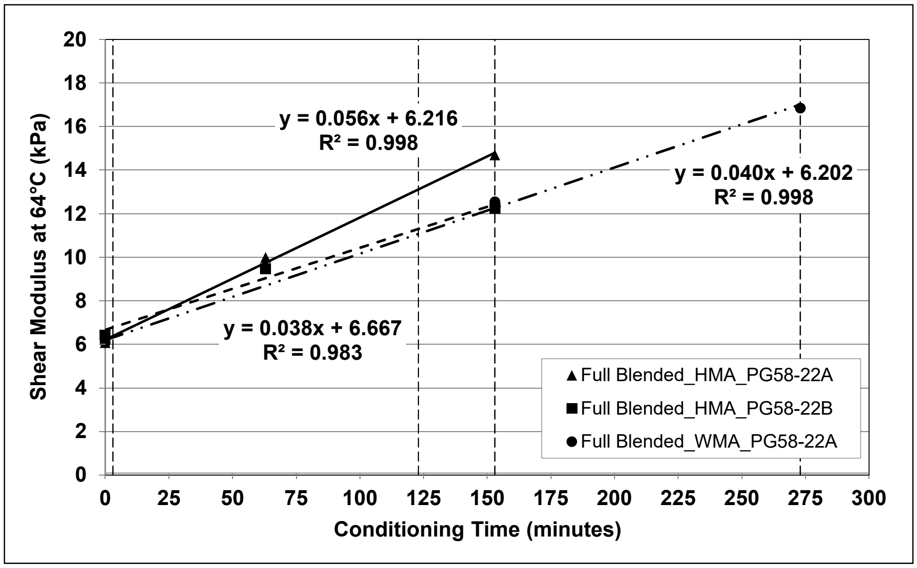


Figure 5.8: Aging coefficient for HMA and WMA production paths.

The diffusion coefficient (D) of the wafer composite specimen was obtained by minimizing the sum of squared errors (SSE) between predicted shear modulus values (calculated using Equation 5.7) and the laboratory measured shear modulus value, considering the effect of aging over time. The diffusion coefficient was 4.876E-11 m^2/second for HMA, while for WMA, the best diffusion coefficient was 2.521E-11 m^2/second, determined by fitting the predicted complex shear modulus to laboratory measurements up to 63 minutes. If the diffusivity maintained this level, full blending would be achieved after 273 minutes. The complex shear modulus of the diffused specimens on the HMA and WMA production paths, determined from modeling estimations and laboratory measurements, are plotted in Figure 5.9 and Figure 5.10, respectively. It should be noted that in reality the diffusion coefficient is a function of temperature and concentration. However, in this study the diffusivity is considered constant within the range of tested temperatures for HMA or WMA production conditions.

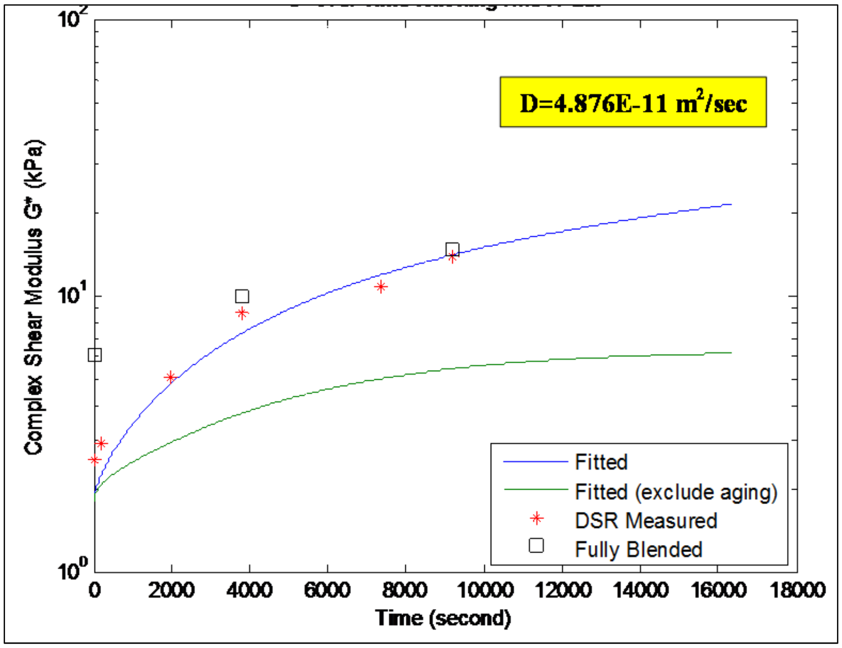


Figure 5.9: Change in complex shear modulus over time for HMA production paths.

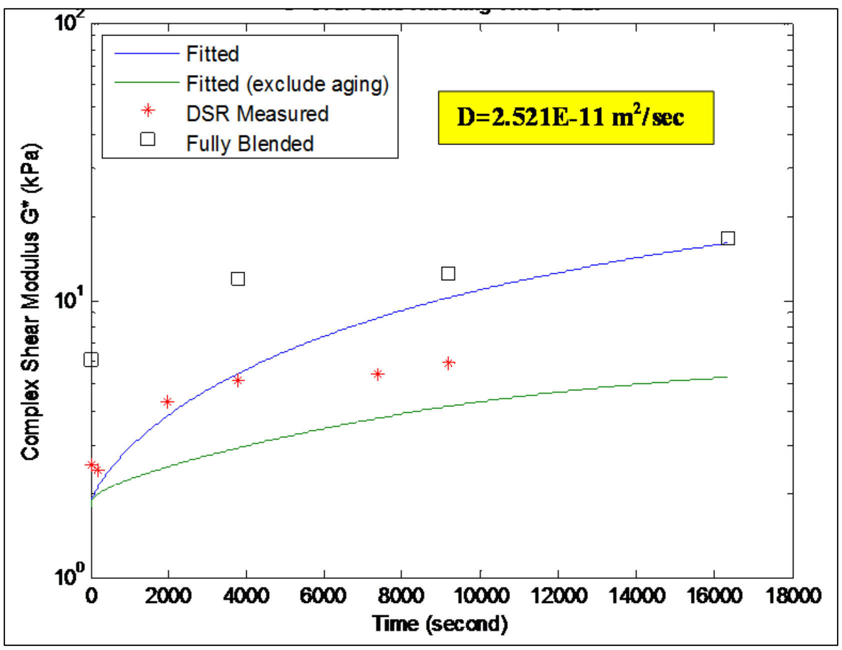


Figure 5.10: Change in complex shear modulus over time for WMA production paths.

5.5 Phase 1b Test Summary

Supplementary laboratory testing to investigate the blending between virgin and RAP binders revealed the following:

- The DSR wafer composite-binder testing method was shown to be an effective approach for examining the level of blending between new and age-hardened binders. The sample preparation and test procedure is straightforward and applicable for both practitioners and researchers.
- The diffusion mechanism in the blending process was shown to be temperature and time dependent:
  + The 153 minutes for the HMA time-temperature path resulted in nearly complete blending of the new and simulated RAP binders.
  + The 153 minutes for the WMA time-temperature path resulted in only partial blending.
  + The diffusion coefficient increased with temperature.
- A finite control volume approach was used to numerically solve Fick's law of diffusion and the representative constant diffusivity for wafer composite specimens under an HMA production temperature path was successfully estimated.
- The predicted complex modulus values of the wafer specimens following the WMA production path for longer than 63 minutes conditioning time were found to be higher than the actual measured values and were close to the values corresponding to the fully blended binder specimen.

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6. PHASE 1c: PRELIMINARY MORTAR TESTING

6.1 Introduction

Phase 1c of this UCPRC study focused on evaluating techniques that do not require chemical extraction for characterizing the performance properties of composite asphalt binders. Based on a preliminary literature review *(11)* and discussions with other practitioners, a decision was made to undertake asphalt mortar testing with a DSR as a potentially appropriate approach for this testing. Asphalt mortar is defined as a homogeneous blend of asphalt binder and fine aggregates passing the 300 µm (#50) sieve and retained on the 150 µm (#100) sieve. The asphalt binder content and the aggregate gradation of the mortar must be representative of the binder content and gradation of the same fine portion of a full-graded asphalt mix. Two samples are tested in this process: one sample consisting of virgin binder plus RAP, and the other consisting of virgin binder plus the aggregates obtained from processing RAP in an ignition oven (i.e., the RAP binder is burned off in an ignition oven). Any differences in the critical temperatures can then be attributed to the RAP binder, provided that the aggregate gradations and total binder contents are exactly the same for both samples.

The experimental plan for this part of the study included preparing asphalt mortar specimens at various binder replacement rates (15, 25, 30, and 35 percent) and performing DSR tests on them. Only one source of RAP was considered for this testing since the Phase 1a test results on recovered binders from three different California RAP sources indicated that the binder properties were similar (see Table 4.3). A softer binder (PG 58-22) was selected for this initial mortar testing as it would likely be more workable and easier to test in the DSR than the stiffer PG 64 or PG 70 binders.

6.2 Experiment Design

6.2.1 Material Sampling and Testing Factorial

Table 6.1 summarizes the sampling and testing factorial for the materials assessed in Phase 1c.

Table 6.1: Experimental Design Factors and Factorial Levels for Phase 1c

Factor	Factorial Level	Details
Asphalt binder source and grade	1	PG 58-22[1] (sourced from Refinery-A)
Aggregate type	1	Granitic
RAP source	1	RAP-A (Sacramento)
RAP content (by binder replacement)	5	0%, 15%, 25% and 35%

[1] PG 58-22 binder was selected as it was considered to be more workable as a mortar than stiffer binders

6.2.2 Sample Preparation

The mortar sample preparation procedure developed by Hajj et al. and summarized in Figure 6.1 *(11)* was investigated prior to sample preparation. Hajj et al. were able to measure high and intermediate temperatures of the mortar samples in a DSR and low temperatures in a BBR. However, most of the mortar samples tested had relatively low RAP binder replacement values (< 15 percent by weight of the binder) and consequently the tests were not unduly influenced by the high stiffnesses typical of samples with higher RAP binder replacement values.

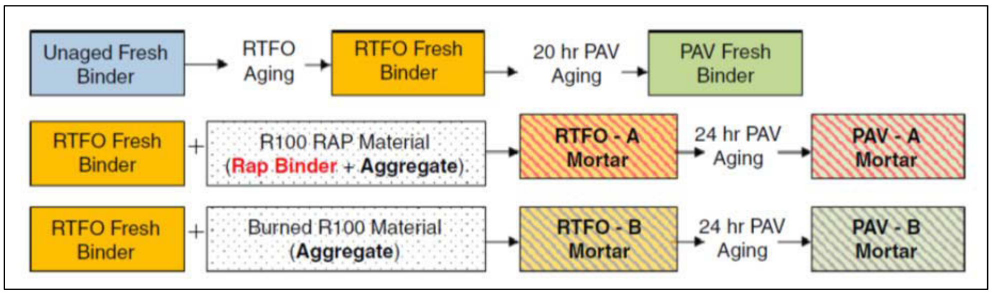


Figure 6.1: Sample preparation for asphalt mortar testing (After Hajj et al. *[11]*).

The same procedure was followed for preparation of the UCPRC samples. PG 58-22 virgin binder was mixed with single size fine RAP material passing the 300 µm (#50) sieve and retained on the 150 µm (#100) sieve at 15, 25, 30, and 35 percent binder replacement rates. The mix temperature was set at 163°C (325°F), which is typical of plant production temperatures of high RAP-content mixes. The binder content of the fine RAP was set at 10 percent by weight of the mortar, based on ignition oven test results.

Attempts to fabricate DSR and BBR test specimens from the mortar samples provided varied results. Samples with binder replacement rates of 25 percent and less were sufficiently workable to fabricate the required specimens. Samples with higher binder replacement rates (i.e., more than 30 percent) were unworkable and specimens could not be fabricated. Given that this UCPRC study was focused on investigating the influence of higher binder replacement rates (i.e., 25 percent and higher) on the performance properties of the blended binders, only limited DSR testing on the mortar samples was undertaken. Extensive testing was not attempted until alternative test approaches (i.e., fine aggregate matrix mixes [discussed in Chapter 7]) could be investigated.

6.3 Preliminary Test Results

Asphalt mortar specimens were tested in a DSR with 25 mm parallel plate geometry and with 2 mm plate-to-plate spacing to measure the rheological properties of the mortar at high in-service temperatures.

Limited amplitude sweep strain tests were performed on selected asphalt mortar specimens to determine the linear viscoelastic range of behavior at which the stiffness of the mortar was independent of the level of applied stress or strain. The amplitude sweep strain tests were performed by measuring the shear modulus of the mortar specimens at 58°C and 1.59 Hz when the applied shear strain amplitude increased from 1 to 16 percent. The test results are shown in Figure 6.2. The results show that the linear viscoelastic region narrowed increasingly with increasing RAP content in the mortar. This trend was expected given that the stiffness of blended binders is influenced by the age-hardened RAP binder, which reduces the tolerable strain level in linear viscoelastic behavior.

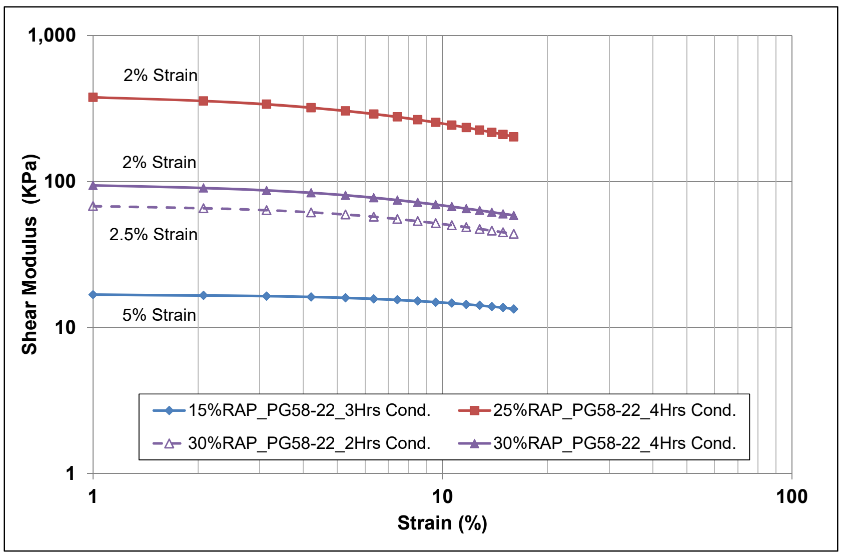


Figure 6.2: Results of amplitude sweep strain tests on asphalt mortar.

Other observations from the testing procedure and results include the following:

- The gradation and binder content of mortar specimens may not be representative of the mortar fraction in corresponding full-graded mixes.
- The conditioning times and temperatures required to prepare workable mortar specimens may not be representative of asphalt plant conditions, which may affect the degree of binder aging and consequently, the DSR test results.

6.4 Phase 1c Test Summary

Preliminary laboratory testing to investigate the properties of asphalt mortars prepared in the laboratory revealed the following:

- Mortar samples with binder replacement rates of up to 25 percent were sufficiently workable to fabricate specimens that could be tested in a DSR. Samples with binder replacement rates greater than 25 percent were generally unworkable and specimens could not be fabricated satisfactorily.

- Although the mortar test deserves further investigation, it may not be appropriate for testing samples with high binder replacement rates (i.e., >25 percent). Given that this UCPRC study was focused on investigating the influence of binder replacement rates of up to 40 percent on the performance properties of the blended binders, the use of mortar testing was considered unsuitable for the remainder of the study.

7. PHASE 1d: PRELIMINARY FINE AGGREGATE MATRIX TESTING

7.1 Introduction

Fine aggregate matrix (FAM) mixes are defined as a homogeneous blend of asphalt binder and fine aggregates with size passing either the 4.75 mm (#4), 2.36 mm (#8), or 1.18 mm (#16) sieves. The asphalt binder content and the aggregate gradation of the FAM mix must be representative of the binder content and gradation of the fine portion of the full-graded asphalt mix. The performance properties are determined by testing small cylindrical or beam specimens of the FAM mix with a solid torsion bar fixture in a DSR, known as a dynamic mechanical analyzer (DMA). Based on the literature review, the FAM mix approach was considered to be a potentially appropriate alternative to binder extraction and recovery and asphalt mortar testing.

7.2 Experiment Design

7.2.1 Material Sampling and Testing Factorial

Table 7.1 summarizes the sampling and testing factorial for the materials assessed in Phase 1d.

Table 7.1: Experimental Design Factors and Factorial Levels for Phase 1d

Factor	Factorial Level	Details
Asphalt binder source and grade	5	PG 64-16 and PG 58-22 (sourced from Refinery-A) PG 64-16[1] and PG 58-22 (sourced from Refinery-B) PG 64-16 (sourced from Refinery-C)
Aggregate type	1	Granitic
RAP source	1	RAP-A (Sacramento)
RAS source	1	Tear-off shingles (Oakland)
RAP content (by binder replacement)	3	0% (all five binders tested) 25% (all five binders tested) 40% (two Refinery-A binders tested)
RAS content	1	5% total weight of mix (~15% by binder replacement)
Rejuvenating agent	1	Petroleum based (sourced from Refinery-C) 12% by weight of total binder used in the mix
[1] Although PG 64-16 binder was requested from Refinery-B, the binder supplied met the requirements for PG 64-22		

7.2.2 Asphalt Binder Testing

Asphalt binder testing was carried out as described in Section 4.2.2. In this phase, only the high PG limits of the blended binders were determined. Low-temperature testing (in a BBR) was not performed since the low-temperature properties of the blended binders were not the primary focus in this phase.

7.2.3 Blended Binder Preparation

Blended asphalt binders were prepared by mixing virgin asphalt binders and recovered RAP binder at rates of 75:25 and 60:40 (representing binder replacement rates of 25 and 40 percent), and recovered RAS binder at a rate of 85:15 (representing a binder replacement rate of 15 percent). The binders were mixed with a glass stirrer until a homogeneous blend was obtained. After mixing, the blended binders were conditioned in an RTFO according to AASHTO T 240 to simulate the short-term aging that occurs during asphalt mix production. Attempts to prepare a homogenized recovered RAS and virgin binder blend were again unsuccessful (see discussion in Section 4.5), and therefore blended binder testing was only conducted on blended extracted RAP and virgin binders.

7.2.4 Trial FAM Mix Sample and Specimen Preparation

Trial FAM sample and specimen preparation methods were based on those cited in the literature *(12-14)*. Mixes were prepared with material passing the 4.75 mm (# 4), 2.36 mm (# 8), and 1.18 mm (# 16) sieves. The 4.75 mm (# 4) and 2.36 mm (# 8) mixes provided satisfactory quantities of FAM; the 1.18 mm (# 16) mixes were difficult to sieve and very large samples needed to be prepared to obtain sufficient quantities of mix to prepare compacted specimens.

7.2.5 UCPRC FAM Mix Sample and Specimen Preparation Method

After a series of trial tests, the following improved procedure was developed and adopted for the preparation of FAM mix samples and specimens for the UCPRC study:

After a series of trial tests, the following refined procedure was developed and adopted for the preparation of FAM mix samples and specimens for the UCPRC study:

1. Prepare a full-graded asphalt mix at optimum binder content with virgin binder and virgin aggregates according to AASHTO R 35.
2. Short-term age the loose asphalt mix for two hours at the mix compaction temperature following AASHTO R 30.
3. Determine the theoretical maximum specific gravity according to AASHTO T 209 (RICE test).
4. Sieve the loose asphalt mix to obtain approximately 1.5 kg of material passing the selected sieve (i.e., 4.75 mm [# 4], 2.36 mm [# 8], or 1.18 mm [# 16]). Where required, gently tamp down the mix to break up agglomerations. Mixes passing the 1.18 mm (# 16) sieve are not recommended given that large volumes of material need to be prepared to obtain sufficient mix to prepare compacted specimens.
5. Sieve the RAP material to obtain approximately 1.5 kg of the required gradation (i.e., 4.75 mm [# 4], 2.36 mm [# 8], or 1.18 mm [# 16]).
6. Determine the binder content of the fine mix by extraction and recovery (AASHTO T 164). (Extraction and recovery was used in this UCPRC study as an alternative to ignition oven testing [AASHTO T 308] due to concern about losing very fine aggregate particles during the ignition process).
7. Determine the binder content and gradation of the fine RAP particles by extraction and recovery.
8. Determine virgin binder, virgin aggregate, RAP, and RAP aggregate quantities for selected binder replacement values based on the binder content and aggregate gradations determined from the extraction and recovery tests (Step 6 and Step 7).

9. Prepare asphalt mixes with different percentages of RAP based on the required binder replacement rate.
10. Determine the theoretical maximum gravity of the FAM mix.
11. Short-term age the loose FAM mix by conditioning for two hours at the mix compaction temperature following AASHTO R 30.
12. Compact the FAM mix in a Superpave gyratory compactor (following AASHTO T 312) to fabricate a specimen with 150 mm diameter and 50 mm height with 10 to 13 percent target air-void content.
13. Subject the compacted specimen to long-term aging if required for the testing phase (e.g., five days at 85°C following AASHTO R 30.).
14. Core 12.5 mm cylindrical FAM mix specimens from the 150 mm diameter specimen. Examples of a 150 mm compacted specimen and cored 12.5 mm specimens are shown in Figure 7.1.

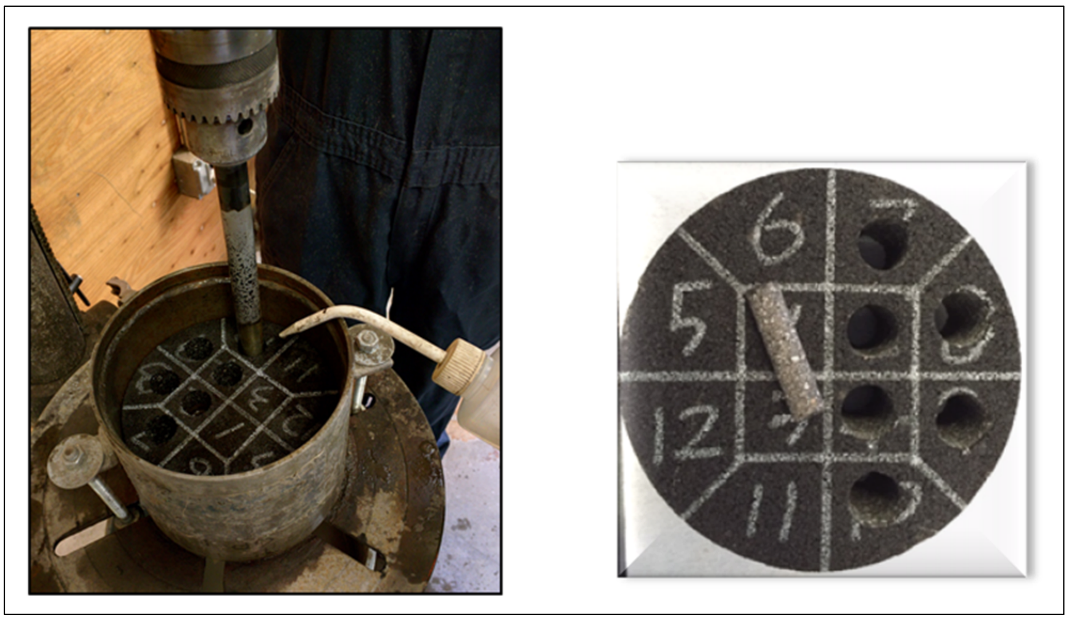


Figure 7.1: FAM mix specimens cored from a Superpave gyratory-compacted specimen.

15. Determine the air-void content of the FAM mix specimens by first determining the saturated surface-dry (SSD) specific gravity (AASHTO T 166A) and then calculating the air-void contents with this and the previously measured theoretical specific gravity (Step 10) according to AASHTO T 269.
16. Dry the FAM mix specimens and store them in a sealed container to prevent damage and excessive shelf-aging prior to testing.

After preparation of a number of trial mixes, it was observed that the 4.75 mm mixes had visible large aggregates relative to the diameter of the 12.5 mm core. It was concluded that the presence of these larger aggregates could potentially influence the test results and introduce variability between test results within the same mix. Consequently all further testing was restricted to mixes prepared with material passing a 2.36 mm (# 8) sieve.

7.2.6 FAM Mix Test Setup

FAM mix specimens were tested using a solid torsion bar (dynamic mechanical analyzer [DMA]) fixture in an Anton Paar MCR302 DSR.

When performing tests on FAM mix specimens, special attention must be given to ensuring that the specimen is correctly aligned and securely clamped in the DSR. Each specimen must be carefully inspected and checked to ensure that its edges are clean and undamaged in the clamping zone, and that there are no localized weak areas (e.g., aggregates torn out during coring) that could influence the results. In other studies *(12-14,36)*, reference is made to the use of steel caps, glued to both ends of the FAM mix specimen, to secure the specimen in the testing frame. Initial testing at the UCPRC compared tests with and without the caps, but this approach was ultimately not pursued based on discussions with the DSR manufacturer, who stated that the glue zone between the cap and the specimen would likely have a significant influence on the results. Instead a custom clamp recommended by the DSR manufacturer was used. Figure 7.2 shows the fixed specimen in the DSR-DMA used in this project.

Figure 7.2: DSR-DMA torsion bar fixture used for FAM mix testing.

7.2.7 Amplitude Sweep Tests

Amplitude sweep tests were performed on the FAM mix specimens to determine the linear viscoelastic range of material behavior. The shear modulus of each FAM mix specimen was measured at 4°C and a frequency of 10 Hz when the shear strain increased from 0.001 to 0.1 percent incrementally. An example test result is shown in Figure 7.3. The shear stiffness of the FAM mix specimen is independent of the rate of shear stain in the linear viscoelastic region.

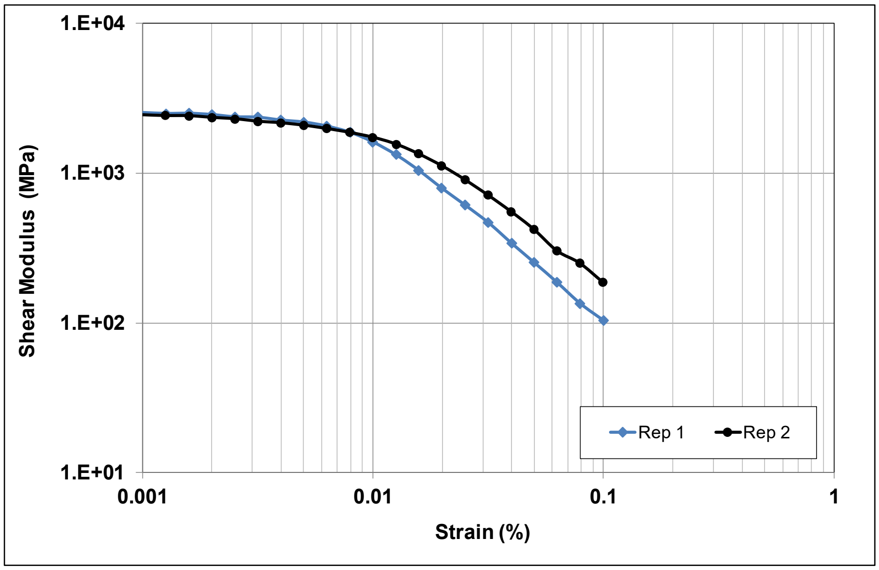


Figure 7.3: Example FAM mix specimen amplitude sweep test results.

7.2.8 Frequency Sweep Tests

Frequency sweep tests measured the complex shear modulus in a wide range of frequencies (0.1 Hz to 25 Hz) at three different temperatures (4°C, 20°C, and 40°C). Based on the results of the amplitude sweep tests, frequency sweep tests at a strain rate of 0.002 percent were completed to ensure that the material was in the linear viscoelastic region. FAM mix specimen shear modulus master curves were constructed based on time-temperature superposition principles using the measured moduli over the range of temperatures and frequencies. Equations 4.1, 4.2 and 4.3 were used to construct shear modulus master curves for the FAM mix specimens. Examples of shear modulus and developed master curves at the 20°C reference temperature for a FAM mix are shown in Figure 7.4 and Figure 7.5, respectively.

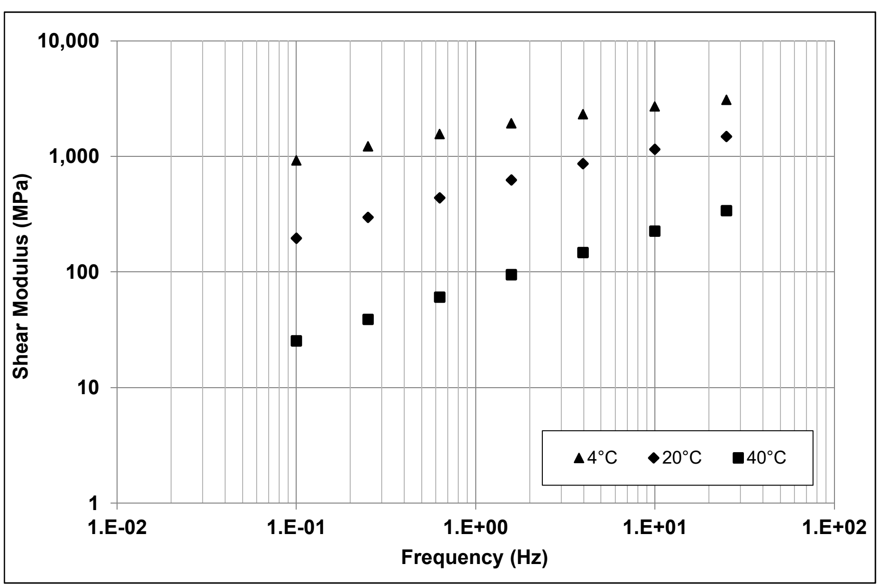


Figure 7.4: Example of measured shear modulus of a FAM mix specimen at 20°C.

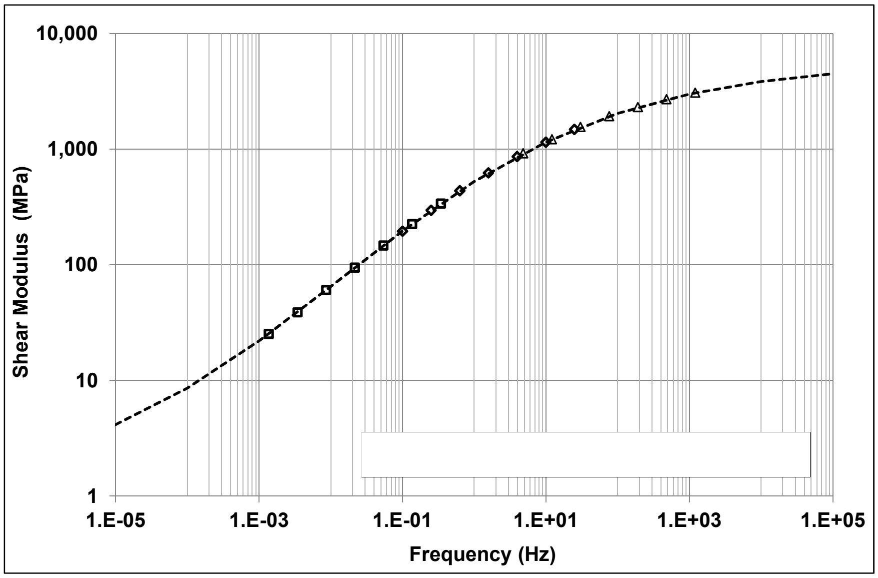


Figure 7.5: Example of shear modulus master curve of a FAM mix specimen at 20°C.

7.3 RAP and RAS Binder Characterization

Representative samples of RAP and RAS materials were collected and sent to a contracting laboratory for extraction and recovery of the asphalt binder. The binder was extracted using trichloroethylene (AASHTO T 164) and recovered using the Abson method (ASTM D 1856). The extracted RAP binder was tested according to the NCHRP 9-12 guidelines discussed in Section 4.2.2.

The performance grading criteria and mean temperature values of the recovered RAP binders are listed in Table 7.2 and suggest a mean grading equating to PG 87-6. The results were considered to be reasonably representative of an aged binder. It is not known whether the chemical solvents used in the extraction process influenced the results.

Table 7.2: High, Intermediate, and Low Critical Temperatures of RAP Binders

Critical Temperature	Test Parameter	Mean Temperature[1] (°C)	S (MPa)	m
High (Original) High (RTFO-aged) Intermediate (RTFO-aged)	G*/sinδ ≥ 1.00 kPa G*/sinδ ≥ 2.20 kPa G* x sinδ ≤ 5,000 kPa	92.8 (~ 93) 86.9 (~87) 43.9 (~44)		
Low @ 0°C (RTFO-aged) Low @ 10°C	Tested at 0°C Tested at 10°C	-6.3 (~6)	310 127	0.262 0.365
[1] Mean of two tests				

The binder recovered from the RAS could not be tested according to AASHTO M 320 since it was not sufficiently workable to allow molding of the test specimens after three hours of heating at 190ºC. This finding was consistent with the testing of extracted RAS binders discussed in Chapter 4.

7.3.1 Blended RAP and Virgin Binder Characterization

A second sample of RAP material was sent to an external laboratory for binder extraction and recovery. A toluene-ethanol mix (85:15), which has been shown to have less detrimental effect on the chemistry and rheology of extracted asphalt binders *(46),* was used as the solvent in this extraction. The recovered RAP binder was blended with the different virgin binders to simulate 25 percent and 40 percent binder replacement. A partial factorial experiment of testing was completed to evaluate the properties of these blended binders (see Table 7.1) as follows:

- All five binders were tested at 25 percent binder replacement
- Two of the binders (sampled from Refinery-A) were tested at 40 percent binder replacement
- One of the binders (Refinery-A PG 64-16) was tested with a rejuvenating agent at 40 percent binder replacement

The virgin and blended binders were short-term aged in an RTFO and then tested in a DSR (8 mm parallel plate with 2 mm gap setting) to measure the shear moduli of the binders at three temperatures (4°C, 20°C, and 40°C) and a range of frequencies (0.1 to 100 Hz). The master curve parameters for the evaluated binders are provided in Table 7.3.

Table 7.3: Master Curve Parameters for Virgin and Blended Binders

Binder Replacement (%)	Mix Identification[1]	Master Curve Parameters				
		δ	α	β	γ	E_a (J/mol)
0	PG 64A	-3	4.73	1.32	0.69	191,301
	PG 64B	-3	4.61	1.34	0.70	194,798
	PG 64C	-3	4.89	1.29	0.78	191,105
	PG 58A	-3	4.53	1.08	0.76	181,467
	PG 58B	-3	4.49	0.80	0.81	167,421
25 (RAP)	25%RAP_PG 64A	-3	5.04	-1.39	-0.62	203,802
	25%RAP_PG 64B	-3	5.02	-1.49	-0.58	211,663
	25%RAP_PG 64C	-3	4.98	-1.75	-0.69	211,792
	25%RAP_PG 58A	-3	5.08	-1.12	-0.60	195,467
	25%RAP_PG 58B	-3	5.07	-1.03	-0.61	192,711
40 (RAP)	40%RAP_PG 64A	-3	4.99	-1.83	-0.61	217,237
	40%RAP_PG 64A+RA	-3	5.05	-1.14	-0.67	198,743
	40%RAP_PG 58A	-3	5.01	-1.52	-0.58	208,848
15 (RAS)	Not tested					

[1] A, B, and C denote the source refinery. RA = Rejuvenating agent

Figure 7.6 shows the master curves of the five virgin binders evaluated. The following observations were made:

- The moduli of the PG 58 asphalt binders were lower than the PG 64 binders, as expected. The PG 58-22 binder from Refinery-B was softer than the equivalent binder from Refinery-A.
- The three PG 64 binders had similar shear moduli, with one binder (from Refinery-C) being slightly softer at low frequencies and stiffer at high frequencies.

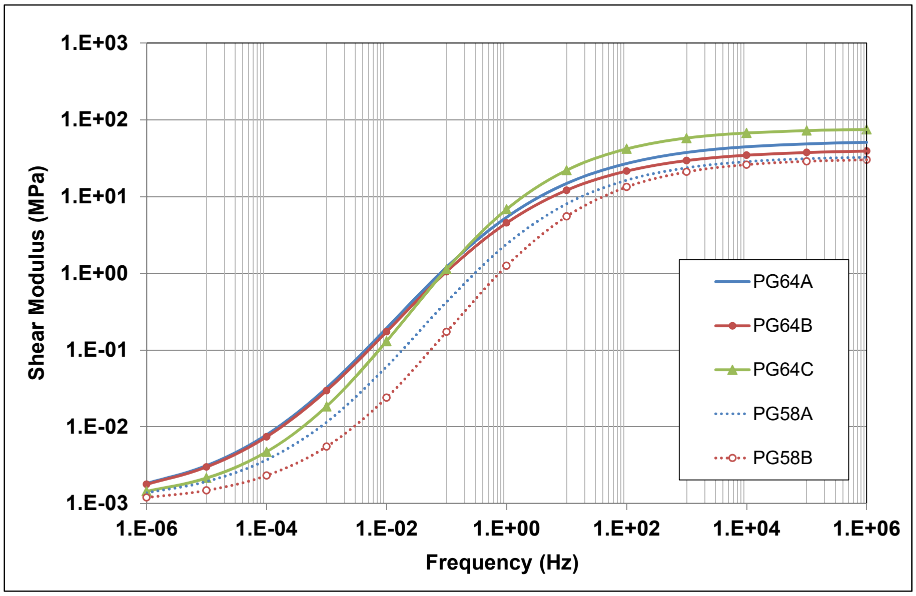


Figure 7.6: Shear moduli of virgin asphalt binders (20°C).

Figure 7.7 shows the shear modulus master curves for blended binders with 25 percent RAP binder replacement. The following observations were made:

- Although the RAP binder reduced the differences between the moduli of the five asphalt binders, the ranking of the binders was still controlled by the properties of the base binders.
- The master curves of the blended binders merged at high frequencies (> 1,000 Hz), regardless of the base binder source and grade.

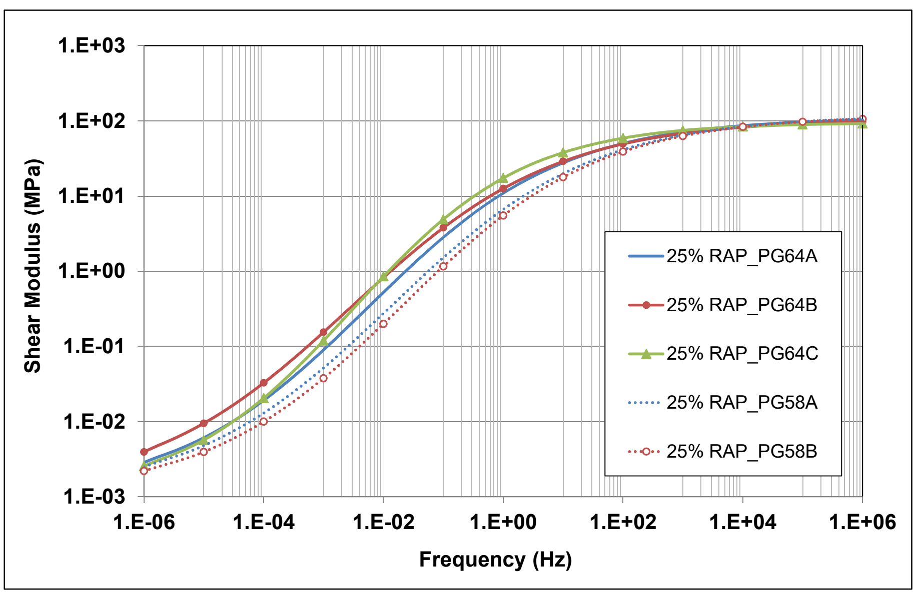


Figure 7.7: Shear moduli of binders with 25 percent RAP binder replacement (20°C).

Figure 7.8 shows the shear modulus master curves for blended binders containing 40 percent RAP binder replacement. The following observations were made:

- The PG 64-16 base binder blend was stiffer than the PG 58-22 blend, as expected.
- The rejuvenating agent reduced the stiffness of the blended binder to a level approximately equal to that of the virgin binder.

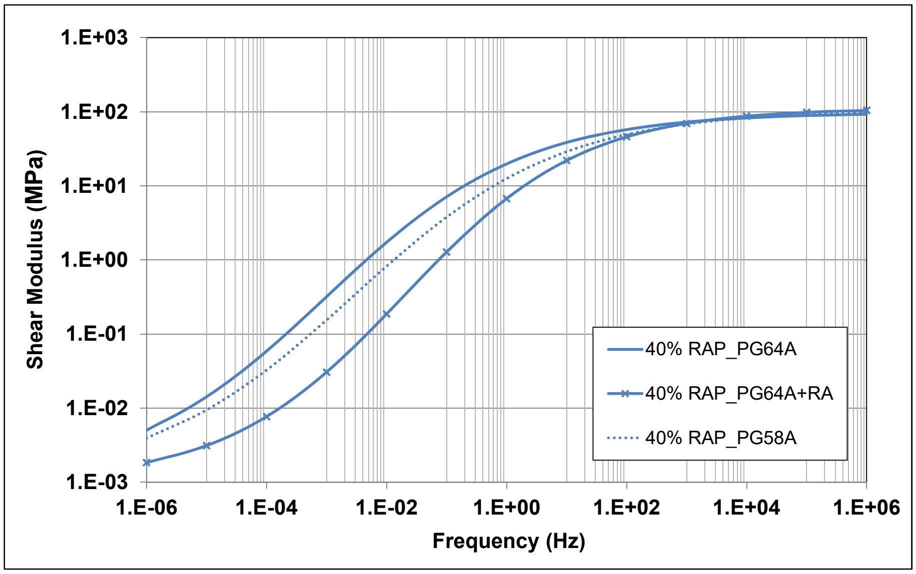
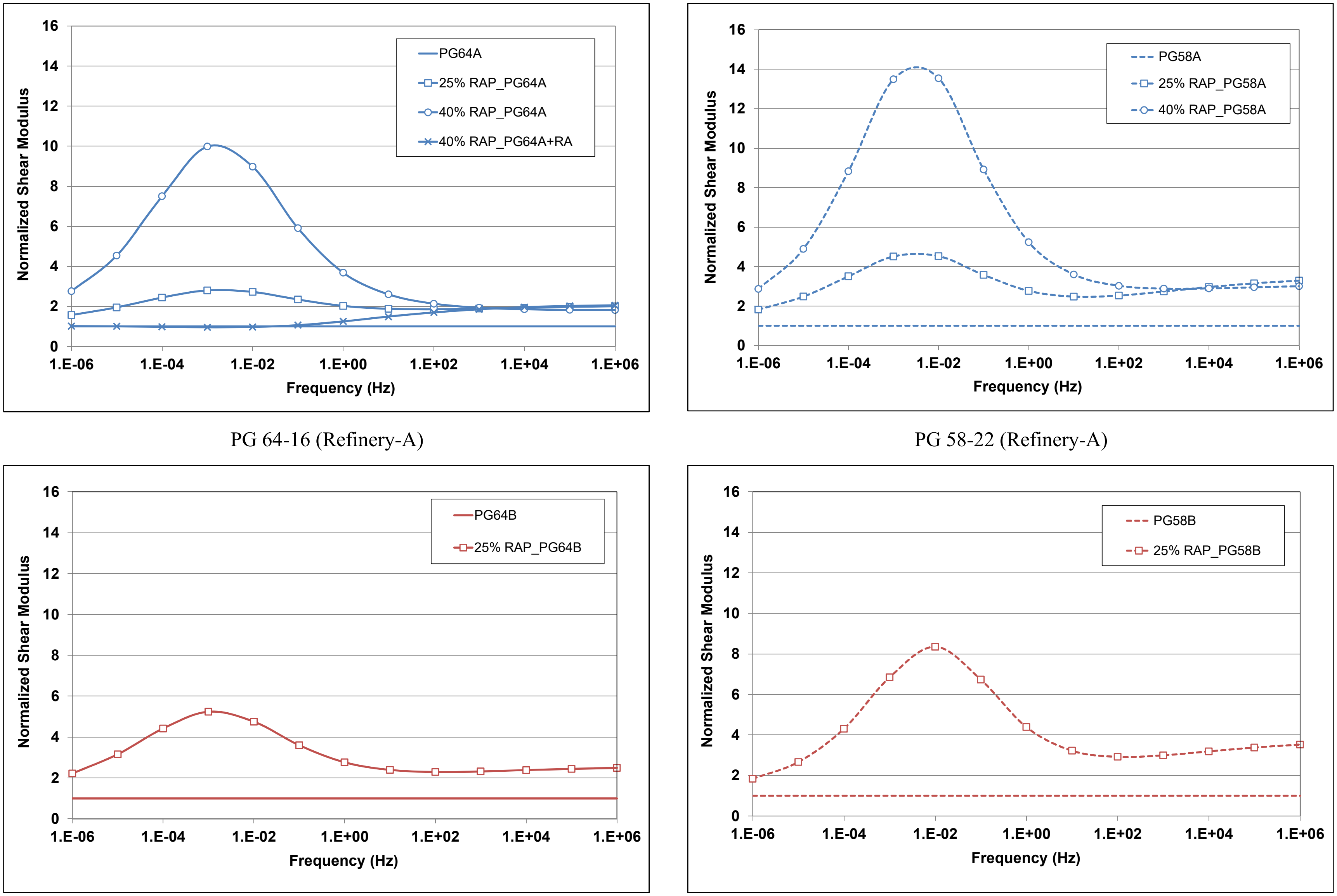


Figure 7.8: Shear moduli of binders with 40 percent RAP binder replacement (20°C).

The master curves of the blended binder were normalized to their corresponding virgin binder master curves to more easily compare the effects of incorporating RAP into the different virgin asphalt binders (Figure 7.9). This analysis showed the following:

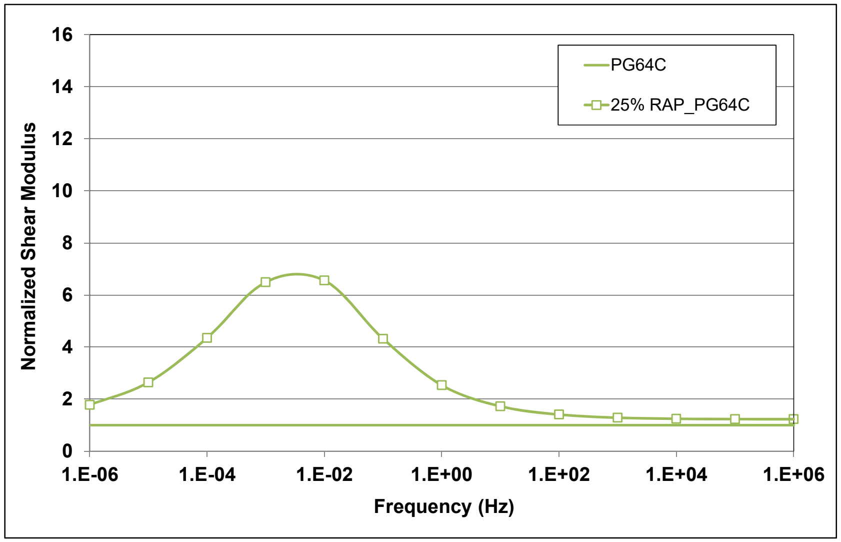
- Using 25 percent RAP binder replacement increased the modulus of the virgin binder by up to eight times, depending on the binder source, binder grade, and testing frequency.
- The stiffness of the PG 58 binders increased more than that of the PG 64 binders for binders from the same refinery.
- The binders from Refinery-A were least affected by the addition of RAP.
- Using 40 percent RAP binder replacement increased the stiffness of the blended binder by up to 13.5 times that of the virgin binder.
- After a rejuvenating agent was added, the normalized curve confirmed that the shear modulus of the blended binder with 40 percent RAP binder replacement was similar to that of the virgin binder over the range of testing frequencies.
- Increases in the shear modulus of blended binders mostly occurred in the frequency range of 0.00001 Hz and 0.1 Hz.



PG 64-16 (Refinery-A) PG 58-22 (Refinery-A)

PG 64-16 (Refinery-B) PG 58-22 (Refinery-B)

Figure 7.9: Comparison of normalized shear moduli master curves for blended binders.



PG 64-16 (Refinery-C)

Figure 7.9: Comparison of normalized shear moduli master curves for blended binders *(continued)*.

7.4 Fine Aggregate Matrix Mix Test Results

FAM mix specimens were prepared according to the procedure described in Section 7.2.5. A total of 26 FAM mixes were evaluated. The binder contents of the RAP and RAS were determined to be 7.1 and 23.7 percent respectively, by total weight of the mix, using the AASHTO T 164 asphalt binder extraction test. The target aggregate gradation used was the same for all the FAM mixes regardless of the binder grade and RAP or RAS content, and is shown in Figure 7.10. The gradation and quantity of virgin aggregate were adjusted according to the quantity and gradation of the RAP and/or RAS in the mix to meet the target FAM gradation. The FAM mixes containing RAS had a slightly coarser gradation than the FAM mixes with virgin binder only and with RAP binder due to the coarser gradation of the RAS materials. However, the difference was not significant given that only 5.4 percent RAS (by total weight of mix) was used.

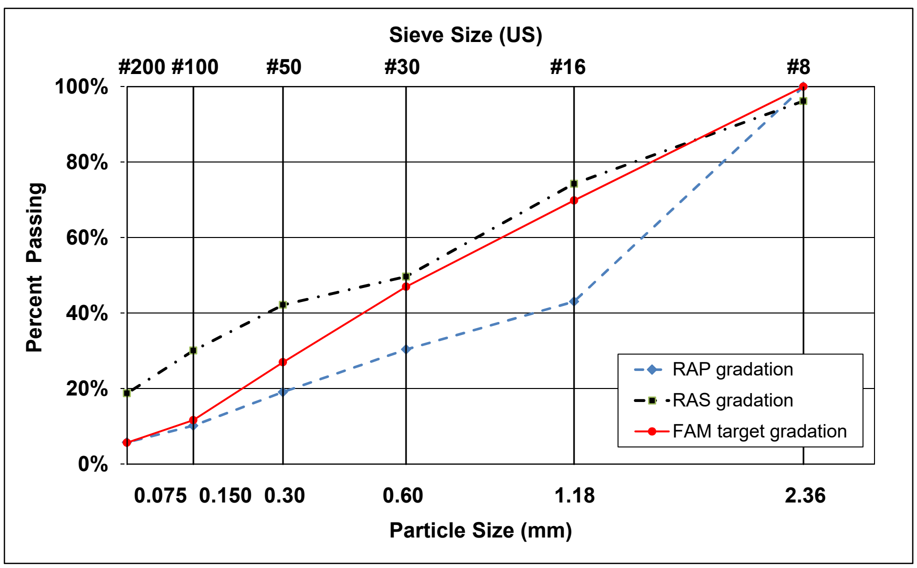


Figure 7.10: Gradation of FAM, RAP, and RAS materials.

7.4.1 FAM Mix Specimen Air-Void Content

A main consideration regarding the repeatability of test results using FAM mix specimens is the range of air-void contents per mix type. Figure 7.11 and Figure 7.12 show the air-void contents measured on the specimens (four specimens per mix). The air-void contents ranged between 10.5 and 12.5 percent, which was within the target range and considered acceptable for this study. The air-void contents of the RAS binder specimens were generally higher than the RAP binder specimens. Air-void contents were considered in all test result analyses.

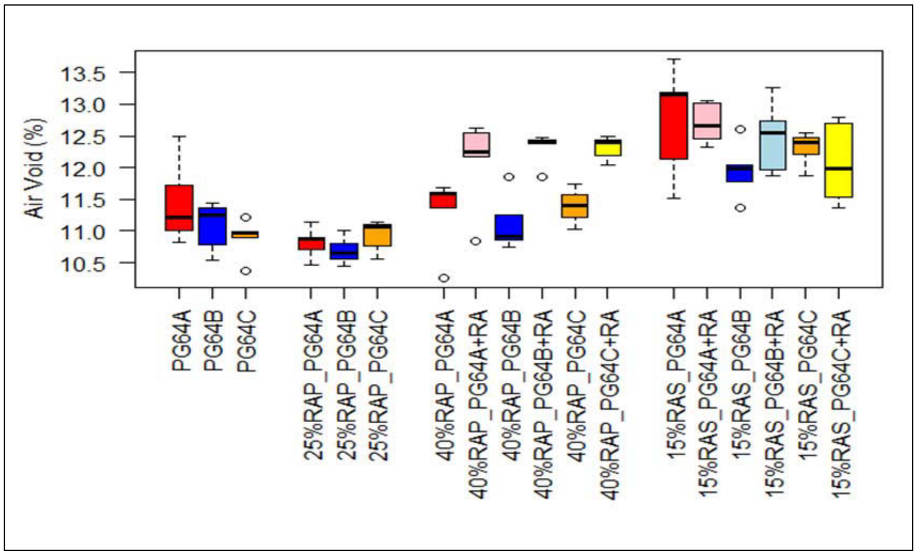


Figure 7.11: FAM mix specimen air-void contents for PG 64 mixes.

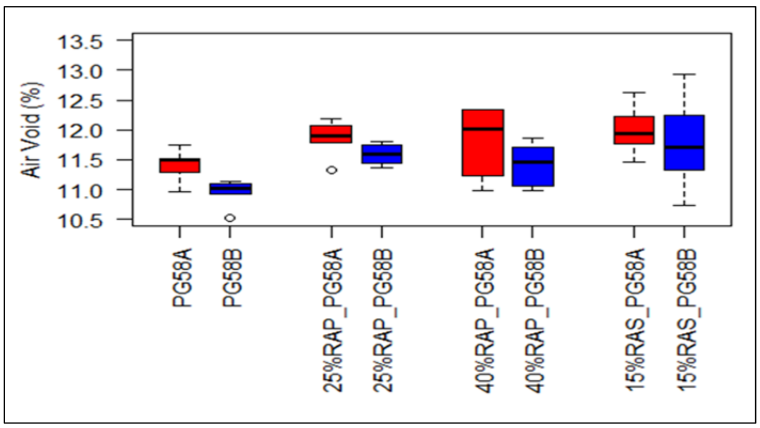


Figure 7.12: FAM mix specimen air-void contents for PG 58 mixes.

7.4.2 Amplitude Sweep Strain Test Results

The strain limits for linear viscoelastic (LVE) behavior of the FAM mixes, determined from the results of the amplitude sweep test, are shown in Figure 7.13 and Figure 7.14. The following observations were made:

- The LVE strain limits were influenced by virgin binder grade, binder source, and RAP or RAS content. The effect of binder source appeared to have a lesser influence on the results of the PG 64 binders compared to the PG 58 binders.
- The RAP binder appeared to mobilize and blend with the virgin binder during mixing, thereby changing the viscoelastic properties of the mix as shown by the reduction in the LVE strain limit.
- The LVE strain limit decreased with increasing RAP content, as expected. Replacing 25 percent of the virgin binder with aged binder from the RAP resulted in between 20 and 70 percent reduction in the LVE strain limit. Replacing 40 percent of the virgin binder resulted in between and 70 and 90 percent reduction.

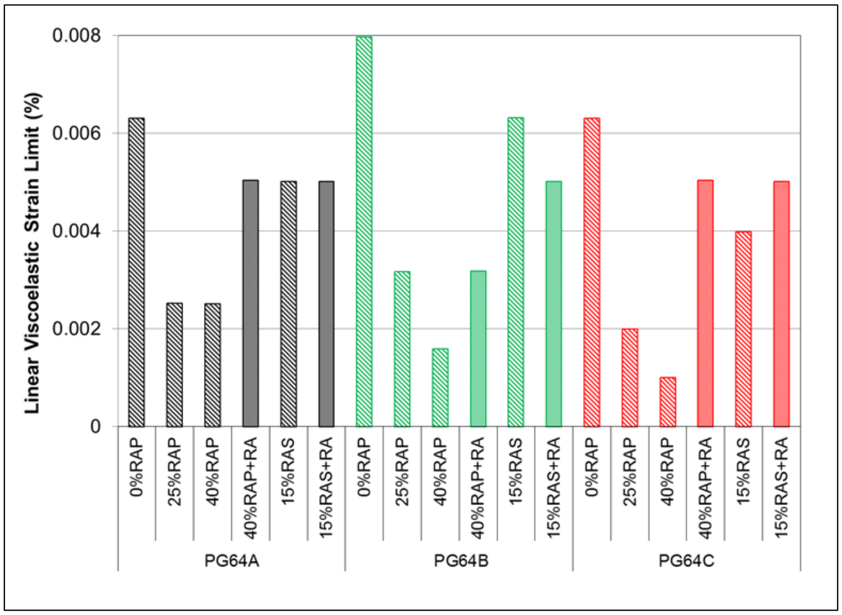


Figure 7.13: FAM mix specimen LVE range for mixes with PG 64 virgin binders.

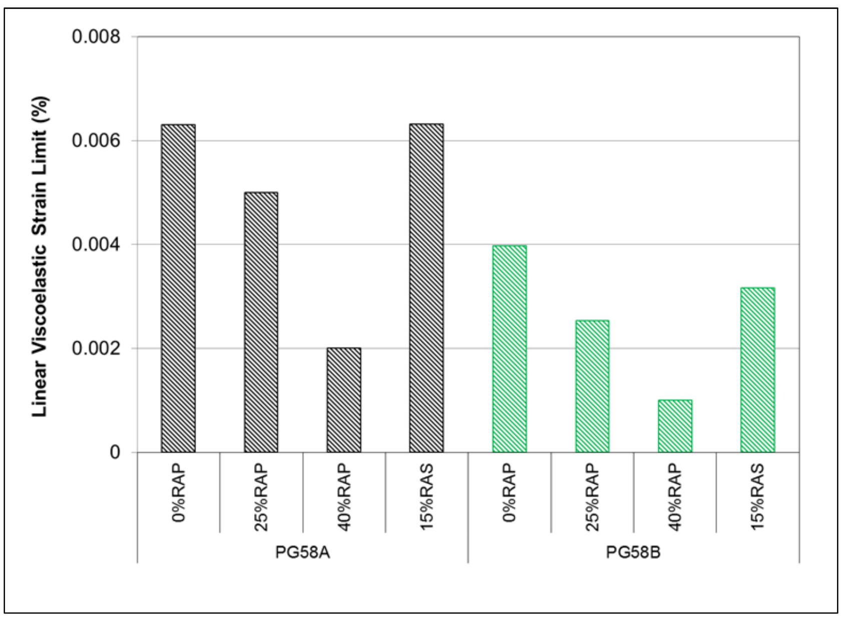


Figure 7.14: FAM mix specimen LVE range for mixes with PG 58 virgin binders.

- Reductions in LVE were also noted on the mixes containing RAS, with the change consistent with the percent binder replacement (15 percent).
- Rejuvenating agent had a notable influence on the mixes containing RAP, but only a marginal influence on the mixes containing RAS. This implies that the RAS binder might not have been effectively mobilized at the mix production temperatures used in this study and did not effectively blend with the virgin binder even when a rejuvenating agent was added. In this case, the observed reductions in LVE on the RAS mixes can probably be attributed to the effective lower virgin binder content, rather than the effect of the stiffer blended binder.

7.4.3 Frequency and Temperature Sweep Test Results

Sigmoidal function master curves were constructed using the measured shear modulus at various combinations of temperature and frequency. The estimated parameters of the sigmoidal function (Equation 4.1) and activation energy term in the Arrhenius shift factor (Equation 4.3) for the FAM mixes are provided in Table 7.4.

Table 7.4: Master Curve Parameters for FAM Mixes

Binder Replacement (%)	Mix ID[1]	Master Curve Parameters				
		δ	α	β	γ	E_a (J/mol)
0	PG 64A	0	3.76	-0.96	-0.52	164,414
	PG 64B	0	3.87	-0.93	-0.43	174,701
	PG 64C	0	3.63	-1.41	-0.62	172,503
	PG 58A	0	3.71	-0.79	-0.52	162,828
	PG 58B	0	3.74	-0.53	-0.51	158,722
25 (RAP)	25%RAP_PG 64A	0	4.17	-1.06	-0.39	176,435
	25%RAP_PG 64B	0	3.99	-1.19	-0.38	179,082
	25%RAP_PG 64C	0	4.10	-1.22	-0.45	179,341
	25%RAP_PG 58A	0	3.96	-1.07	-0.42	170,216
	25%RAP_PG 58B	0	3.99	-1.19	-0.38	165,906
40 (RAP)	40%RAP_PG 64A	0	4.21	-1.06	-0.34	180,414
	40%RAP_PG 64A+RA	0	3.84	-1.03	-0.46	166,743
	40%RAP_PG 64B	0	4.08	-1.14	-0.36	177,121
	40%RAP_PG 64B+RA	0	4.14	-0.86	-0.40	170,255
	40%RAP_PG 64C	0	4.60	-0.94	-0.35	173,209
	40%RAP_PG 64C+RA	0	3.95	-1.17	-0.49	167,399
	40%RAP_PG 58A	0	4.10	-1.15	-0.38	171,885
	40%RAP_PG 58B	0	4.29	-0.85	-0.36	169,832
15 (RAS)	15%RAS_PG 64A	0	3.74	-0.93	-0.45	170,253
	15%RAS_PG 64A+RA	0	3.80	-0.70	-0.48	162,233
	15%RAS_PG 64B	0	3.65	-0.88	-0.42	171,575
	15%RAS_PG 64B+jA	0	3.47	-0.87	-0.49	169,124
	15%RAS_PG 64C	0	3.77	-1.18	-0.53	166,295
	15%RAS_PG 64C+RA	0	3.98	-0.74	-0.54	160,332
	15%RAS_PG 58A	0	3.79	-0.88	-0.42	170,828
	15%RAS_PG 58B	0	3.82	-0.65	-0.44	161,161

[1] A, B, and C denote the source refinery. RA = Rejuvenating agent

The shear modulus master curves for the FAM mixes differentiated by binder replacement rate are shown in Figure 7.15 through Figure 7.18, and differentiated by binder source are shown in Figure 7.19 through Figure 7.23. Normalized master curves are included with the latter group of plots to better illustrate the effect of the RAP and RAS. The normalized curves were obtained by dividing the moduli of the FAM mixes with binder replacement by the corresponding moduli of the control mixes at each respective frequency.

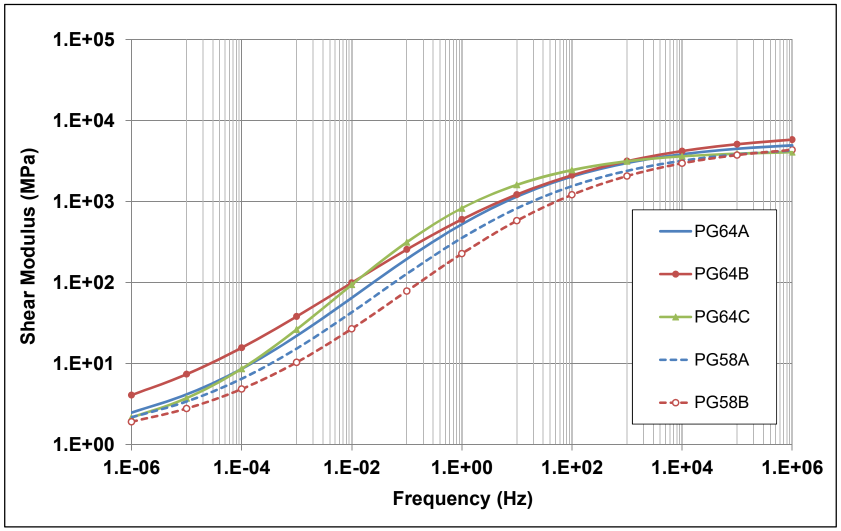


Figure 7.15: Master curves of control FAM mixes.

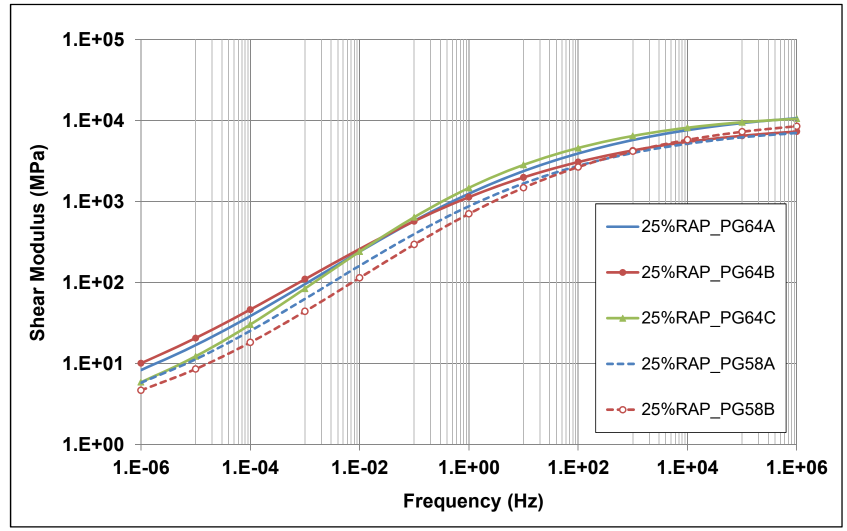


Figure 7.16: Master curves of FAM mixes with 25 percent RAP binder replacement.

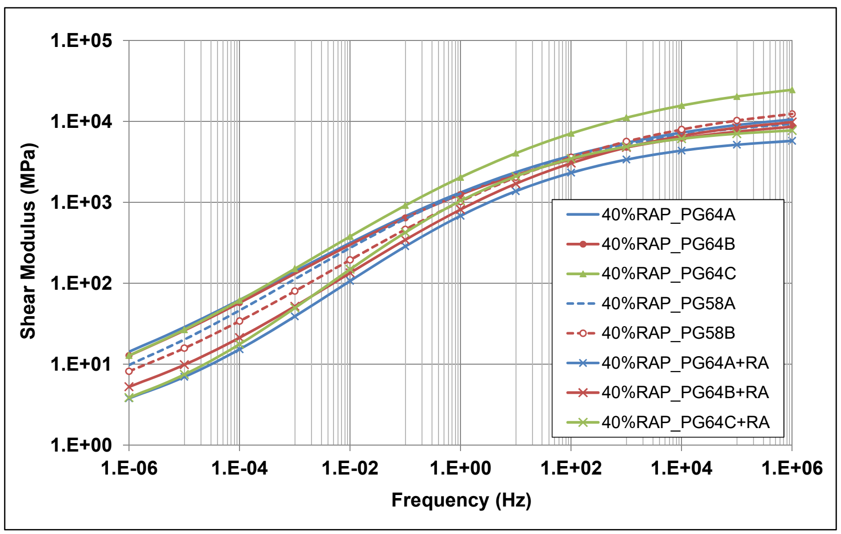


Figure 7.17: Master curves of FAM mixes with 40 percent RAP binder replacement.

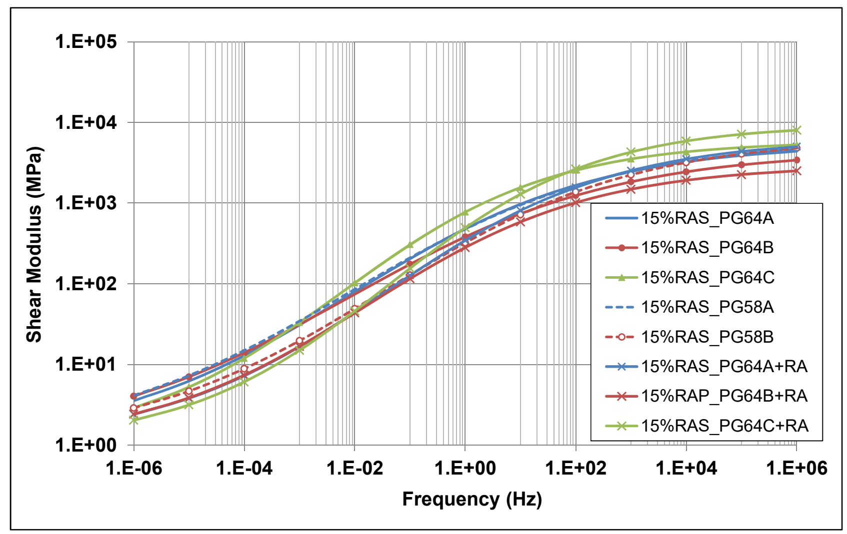


Figure 7.18: Master curves of FAM mixes with 15 percent RAS binder replacement.

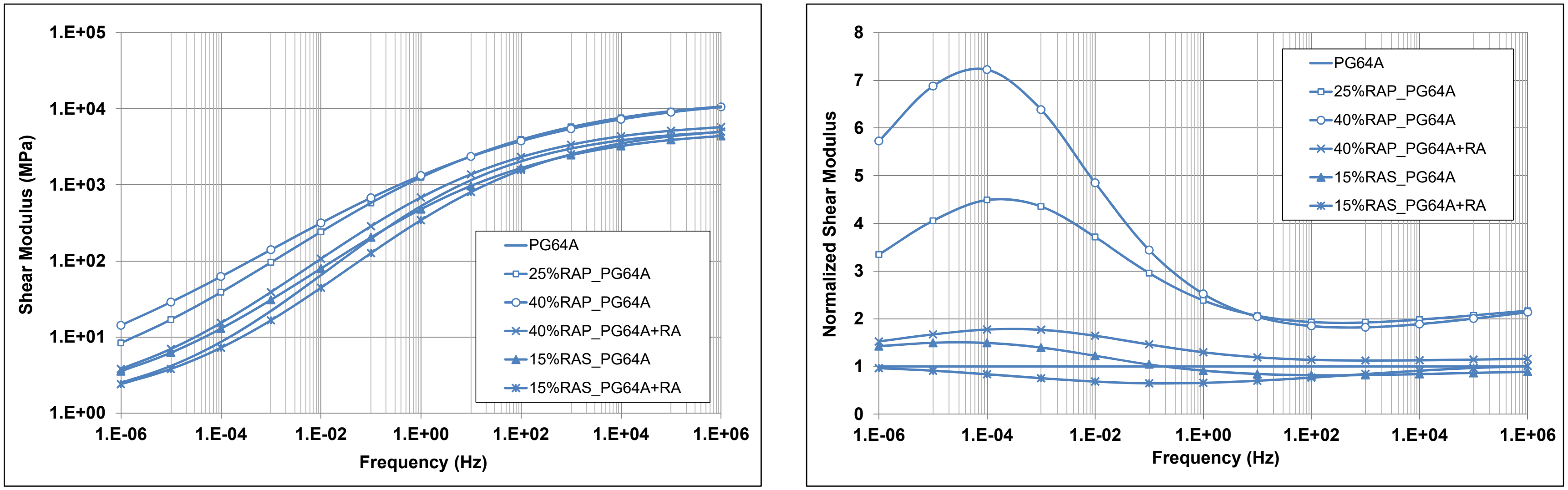


Figure 7.19: PG 64-16-A: Shear and normalized modulus master curves of FAM mixes.

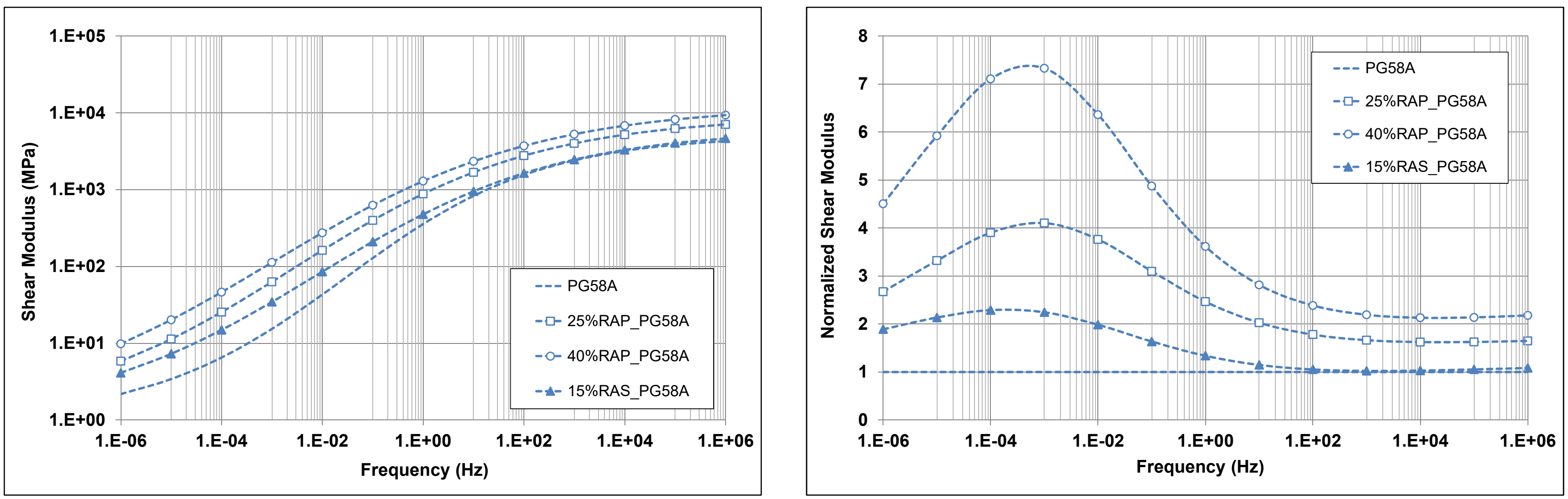
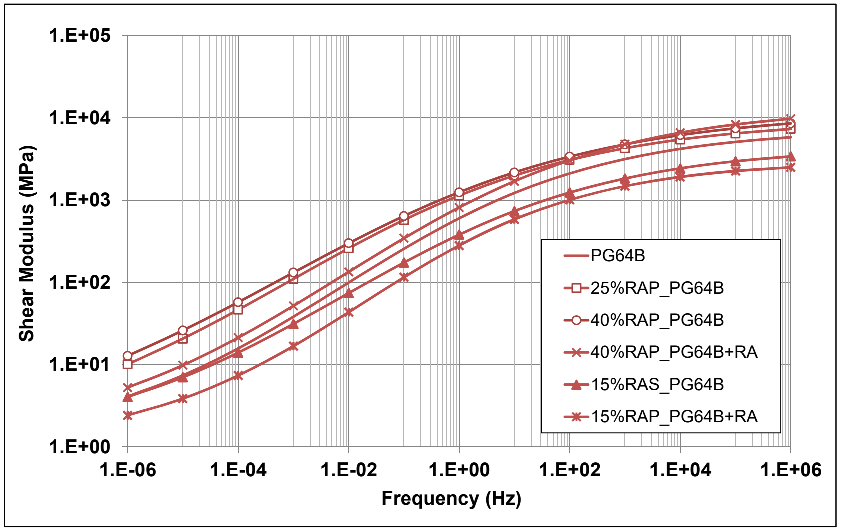


Figure 7.20: PG 58-22-A: Shear and normalized modulus master curves of FAM mixes.



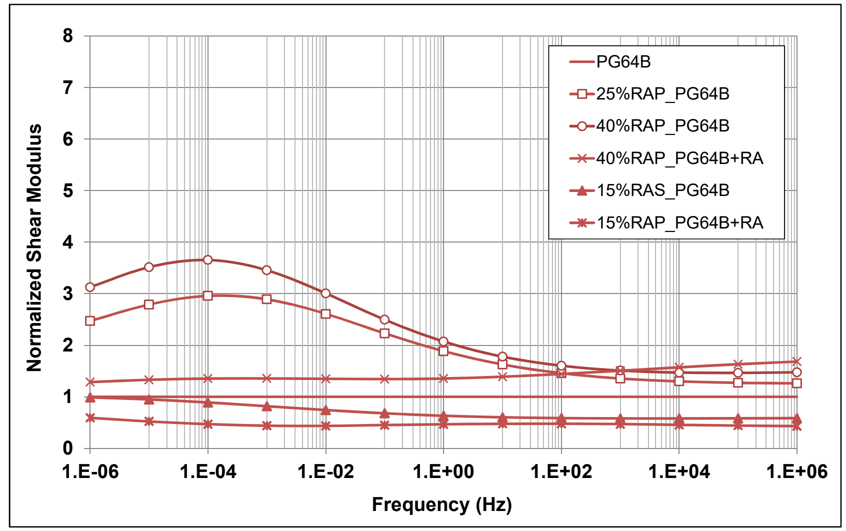
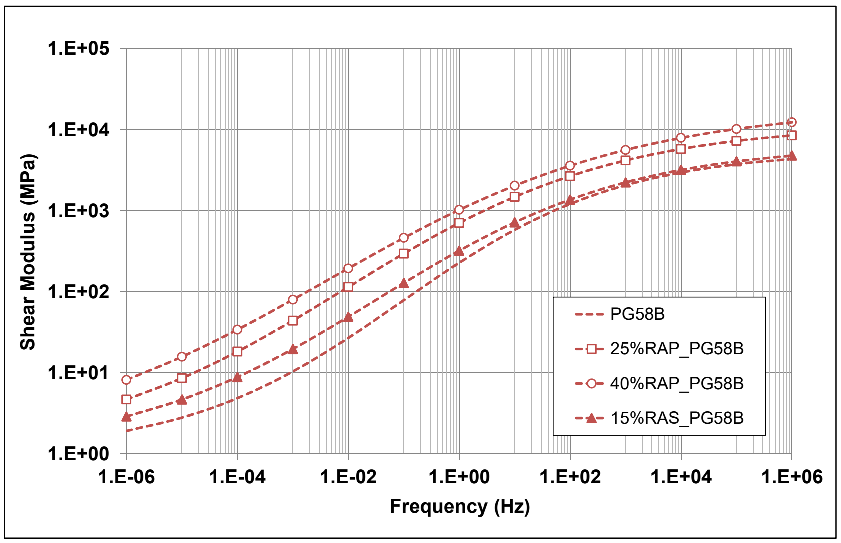


Figure 7.21: PG 64-16-B: Shear and normalized modulus master curves of FAM mixes.



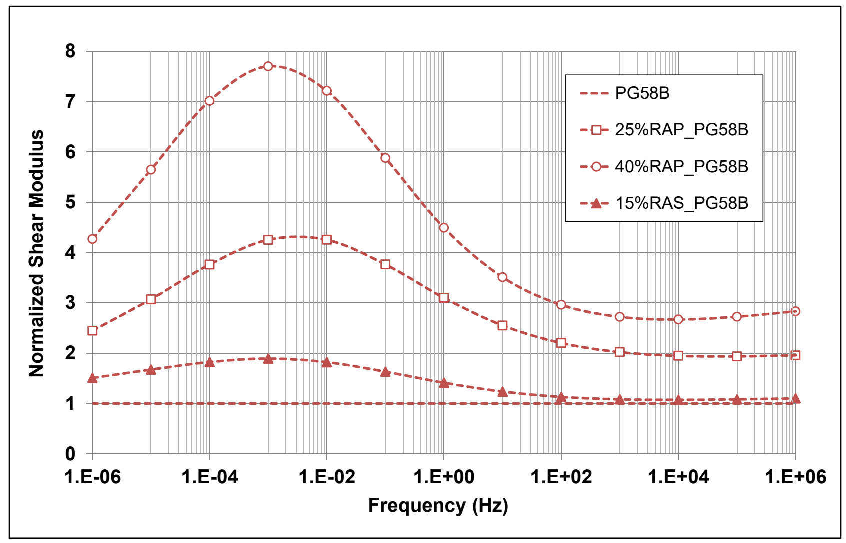


Figure 7.22: PG 58-22-B: Shear and normalized modulus master curves of FAM mixes.

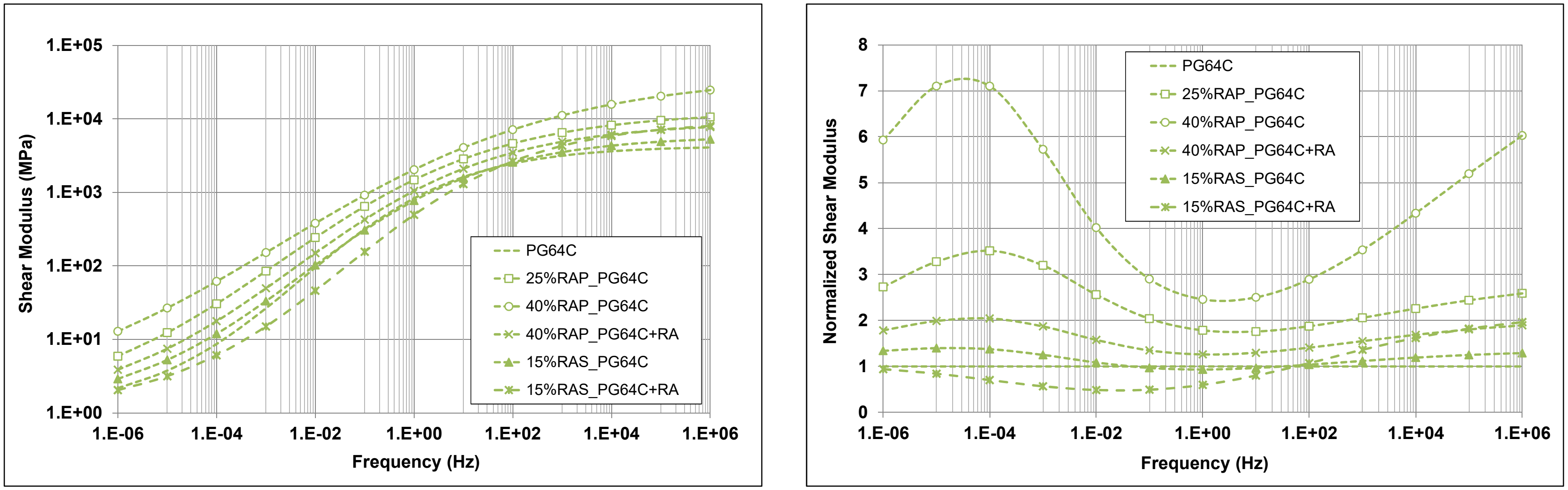


Figure 7.23: PG 64-16-C: Shear and normalized modulus master curves of FAM mixes.

The following observations were made:

- The differences in shear modulus between the different control mixes were consistent with the differences in binder grade. Minor differences were noted between the binders with the same grade but from different refineries; this was attributed to the slight differences between the air-void contents of each specimen and potentially to the binder (i.e., crude oil) source. Mixes produced with PG 58 binders were less stiff than the mixes produced with PG 64 binders, as expected.
- Adding RAP to the mix increased the stiffness of all the mixes at all frequencies, as expected. The mixes with 40 percent binder replacement were correspondingly stiffer than those with the 25 percent binder replacement, especially at the lower testing frequencies. The normalized plots show that 25 percent and 40 percent RAP binder replacement caused respective stiffness increases up to 4.5 times and 7.5 times that of the virgin binder. The variation between the different mixes and binder grades was less apparent when compared to the mixes without RAP binder replacement.
- Adding RAS to the mixes appeared to have little effect on the shear modulus, supporting the conclusion in Section 7.4.2 that the RAS binder did not fully blend with the virgin binder and that differences in performance between the virgin and blended binders are attributable to differences in the effective binder content and to air-void content (see Figure 7.11 and Figure 7.12).
- The shear moduli of the FAM mixes with rejuvenating agent were lower than those of the corresponding mixes without the rejuvenator, as expected. The effect of the rejuvenating agent was more noticeable in the mixes containing RAP than in the mixes containing RAS.

7.4.4 Analysis of Variance (ANOVA)

The ANOVA approach was used to statistically identify the significance level of influential factors, which include the virgin binder source and grade, percentage of RAP and RAS binder replacement, and use of a rejuvenating agent.

The ANOVA was performed using the complex shear modulus (G*) values at 0.001 Hz, 1.0 Hz, and 1,000 Hz frequencies at the reference temperature of 20°C as the dependent variables, and using binder source, binder grade, percent binder replacement, and use of the rejuvenating agent as the independent variables. The choice of $G^*_{0.001\ Hz}$, $G^*_{1\ Hz}$, and $G^*_{1,000\ Hz}$ as the dependent variables eliminated any potential bias caused by frequency and temperature.

The null hypothesis for the analysis was that the mean shear modulus was the same for all independent variable categories (i.e., the sample means of $G^*_{0.001\ Hz}$ would be equal regardless of the amount of binder replacement). A significance level of 0.01 was used in the analysis (i.e., any variable with a p-value larger than 0.01 was considered to be statistically insignificant).

The ANOVA results are listed in Table 7.5. Based on the p-values for the significant variables, the amount of reclaimed asphalt material used was the most significant factor influencing shear modulus at the three defined testing frequencies. The use of the rejuvenating agent was the next most significant factor. Asphalt binder source and binder grade had the least influence on the shear modulus of the evaluated FAM mixes at the selected frequencies. It should be noted that binders from just three California refineries were assessed in this study; additional testing on different binder grades sourced from a larger geographical selection of refineries may increase the significance of binder grade and source.

Table 7.5: ANOVA Results

Variable	Type	$G^*_{0.001\ Hz}$		$G^*_{1\ Hz}$		$G^*_{1,000\ Hz}$	
		F-value	p-value	F-value	p-value	F-value	p-value
% Binder Replacement	0% 25% RAP 40% RAP 15% RAS	135.789	2.52e-15	121.726	1.63e-14	47.579	1.3e-08
Binder Source	Refinery-A Refinery-B Refinery-C	0.217	0.806	15.859	5.77e-06	9.204	0.000434
Binder Grade	PG 64-16 PG 64-16 PG 58-22	2.920	0.064	1.043	0.361	0.174	0.841182
Rejuvenating Agent (RA) Effect	No RA With RA	91.360	1.68e-12	69.448	9.58e-11	15.319	0.000298

7.4.5 Comparing Asphalt Binder and FAM Mix Test Results

Figure 7.24 through Figure 7.26 show the relationship between the shear moduli of extracted asphalt binders and the corresponding shear moduli of the FAM mixes at frequencies of 0.1 Hz, 1.0 Hz, and 10 Hz (at the 20°C reference temperature), obtained from frequency sweep testing. These frequencies were selected since loading frequencies beyond this range are not typical on in-service pavements. Reasonable correlations (r^2 values) were observed between the asphalt binder stiffnesses and the FAM mix stiffnesses at these three frequencies. Discrepancies between the two measured stiffnesses may be an indication that complete blending of the virgin and reclaimed asphalt binders was not achieved in the FAM mix, but was forced during the chemical extraction and recovery. Although these preliminary results appear promising, only a limited number of tests were completed, and additional testing will be required before firm conclusions can be drawn.

7.5 Phase 1d Test Summary

Key observations and findings from this phase of the study include the following:

- Preliminary testing of FAM mixes indicated that this approach appears to be repeatable (consistent results on multiple specimens by the same operator) and reproducible (consistent results by different operators), and produces representative results for characterizing the performance-related properties of composite binder at binder replacement rates up to 40 percent and possibly higher. Although some experimentation with materials passing the 4.75 mm and 1.18 mm (#4 and #16) was carried out, use of materials passing the 2.36 mm (#8 sieve) is recommended to facilitate specimen preparation and to minimize variability in the results.

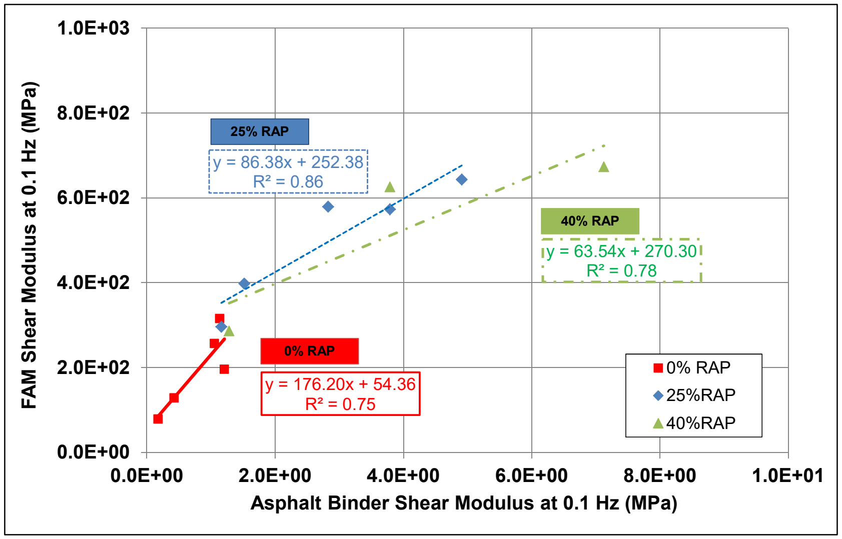


Figure 7.24: Comparison of asphalt binder and FAM mix shear modulus (0.1 Hz at 20°C).

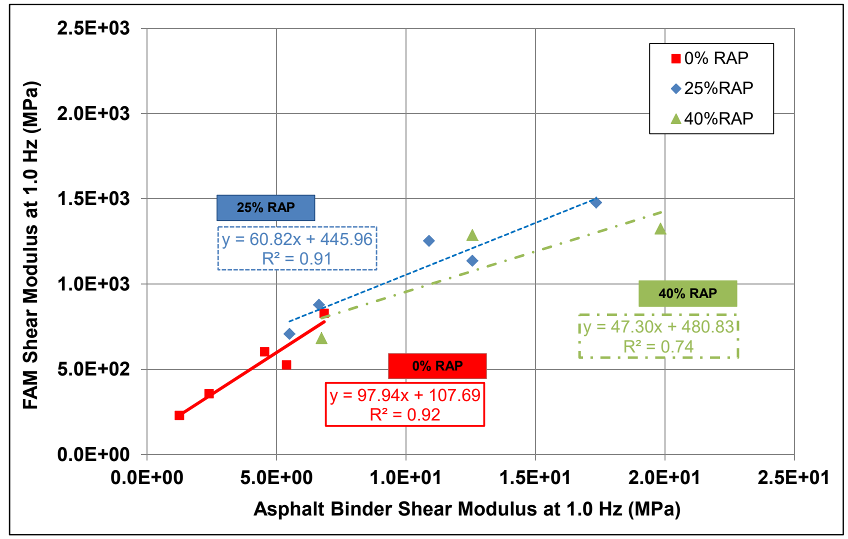


Figure 7.25: Comparison of asphalt binder and FAM mix shear modulus (1.0 Hz at 20°C).

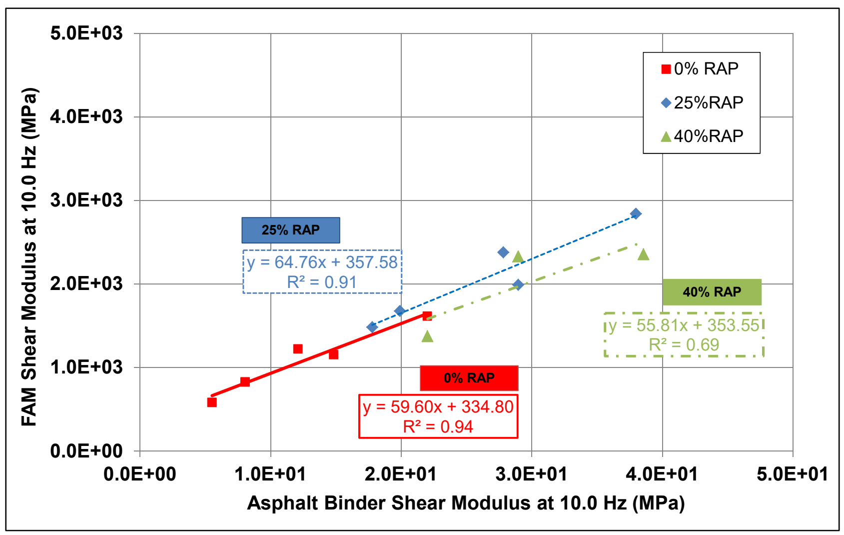


Figure 7.26: Comparison of asphalt binder and FAM mix shear modulus (10 Hz at 20°C).

- Asphalt binder extracted and recovered from RAS could not be tested due to its very high stiffness. The RAS binder was not sufficiently workable to mold specimens for testing in a DSR or in a BBR.
- The effect of RAP in increasing the stiffness of blended binders was dependent primarily on the asphalt binder grade and, to a lesser extent, by the source of asphalt binder.
- Statistical analyses of the test results indicate that asphalt binder grade and source, RAP and RAS content, and rejuvenating agent all had an influence on FAM mix stiffness, as expected. RAP and RAS content followed by the use of a rejuvenating agent had the most significant influence.
- The FAM mixes containing RAS showed similar stiffnesses to the corresponding control mixes (i.e., containing no reclaimed materials), suggesting that the RAS binder did not effectively blend with the virgin binder at the temperatures and mixing durations used in this study.
- The influence of rejuvenating agent on reducing the blended binder and FAM mix stiffnesses was evident. Additional testing (beyond the scope of this study) is required to evaluate the long-term behavior of mixes produced with rejuvenating agents to determine whether the benefits are limited to production and early life, or whether they extend through the design life of the layer.
- Reasonable correlations were observed between the stiffnesses of extracted blended binders and the stiffnesses of the corresponding FAM mixes at testing frequencies ranging from 0.1 Hz to 10 Hz. Discrepancies between the two measured stiffnesses may indicate that complete blending of the virgin and reclaimed asphalt binders was not achieved in the FAM mix, but was forced during the chemical extraction and recovery. The chemical solvent used in the extraction process also may have influenced the RAP binder properties. These factors warrant further investigation.

Based on the findings from this phase of the study, FAM mix testing is considered to be a potential appropriate alternative procedure to extraction and recovery for evaluating the properties of blended asphalt binder in mixes containing relatively high quantities of RAP and RAS. Further testing on a wider range of asphalt binder grades, asphalt binder sources, and RAP and RAS sources is recommended to confirm this conclusion and to develop models for relating binder properties determined from FAM mix testing to those determined from conventional performance-grade testing. Chemical analyses of blended binders may provide additional insights for interpreting test results and warrant further investigation.

Based on the results of testing the RAS materials, RAS was not included in further phases of this UCPRC study.

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8. PHASE 1e: MIX DESIGN AND SPECIMEN PREPARATION

8.1 Introduction

Phase 1e through Phase 1g of this study was conducted in parallel with a similar study undertaken for the FAA. Given the similarities of the studies, only one set of tests was completed, but the scope of the testing was expanded to maximize learning given the funding available. The FAA's Superpave mix design procedure (Advisory Circular P-401, updated 07/21/2014) was followed for the mix design. This procedure differs slightly from the Caltrans Superpave mix design specifications (Section 39) in terms of gradation and specimen preparation. These differences were not considered to be an issue in terms of understanding the effects of adding high RAP contents to new asphalt mixes and consequently a separate mix Caltrans mix design was considered unnecessary. RAP was sourced from California and two other states (New York and Alabama) to assess the effects of different aged-binder chemistry on the performance of the mixes.

8.2 Experiment Design

Table 8.1 summarizes the sampling and testing factorial for the materials assessed in Phase 1e through Phase 1g of this UCPRC study. This factorial equates to a total of six different mixes. Note that mixes containing RAS were not tested based on the concerns identified during preliminary testing in Phase 1c (see Section 7.4).

Table 8.1: Experimental Design Factors and Factorial Levels for Phase 1e through Phase 1g

Factor	Factorial Level	Details
Asphalt Binder Grade	3	PG 64-22 PG 58-28 PG 76-22 polymer-modified
Virgin Aggregate Type	1	Granitic
RAP Source	3	New York (NY) California (CA) Alabama (AL)
RAP Content (by binder replacement)	3	0% (all three binders tested) 25% (2 binders [PG 64-22, PG 76-22 PM] and 3 RAP sources) 40% (1 [PG 58-28] and 1 RAP source [NY])
Anti-stripping Agent (type and content)	1	Amine-based chemical (0.75% by weight of virgin binder used in the mix)

8.3 Mix Design

The Superpave mix design procedure covers four primary steps, namely:

1. Material selection (aggregate and asphalt binder)

2. Selection of aggregate structure
3. Determination of optimum binder content
4. Controlling for asphalt mix moisture susceptibility

8.3.1 Material Selection

<u>Virgin Aggregate</u>

Granitic aggregates meeting the requirements specified in both the Caltrans Section 39 and FAA P-401 specifications (as tested by the aggregate supplier) were sampled from four stockpiles at an aggregate quarry near Watsonville, California. The aggregate gradations for each stockpile (tested by the UCPRC) are shown in Table 8.2. Oven-dried aggregates were sieved to single sizes (ranging from 19 mm [3/4 in.] to 0.075 mm [#200]). Appropriate quantities of aggregates per size were batched according to the mix design gradations (see Section 8.3.2) to obtain the specified mix volumetric properties.

Table 8.2: Phase 1e: Gradation, Specific Gravity, and Absorption of Virgin Aggregate

Sieve Size		Stockpiles (% Passing)			
mm	in./mesh	3/4 x 1/2	1/2 x #4	1/4 x #10	Sand
25.4	1	100	100	100	100
19.0	3/4	85	100	100	100
12.5	1/2	27	95	100	100
9.50	3/8	10	61	100	100
4.75	#4	4	6	64	100
2.36	#8	3	4	8	86
1.19	#16	0	0	4	59
0.60	#30	0	0	3	38
0.30	#50	0	0	0	20
0.15	#100	0	0	0	9
0.075	#200	0	0	2	5

<u>Asphalt Binders</u>

The FAA P-401 specification states that the initial performance grade (PG) of asphalt binder must be consistent with that specified by the local state department of transportation for Interstate highway projects in the vicinity of the airport. Adjustment of the initial grade (bumping) is required as listed in Table 8.3. The low PG grade of the binder must not be higher (warmer) than -22°C since this may increase the chance of block cracking on airfield pavements. The elastic recovery must be higher than 70 percent for polymer-modified binders.

Table 8.3: FAA Guidance for Binder Performance Grade Adjustment

Aircraft Gross Weight	High Temperature Adjustment to Binder Grade
	All Pavement Types
≤ 12,500 lbs (5,670 kg)	--
< 100,000 lbs (45,360 kg)	1 Grade
≥ 100,000 lbs (45,360 kg)	2 Grade

Using these guidelines, two unmodified asphalt binders (PG 64-22 and PG 58-28) and one polymer-modified binder (PG 76-22 PM) were used in this phase of the UCPRC study. All binder grades were supplied by one local refinery in northern California (Refinery-A in Phase 1a through Phase 1d). The PG 58-28 binder was the same as that used for the base binder in the production of the polymer-modified binder. The high, intermediate, and low performance grading temperatures for the three binders were determined in accordance with AASHTO M 320 and the results are shown in Table 8.4.

Table 8.4: Performance Grading Results of Asphalt Binder

Critical Temperature	Aging Condition	Test Parameter	PG 58-28	PG 64-22	PG 76-22 PM
High High	Unaged RTFO-aged	G*/sinδ ≥ 1.00 kPa G*/sinδ ≥ 2.20 kPa	59.7 60.4	66.5 67.8	80.1 82.5
Intermediate	RTFO-aged	G* x sinδ ≤ 5,000 kPa	16.5	22.7	14.3
Low	RTFO- and PAV-aged	S(60) ≤ 300 MPa[1] m-value ≥ 0.30[1]	184 (at -18°C) 0.35 (at -18°C)	176 (at -12°C) 0.34 (at -12°C)	54 (at -12°C) 0.43 (at -12°C)

[1] Values correspond to testing performed at 10°C warmer than PG grade temperature.

Anti-Stripping Agent

A commercial amine-based liquid anti-stripping agent meeting both the Caltrans Section 39 and FAA P-401 specifications was used in this study to meet moisture resistance specifications.

Reclaimed Asphalt Pavement

Caltrans specifications currently allow up to 25 percent binder replacement from RAP in the upper 0.2 ft (60 mm) of new conventional asphalt mixes and up to 40 percent in layers below this. RAP is currently not allowed in asphalt rubber or open-graded mixes. In Caltrans Type-A mixes with RAP binder replacement rates less than or equal to 25 percent of the specified optimum binder content, a contractor may request that the PG grade (both upper and lower temperature limits) be reduced by 6°C from the specified grade. In mixes with a binder replacement greater than 25 percent, this 6°C grade bump is mandatory. RAS is currently not permitted in the Caltrans specifications.

The current FAA P-401 specification does not allow the use of RAP or RAS in HMA placed in surface layers on runways, taxiways, and aprons. It is, however, permitted in mixes used in lower layers or shoulders. These mixes may contain up to 30 percent RAP by weight of the mix, but the mix must still meet the requirements specified for HMA with no reclaimed material. RAP must have a consistent gradation with a maximum size less than 38 mm (1.5 in.). Mixes containing more than 20 percent RAP by weight of the mix must use a one-grade softer binder (both high and low PG temperatures).

RAP materials were obtained from sources in three different states, California, New York, and Alabama, and these are referred to as CA, NY, and AL respectively in the test results in this report. This diversity of location ensured that a range of RAP binders, and specifically binder chemistries would be assessed, allowing insights into the effect that these might have on new mix performance. The New York RAP materials were sampled at two different times (April 2015 and December 2015) from the same source. The majority of the mixes containing New York RAP were made with materials sampled in April 2015. The Alabama RAP was fractionated into coarse (passing the 9.5 mm [3/8 in.] sieve and retained on the 2.36 mm [# 8] sieve) and fine (passing the 2.36 mm [# 8] sieve) sizes.

The gradation and asphalt binder content of the RAP aggregates were determined using both extraction and recovery (AASHTO T 164 and ASTM D 1856) and ignition oven (AASHTO T 308) tests. The gradations (AASHTO T 30), specific gravities, and absorption for the fine and coarse aggregates (AASHTO T 85 and AASHTO T 84) were determined for both recovered and burned aggregates. The New York RAP materials sampled in December 2015 were tested using extraction and recovery only. Gradations and binder contents for the recovered and the burned aggregates are listed in Table 8.5 and Table 8.6, respectively. Gradations are illustrated in Figure 8.1 to Figure 8.3.

For all three RAP sources, the burned aggregates were slightly finer than the recovered aggregates, as expected, since the ignition oven can result in degradation of the aggregates, which generates more fine material. The New York RAP had a finer gradation than the California RAP. Based on the New York and California RAP gradations, the two Alabama RAP samples were combined into a single sample in a 70 percent coarse to 30 percent fine RAP ratio. Gradations of the three RAP sources are compared in Figure 8.4, which shows that a range of particle size distributions was achieved. These ranges were considered to be representative of typical variability from different RAP sources.

Table 8.5: RAP Gradations and Binder Contents (Chemical Extraction)

Gradation (% Passing)						
Sieve Size		**New York**		**California**	**Alabama**	
mm	**in./mesh**	**Apr. 2015**	**Dec. 2015**		**Retained #8**	**Passing #8**
25.4	1	100	100	100	100	100
19.0	3/4	100	100	100	100	100
12.5	1/2	100	100	100	100	100
9.50	3/8	100	100	96	93	100
4.75	#4	90	89	74	55	100
2.36	#8	63	65	56	22	100
1.19	#16	47	51	43	16	82
0.60	#30	35	39	33	12	57
0.30	#50	23	25	22	7	32
0.15	#100	14	16	13	5	17
0.075	#200	9	11	8	3	9
Asphalt Binder Content (%)						
Total mix		6.30	5.62	4.51	2.73	6.23
Mass of dry aggregate		6.73	5.96	4.57	2.81	6.64

Table 8.6: RAP Gradations and Binder Contents (Ignition Oven)

Gradation (% Passing)					
Sieve Size		New York Apr. 2015	California	Alabama	
mm	in./mesh			Retained #8	Passing #8
25.4	1	100	100	100	100
19.0	3/4	100	100	100	100
12.5	1/2	100	100	99	100
9.50	3/8	100	97	93	100
4.75	#4	91	74	54	100
2.36	#8	63	55	22	100
1.19	#16	49	44	17	83
0.60	#30	37	34	13	60
0.30	#50	25	24	8	36
0.15	#100	17	18	6	23
0.075	#200	12	12	4	15
Asphalt Binder Content (%)					
Total mix		7.19	5.75	2.85	6.89
Mass of dry aggregate		7.75	6.10	2.93	7.40

The binder contents in the RAP are illustrated in Figure 8.5. The ignition oven method resulted in higher binder contents than those obtained by solvent extraction for all the RAP sources. This was attributed to the chemical solvent's inability to extract all the binder in the RAP *(36,46)*. The New York RAP had the highest binder content followed by the California RAP and then the Alabama RAP.

The bulk specific gravity and the absorption of burned and recovered RAP aggregates are shown in Figure 8.6 and Figure 8.7, respectively. Bulk specific gravity was highest for the New York RAP and lowest for the Alabama RAP. Burned aggregates generally had higher bulk specific gravities than extracted aggregates (coarse Alabama RAP was the exception). This was attributed to the different gradations. Extracted aggregates generally had higher absorptions than burned aggregates (coarse Alabama RAP was again the exception).

8.3.2 Selection of Aggregate Structure

The aggregate gradation for airfield mix designs must be selected based on the following three FAA P-401 gradations, with maximum aggregate size not permitted to be greater than one-quarter of the lift thickness:

- Gradation-1: a 3/4 in. (19 mm), 100 percent passing 1 in. (25 mm) coarser gradation mix, which is typically used in thicker lifts of asphalt concrete.
- Gradation-2: a 1/2 in. (12.5 mm), 100 percent passing 3/4 in. (19 mm) mix typically used in thinner lifts or where a smoother, less permeable mix is required.
- Gradation-3: a 3/8 in. (9.5 mm), 100 percent passing 1/2 in. (12.5 mm), which can only be used for leveling course, airfield shoulders, and airfield roadways.

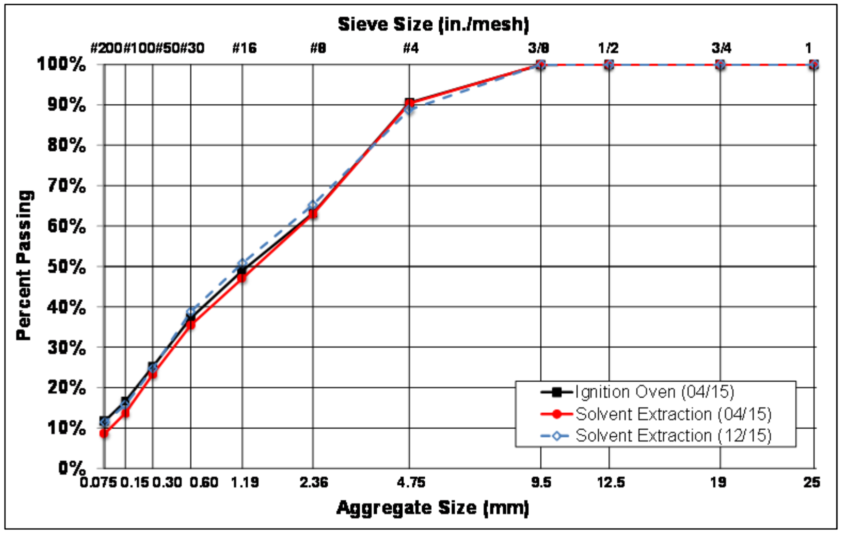


Figure 8.1: Gradation of New York RAP.

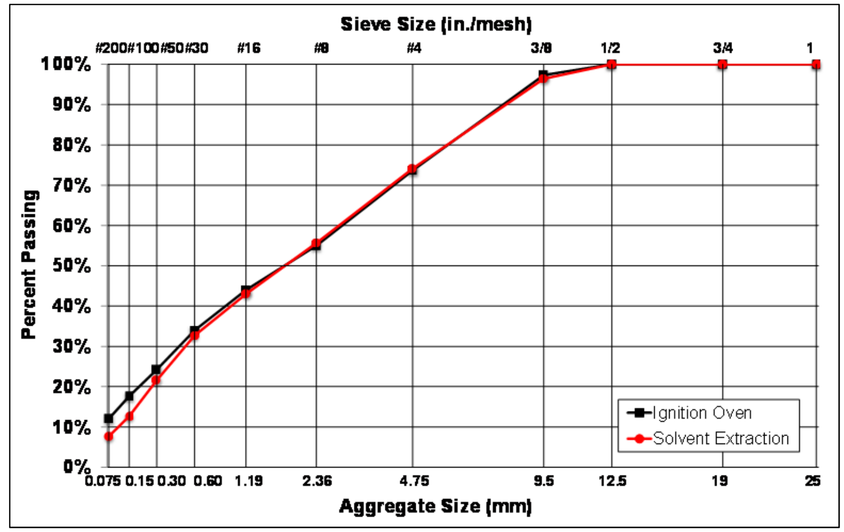


Figure 8.2: Gradation of California RAP.

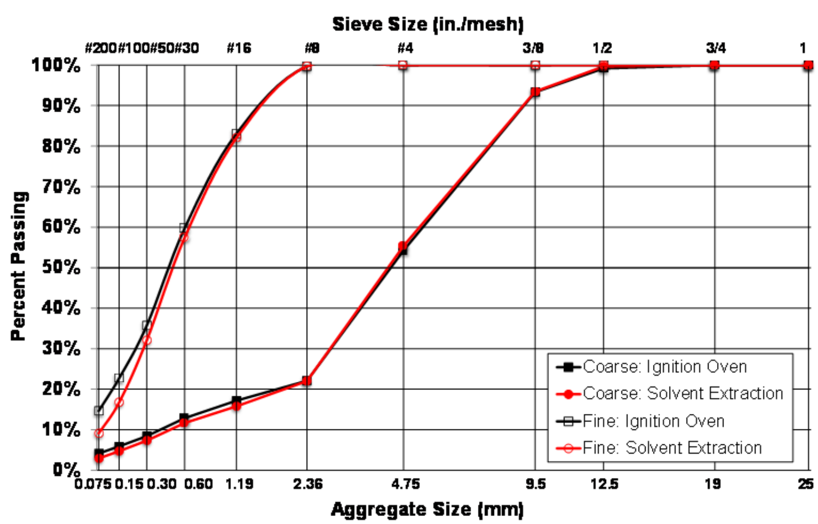


Figure 8.3: Gradation of Alabama RAP.

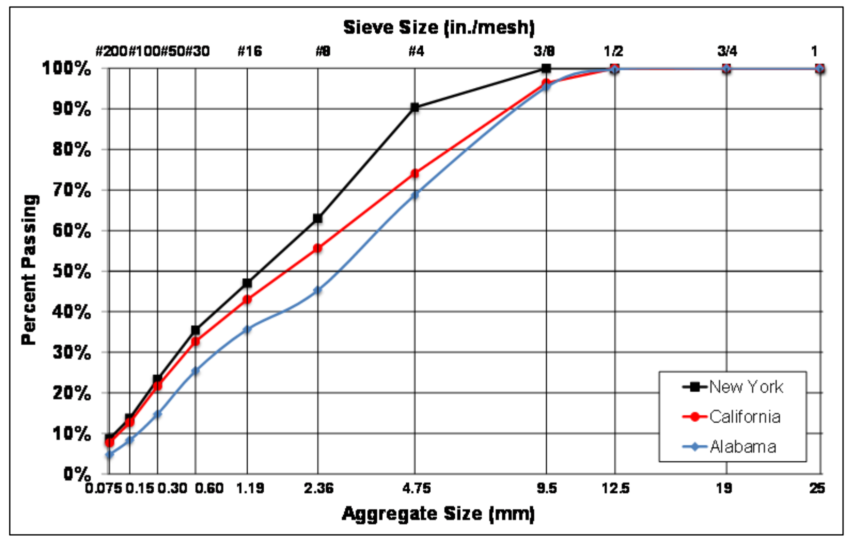


Figure 8.4: Comparison of RAP aggregate gradations by solvent extraction.

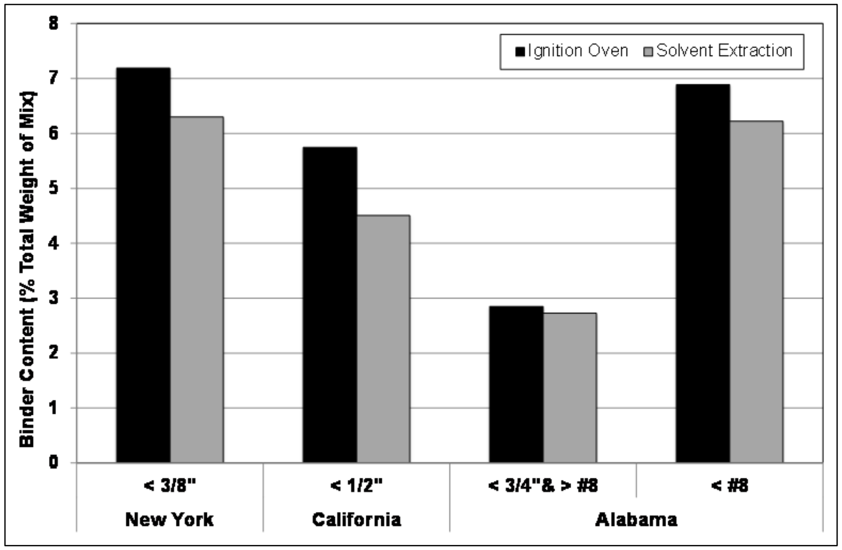


Figure 8.5: RAP asphalt binder contents.

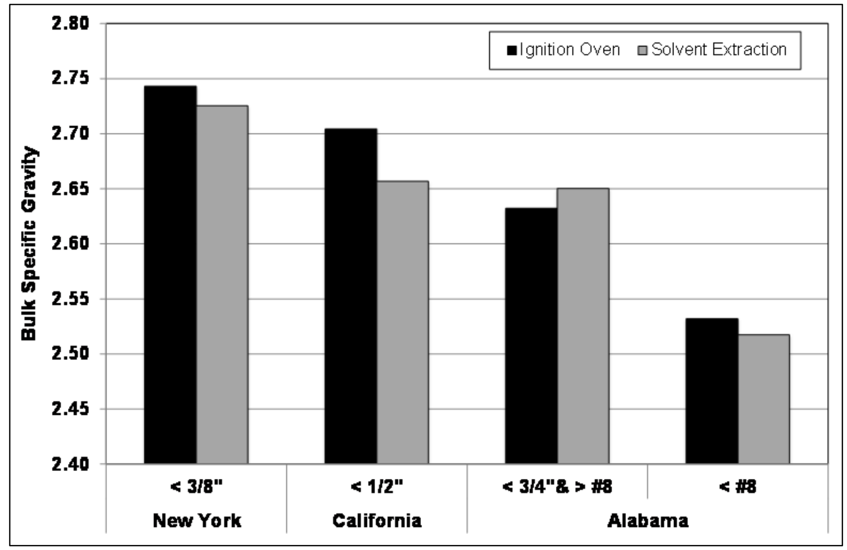


Figure 8.6: Bulk specific gravity of RAP aggregate.

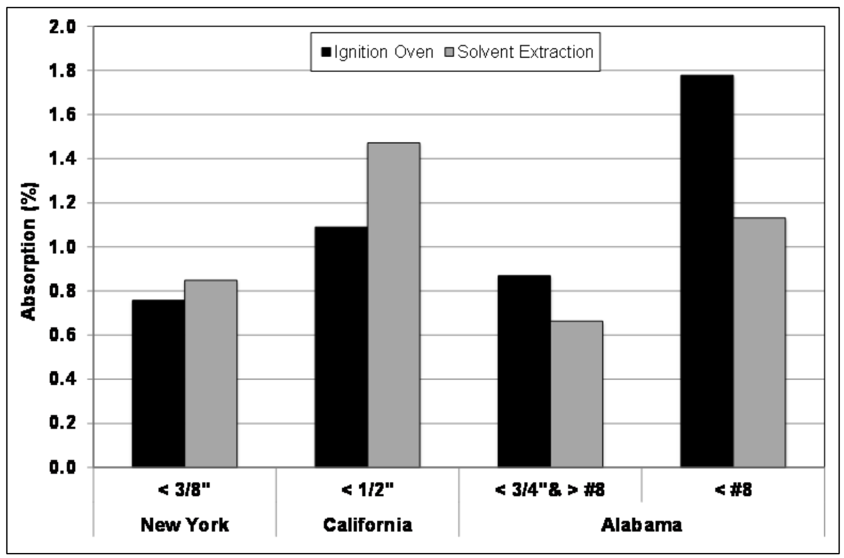


Figure 8.7: Absorption of RAP aggregate.

Gradation-1 was selected for this study. The FAA P-401 and Caltrans Section 39 gradations for 3/4 in. mixes are similar and are shown in Table 8.7. A number of trial formulations were evaluated to select an appropriate gradation that met the specified individual size ranges as well as the volumetric requirements, primarily voids in mineral aggregate (VMA).

Table 8.7: Caltrans and FAA Aggregate Gradation Specifications for 3/4 in. Asphalt Mixes

Sieve Size		Gradation (% Passing)	
mm	**in./mesh**	**Caltrans**	**FAA**
25.4	1	100	100
19.0	3/4	90-98	76-98
12.5	1/2	70-90	66-86
9.50	3/8	-	57-77
4.75	#4	42-58	40-60
2.36	#8	29-43	26-46
1.19	#16	-	17-37
0.60	#30	-	11-27
0.30	#50	10-23	7-19
0.15	#100	-	6-16
0.075	#200	2-7	3-6

Four trial gradations of the virgin aggregate were assessed, as shown in Table 8.8 and in Figure 8.8. All gradations were selected to fall within the Caltrans and FAA P-401 specified gradation limits for 3/4 in. mixes.

Table 8.8: Virgin Aggregate Trial Gradations for Mix Design

Sieve Size		Gradation (% Passing)			
mm	**in./mesh**	**Trial #1**	**Trial #2**	**Trial #3**	**Trial #4**
25.4	1	100	100	100	100
19.0	3/4	87	96	96	96
12.5	1/2	76	84	84	84
9.50	3/8	67	75	75	75
4.75	#4	50	55	48	55
2.36	#8	36	40	29	35
1.19	#16	27	28	18	20
0.60	#30	19	19	12	12
0.30	#50	13	11	8	7
0.15	#100	11	7	6	6
0.075	#200	5	4	3	3

8.3.3 Determination of Optimum Binder Content

The determination of optimum binder content in Caltrans mixes must follow the *Superpave Mix Design: Superpave Series No. 2* manual by the Asphalt Institute *(80)*. Volumetric requirements for 3/4 in. Type-A mixes are summarized in Table 8.9. The current FAA P-401 specification requires that the optimum asphalt binder must be determined by preparing asphalt mixes at different binder contents and then compacting them to the number of gyrations specified based on the gross weight of aircraft and tire pressure. The heaviest aircraft traffic was selected for this UCPRC study and therefore trial mixes were compacted to 75 gyrations. Volumetric requirements for the FAA 3/4 in. mix are also summarized in Table 8.9.

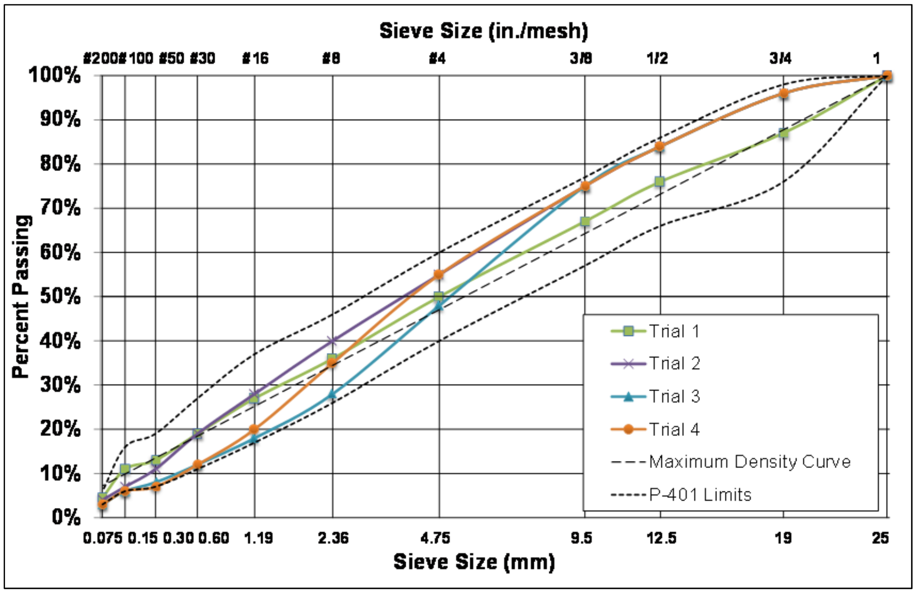


Figure 8.8: Gradation curves for trial aggregate structures.

Table 8.9: Volumetric Requirements for Caltrans and FAA 3/4 in. Mix Design

Parameter	Specification Requirements	
	Caltrans	FAA
Number of gyrations (N_{Design})	85	75
Air-void content (N_{Design}) (%)	4.0	3.5
Voids in mineral aggregate (VMA) (%)	13.5 – 16.5	>14
Dust proportion (DP)	0.6 – 1.3	Not required
Voids filled with asphalt (VFA) (%)	Not required	Not required

Although three grades of asphalt binder were used in this UCPRC study, the control mix design was only conducted on mixes prepared with PG 64-22 binder. It was assumed that the binder grade would not significantly change the mix volumetrics, given that the binder viscosities of the three asphalt binders were relatively similar at the mixing and compaction temperatures.

Asphalt mixes were prepared at an estimated optimum binder content of five percent. After short-term aging of the loose mix for two hours at the compaction temperature (AASHTO R 30), the mixes were compacted to 75 gyrations at 600 kPa (87 psi) pressure using a Superpave gyratory compactor (AASHTO T 312). The air-void content and voids in mineral aggregate (VMA) of the compacted specimens were calculated based on the volumetric equations provided in AASHTO R 35, but modified for a design air-void content of 3.5 percent, as specified in FAA P-401 (the Caltrans design air-void content is 4.0 percent). Table 8.10 shows the measured and estimated volumetrics at the design air-void content. Based on the estimated VMA values, Trial Gradation #3 (Figure 8.9) was selected as the design aggregate structure. Table 8.11 provides the bulk specific gravity (dry), apparent specific gravity, and absorption for the fine and coarse fractions of the selected gradation.

Table 8.10: Volumetrics of Mixes Prepared with Different Gradations

Gradation	Binder Content (%)	Air-Void Content (%)	VMA (%)	Estimated VMA at 3.5% Air Voids
Trial #1	5	1.1	10.2	10.3
Trial #2	5	3.5	12.6	12.5
Trial #3	**5**	**6.1**	**14.4**	**14.6**
Trial #4	5	6.6	15.3	15.5

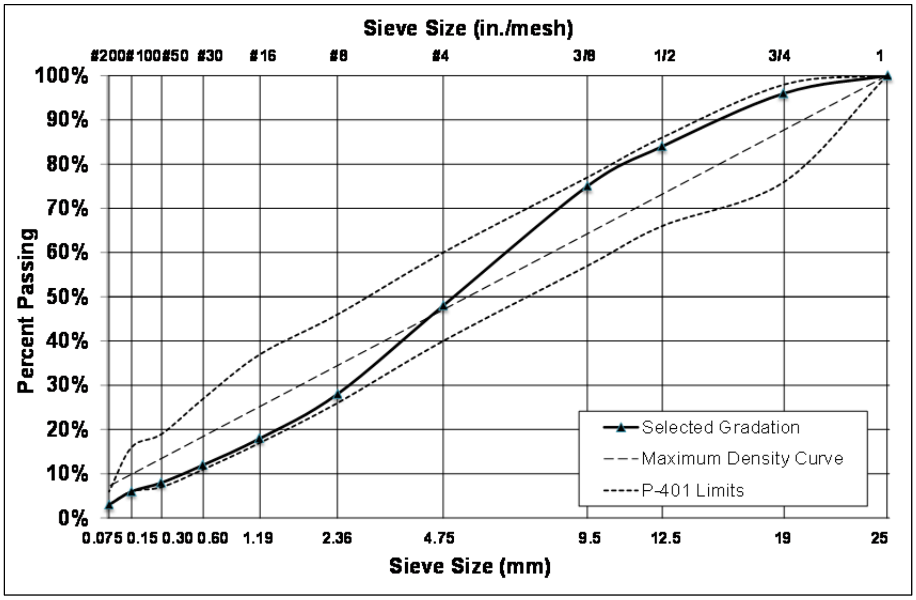
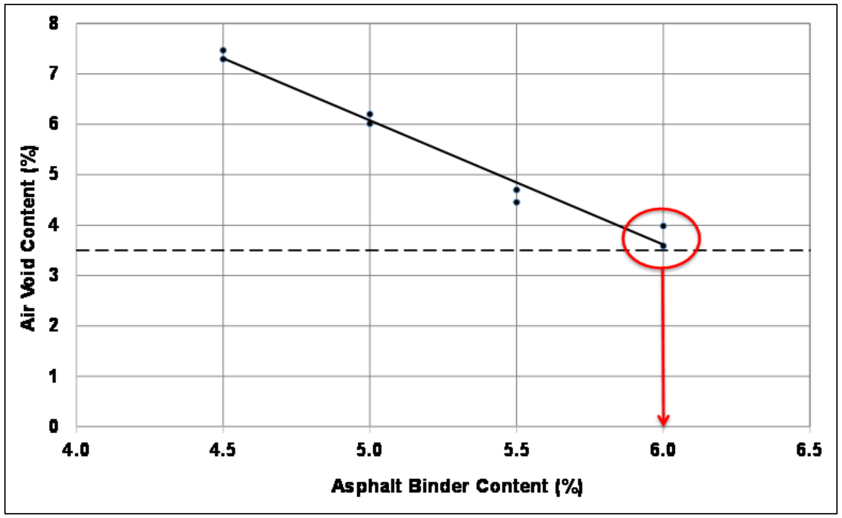


Figure 8.9: Gradation curve for selected aggregate structure.

Table 8.11: Specific Gravity and Absorption Values in the Selected Gradation

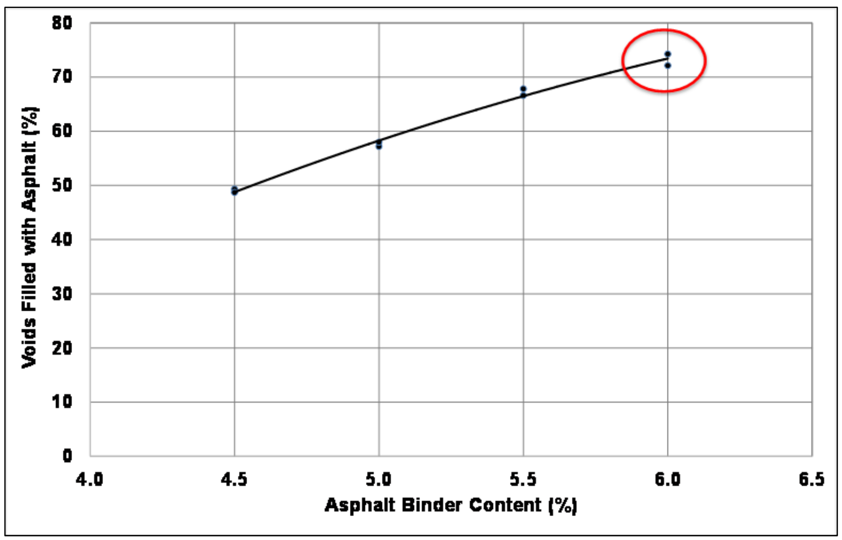
Property	Fine Aggregate	Coarse Aggregate
Bulk specific gravity (Dry)	2.690	2.720
Bulk specific gravity (SSD[1])	2.743	2.763
Apparent specific gravity	2.841	2.843
Absorption (%)	1.988	1.592
[1] Saturated surface-dry		

Asphalt mixes were then prepared at four different binder contents (4.5, 5.0, 5.5, and 6.0 percent) to determine the optimum binder content for the selected aggregate gradation (i.e., Trial #3). The loose mixes were aged for two hours at the compaction temperature followed by compaction with 75 gyrations. Bulk specific gravity, VMA, voids filled with asphalt (VFA), and dust proportion values were calculated for each mix prepared at the different binder contents. Although the Caltrans and FAA P-401 specifications do not have limits for VFA and the FAA does not have specifications for dust proportion, they are useful for understanding mix volumetrics and were considered in all mix volumetric calculations. Figure 8.10 shows the relationship between binder content and volumetrics.

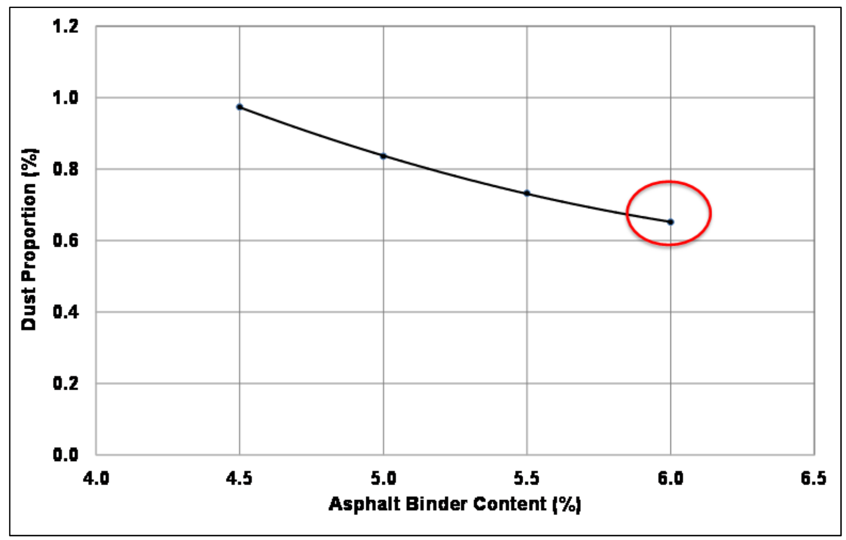


Asphalt binder content vs. air-void content

Asphalt binder content vs. VMA



Asphalt binder content vs. VFA



Asphalt binder content vs. dust proportion

Figure 8.10: Changes in mix volumetrics with different asphalt binder contents.

The optimum binder content to achieve the FAA P-401 design 3.5 percent air-void content was 6.0 percent. VMA, VFA, and dust proportion at 6.0 percent binder content were verified and the results are listed in Table 8.12. This mix was considered to have similar volumetric properties to a mix produced following the Caltrans mix design procedure.

Table 8.12: Asphalt Mix Volumetrics at Optimum Binder Content

Mix Volumetrics	Values	Meets Specifications	
		Caltrans	FAA
Asphalt binder content (%)	6.0	N/A	N/A
Air-void content (%)	3.5	No	Yes
Voids in mineral aggregates (%)	14.1	Yes	Yes
Dust proportion	0.65	Yes	N/A
Voids filled with asphalt (%)	74.0	N/A	N/A

8.3.4 Controlling for Mix Moisture Susceptibility

The Caltrans and FAA specifications for moisture resistance are different (Table 8.13). The FAA P-401 specification requires that the tensile strength ratio (TSR) of the asphalt mix (based on AASHTO T 283) shall not be less than 75 when tested at a 70 to 80 percent saturation level. A liquid anti-stripping agent can be used to remedy moisture susceptibility problems.

Table 8.13: Moisture Resistance Requirements for Caltrans and FAA Mix Design

Parameter	Specification Requirements	
	Caltrans	FAA
Moisture susceptibility, dry strength (psi)	100	Not required
Moisture susceptibility, wet strength (psi)	70	Not required
Tensile strength ratio	Not required	75
HWTT (min. number of passes to 0.5 in. rut)		Not required
PG 58	10,000	-
PG 64	15,000	-
PG 70	20,000	-
PG 76	25,000	-
HWTT (min. number of passes to inflection point)		Not required
PG 58	10,000	-
PG 64	10,000	-
PG 70	12,500	-
PG 76	15,000	-

TSR tests were conducted on prepared specimens to check moisture sensitivity. The results are shown in Figure 8.11 and indicate that the dry and wet strengths of the mix were 72 psi and 56 psi (386 kPa and 494 kPa) respectively, and well below the Caltrans specification requirements. The TSR was 78, which was close to the FAA P-401 minimum limit of 75. Since the moisture sensitivity was considered to be marginal, a mix with an amine liquid anti-stripping agent was prepared (0.75 percent by weight of asphalt binder) and tested. The results after treatment showed a considerable improvement in wet strength (67 psi [457 kPa] and slightly below the Caltrans minimum limit) and TSR (98 percent). All mixes tested in this UCPRC study were therefore treated with the anti-stripping agent.

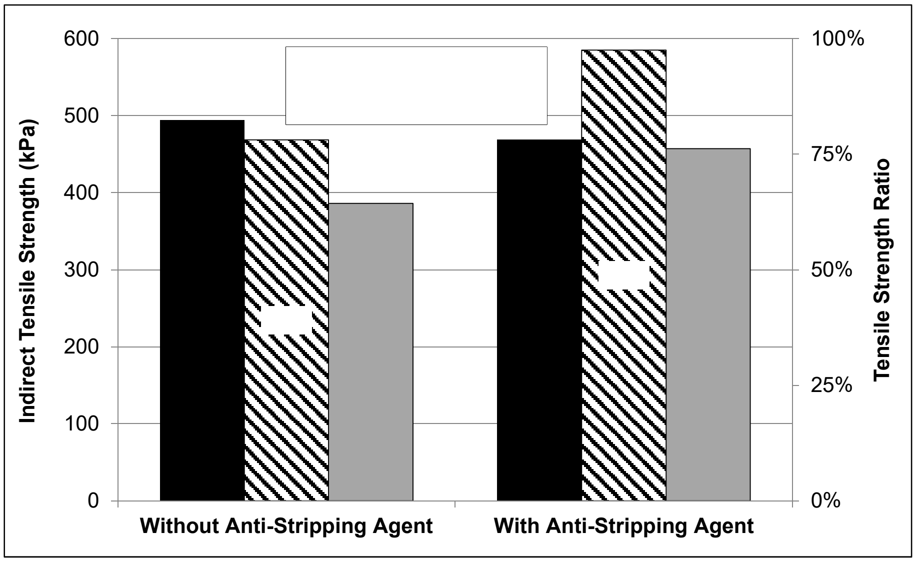


Figure 8.11: Average indirect tensile strength and tensile strength ratio.
(Control mix with PG 64-22 binder before and after adding rejuvenating agent)

8.4 Mix Design: Mixes Containing Reclaimed Asphalt Pavement

The focus of this UCPRC study was to compare the properties and performance of a control mix (i.e., containing no RAP) with those of mixes containing 25 and 40 percent RAP by binder replacement. In order to facilitate this comparison, the combined gradations and binder contents of the RAP mixes were kept as close as possible to the gradation and binder content of the control mix. This was achieved by first calculating the quantity of RAP material that would provide the required binder replacement and then adjusting the gradation of the virgin aggregate so that the combined gradation of virgin aggregate and RAP aggregate was as close as possible to the target gradation of the control mix while still meeting the volumetric requirements. Mixes containing 25 percent RAP were prepared with the same PG 64-22 virgin asphalt binder used in the mix design of the control mix. Mixes containing 40 percent RAP were prepared with the PG 58-28 virgin asphalt binder, in line with the Caltrans specification requirements to compensate for the stiffening effect of the higher RAP binder content. When calculating the mix volumetrics, the properties of the RAP determined from both ignition oven and solvent extraction tests were used.

Gradations of the three mixes containing 25 percent and 40 percent of each RAP source are shown in Figure 8.12. The gradations of the mixes with 25 percent RAP were identical to the target gradation. However, the gradation of the 40 percent RAP mixes were slightly coarser (but still within the Caltrans and FAA P-401 gradation limits) as a result of the higher RAP contents. Only limited adjustment of the grading was possible if all the Caltrans and FAA P-401 specification requirements were to be met.

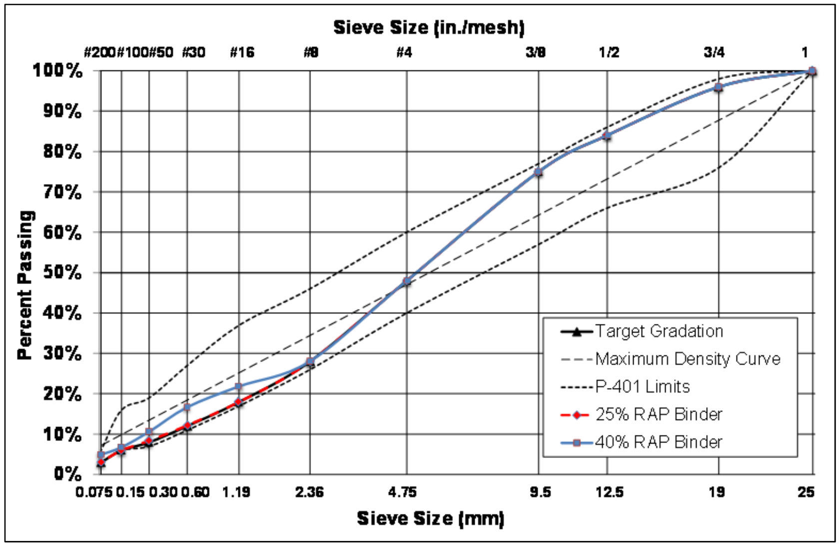
Figure 8.13 through Figure 8.16 show the air-void content, VMA, VFA, and dust proportion for the 25 percent and 40 percent RAP mixes.

The difference in volumetrics resulting from the two binder content determination processes (ignition oven and solvent extraction) was negligible. The mix with 25 percent New York RAP and 6.0 percent total binder content met the volumetric criteria specified in FAA P-401 (i.e., air-void content and VMA), but not in the Caltrans specifications (air-void content was lower and VMA was higher). However, the air-void contents of the mixes with 25 percent California and Alabama RAP were lower than the FAA P-401 specified value of 3.5 percent and therefore the total binder content for these two mixes was lowered to 5.5 percent. The FAA P-401 volumetric criteria for both mixes were met at this binder content. The reduction in binder content was achieved by reducing the quantity of virgin binder; the quantities of RAP and virgin aggregate were not altered. These adjustments to the virgin binder content therefore effectively increased the RAP binder replacement rate to 27 percent for the California and Alabama RAP mixes.

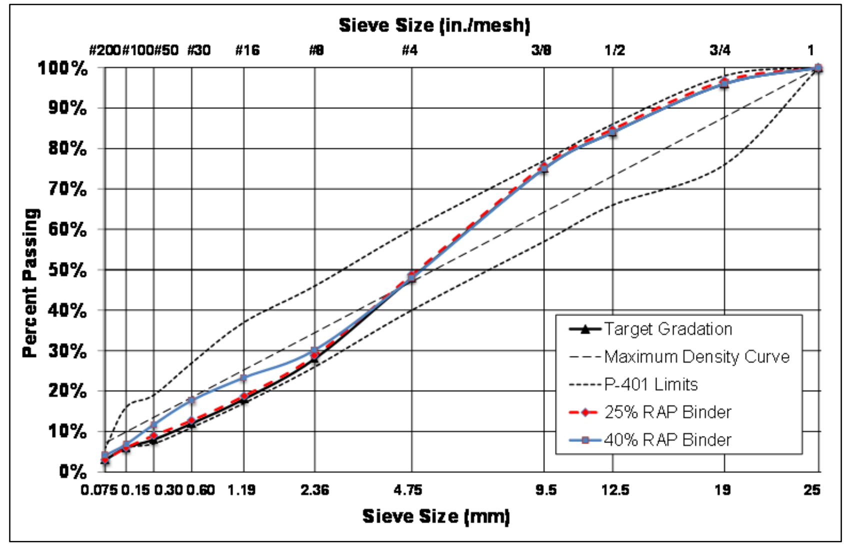
8.5 Fine Aggregate Matrix Mix Design

The binder content and aggregate gradations determined in the mix designs described in the previous sections were used as the basis for the fine aggregate matrix (FAM) mix design. Sample preparation followed the process described in Section 7.2.5. The binder contents of the FAM mixes were determined using the ignition oven test (AASHTO T 308) as it was considered to provide a more accurate indication of the total binder content than solvent extraction. Binder contents and gradations of the RAP aggregates were determined by both ignition oven and by extraction and recovery to identify which method provided the better estimation of the amount of available binder in the RAP materials to mobilize and effectively blend with the virgin binder. The binder content results are shown in Figure 8.17, and based on these results solvent extraction and recovery was selected as the most appropriate method. RAP gradations are shown in Figure 8.18 through Figure 8.20. The gradations of the burned RAP aggregates were finer than the recovered RAP aggregate, which is consistent with other studies that have shown that the very fine portion (≤ 0.075 mm [#200]) can be burned off in the process.

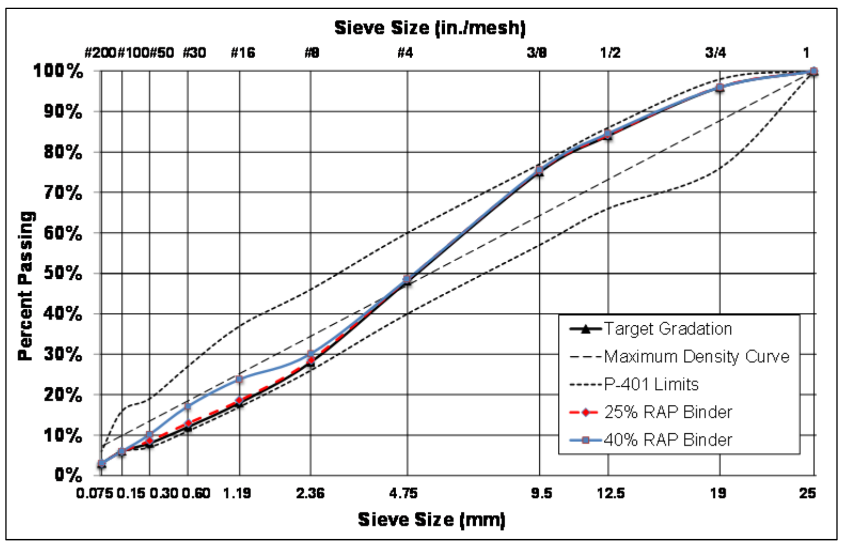
The optimum binder content of the FAM mix was found to be 10.7 percent by weight of the mix. The aggregate gradation and asphalt binder content of the FAM mixes was the same for all mixes. The quantities of RAP required to meet the target binder replacement were first determined, and then the quantity of virgin binder and the quantity and gradation of virgin aggregates were adjusted to preserve the target gradation and binder content. The gradations for each of the FAM mixes are listed in Table 8.14.



New York



California



Alabama

Figure 8.12: Aggregate gradations of mixes with 25 and 40 percent RAP.

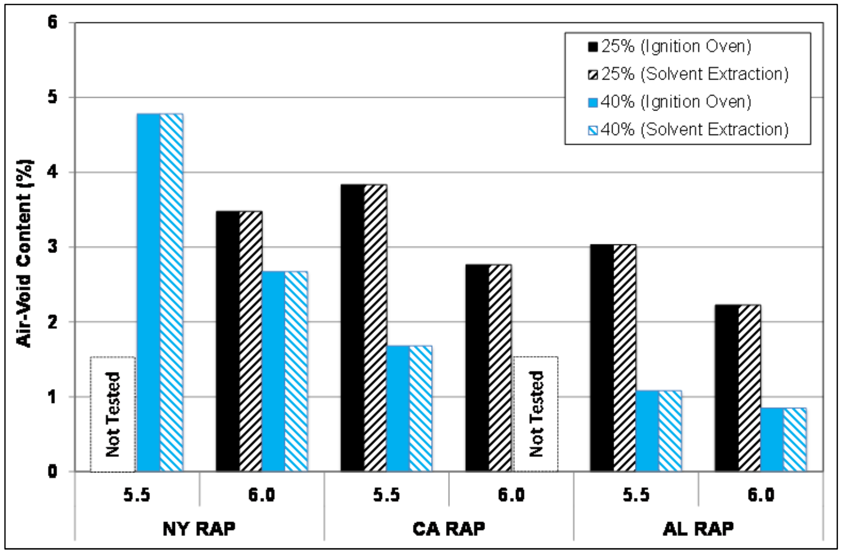


Figure 8.13: Air-void contents.

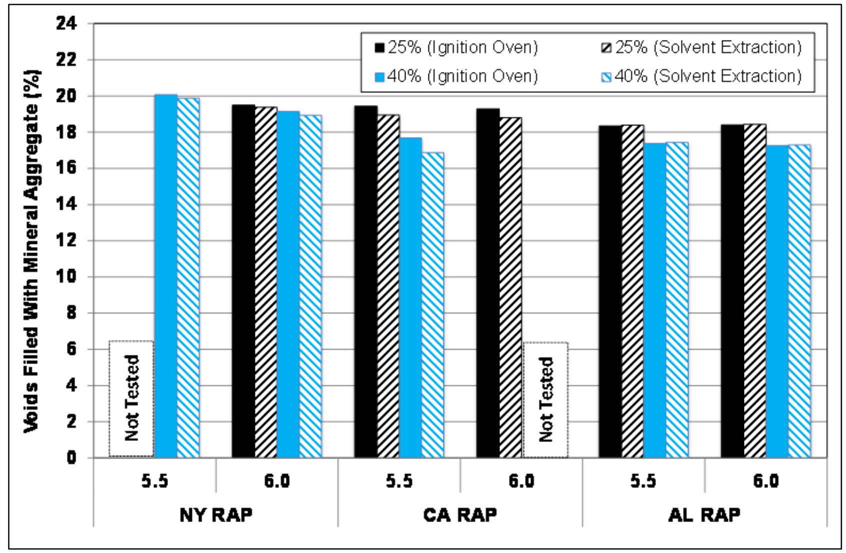


Figure 8.14: Voids filled with mineral aggregate.

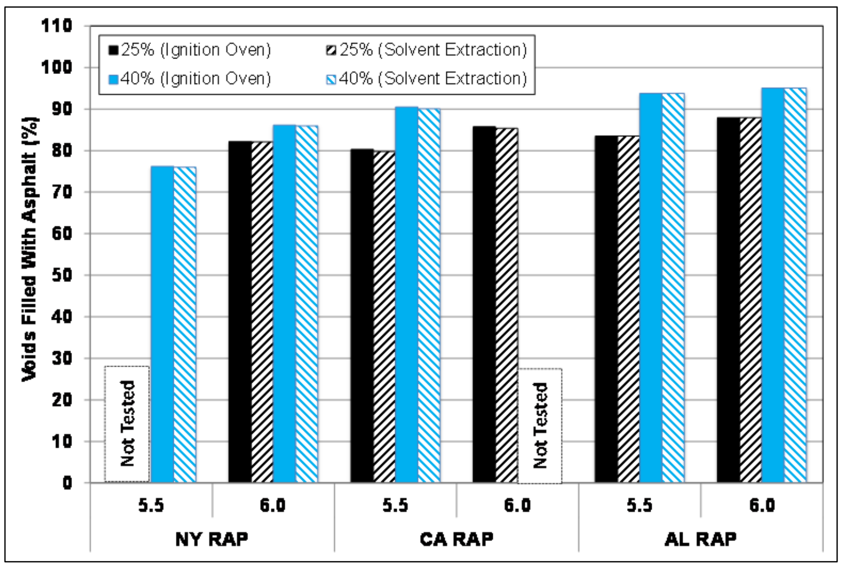


Figure 8.15: Voids filled with asphalt.

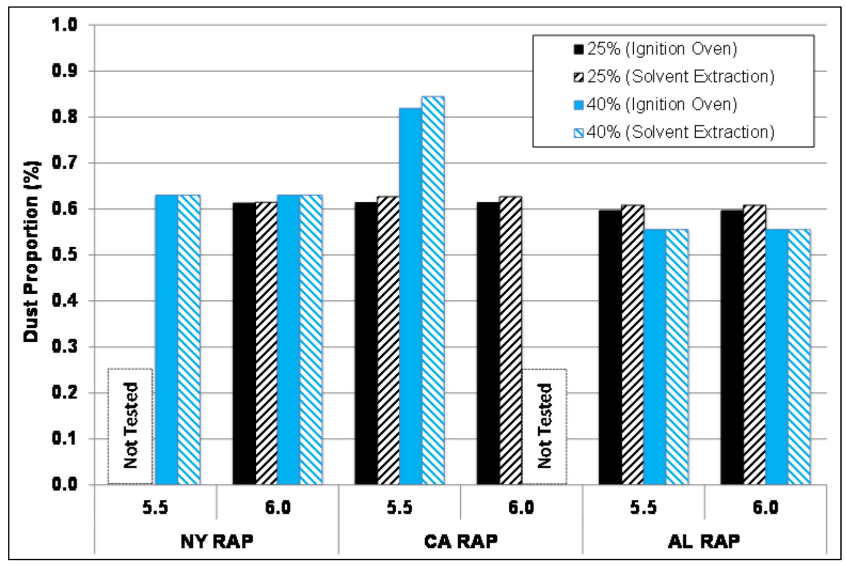


Figure 8.16: Dust proportion.

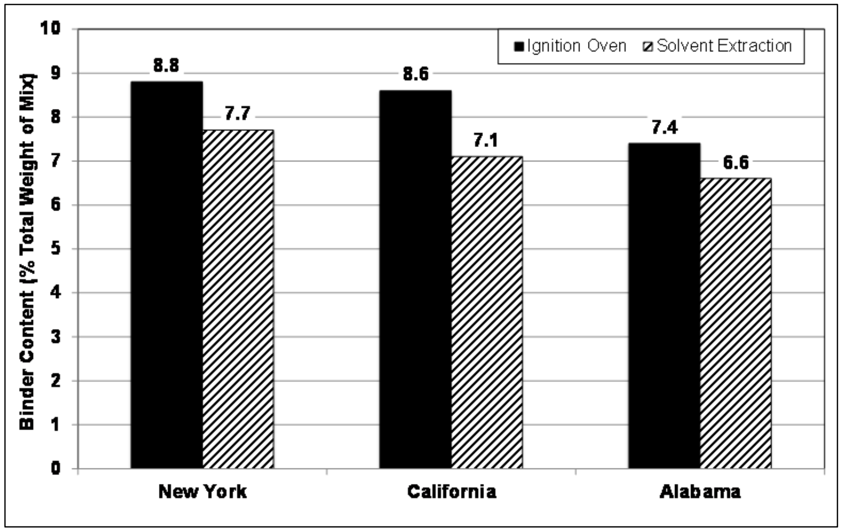


Figure 8.17: Binder content of fine RAP materials.

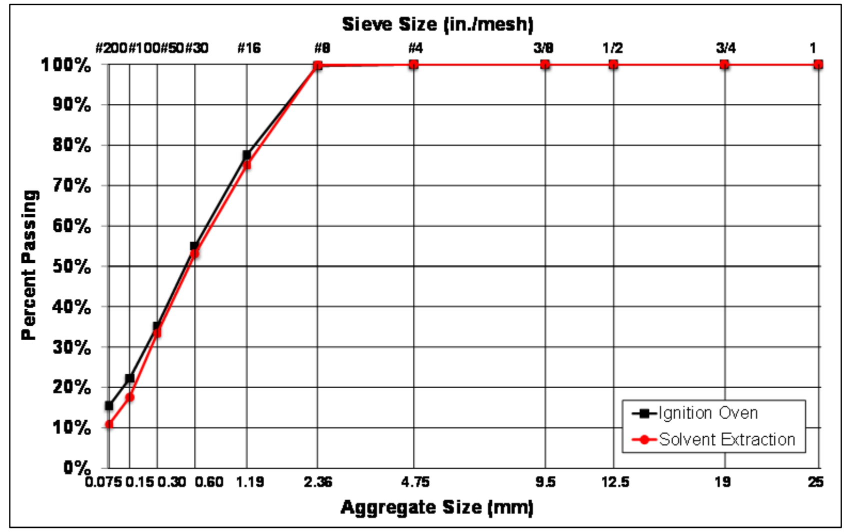


Figure 8.18: Fine aggregate gradation of New York RAP.

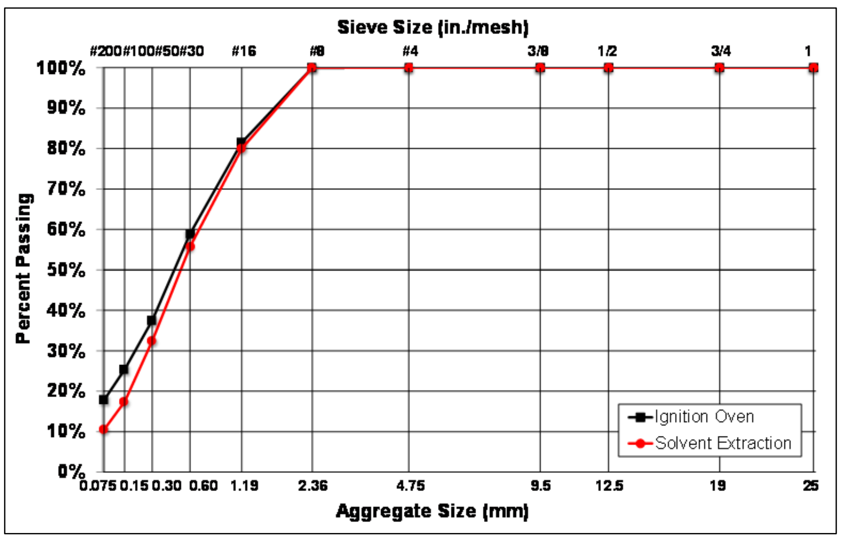


Figure 8.19: Fine aggregate gradation of California RAP.

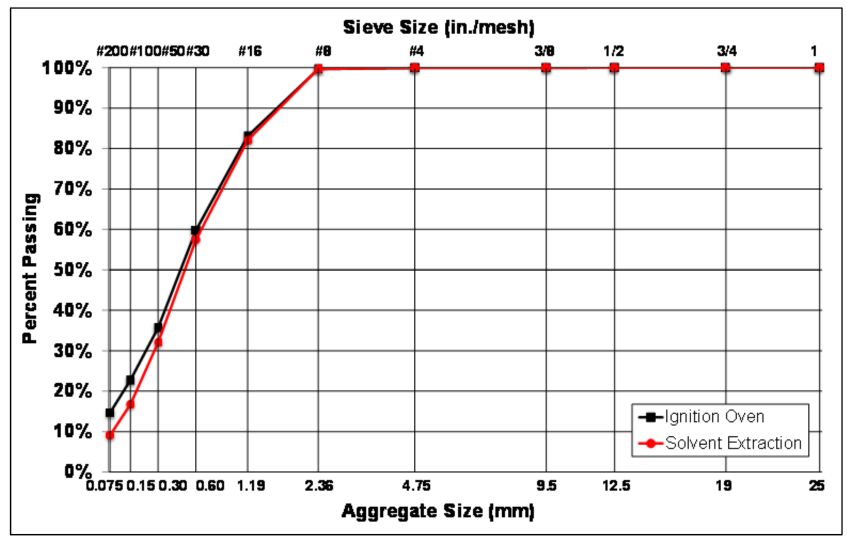


Figure 8.20: Fine aggregate gradation of Alabama RAP.

Table 8.14: RAP Aggregate and Virgin Aggregate Gradations

Sieve Size		FAM Mix Type Gradation (% Passing)				
mm	in./mesh	Control	25% NY RAP	25% CA RAP	25% AL RAP	40% NY RAP
2.36	#8	100	100	100	100	100
1.19	#16	64	54	54	50	38
0.60	#30	43	33	34	31	26
0.30	#50	29	26	27	26	26
0.15	#100	21	22	26	25	26
0.075	#200	11	8	11	12	3

8.6 Mix Design Summary

Based on the mix design results described above, 10 different asphalt mixes were considered for further evaluation of performance-related properties (Table 8.15). The mix identification codes listed in the table are used in Chapters 9 and 10 when discussing the performance of the mixes.

Table 8.15: Asphalt Mixes Selected for Further Evaluation

Mix #	Mix Identification Code	Virgin Binder Grade	RAP Binder Replacement (%)	RAP Source
1	64-0RAP	PG 64-22	0	Control
2	64-25RAP-NY		25	New York (NY)
3	64-25RAP-CA		25	California (CA)
4	64-25RAP-AL		25	Alabama (AL)
5	58-0RAP	PG 58-28	0	Control
6	58-40RAP-NY		40	New York (NY)
7	76-0RAP	PG 76-22 PM	0	Control
8	76-25RAP-NY		25	New York (NY)
9	76-25RAP-CA		25	California (CA)
10	76-25RAP-AL		25	Alabama (AL)

The experimental plan did not include testing of all possible combinations of binder grade, RAP source, and RAP content, for the following reasons:

- PG 58-28 mixes with 25 percent RAP binder replacement were not considered based on the findings of other studies cited in the literature review, which indicated that using softer binders to compensate for stiffness increases associated with the addition of RAP was not justified in mixes with RAP contents of 25 percent and lower.
- PG 58-28 mixes with 40 percent RAP binder replacement from the California and Alabama sources were not included given that the FAA P-401 grading and volumetric property specifications could not be met.
- PG 64-22 and PG 76-22 PM mixes with 40 percent RAP from any of the sources were not considered given that the FAA P-401 grading and volumetric property specifications could not be met.

8.7 Specimen Preparation

8.7.1 Fine Aggregate Matrix Mixes

FAM mixes were prepared according to the procedure described in Section 7.2.5. The asphalt binder mixing temperatures were determined from temperature-viscosity charts provided by the refineries. Virgin aggregates were heated to 15°C (27°F) higher than the corresponding asphalt binder mixing temperature, while RAP materials were preheated to 110°C (230°F) for one hour. FAM mixes were short-term aged for two hours at their corresponding compaction temperatures (obtained from the virgin binder temperature-viscosity charts) before compaction.

8.7.2 Full-Graded Mixes for Performance-Related Testing

Full-graded mixes with the predetermined gradations, RAP contents, and binder contents were short-term aged in loose form for four hours at 135°C (275°F) according to AASHTO R 30, and then heated further to the required compaction temperatures prior to compaction. Mixes were compacted (rolling wheel for fatigue beams, gyratory for all other specimens) to the required air-void contents and then cored/cut to the dimensions specified for each test.

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9. PHASE 1f: BINDER AND FAM MIX TESTING RESULTS

9.1 Introduction

This chapter summarizes the test results of the asphalt binder and fine aggregate matrix (FAM) mix testing. Tests on the asphalt binder included performance grading and shear modulus. Tests on the FAM mixes included air-void content and shear modulus.

9.2 Asphalt Binder Test Results

9.2.1 Asphalt Binder Performance Grading

The performance grade of the virgin binders and recovered RAP binders were determined following the testing procedure explained in Section 4.2.2. The performance grading criteria and values for the virgin and extracted RAP binders are listed in Table 9.1 and Table 8.2, respectively.

Table 9.1: Performance Grade Results of Virgin Binders

Critical Temperature	Aging Condition	Test Parameter	PG 58-28	PG 64-22	PG 76-22 PM
High	Unaged RTFO-aged	G*/sinδ ≥ 1.00 kPa G*/sinδ ≥ 2.20 kPa	59.7 60.4	66.5 67.8	80.1 82.5
Intermediate	RTFO-aged	G* x sinδ ≤ 5,000 kPa	16.5	22.7	14.3
Low	RTFO- and PAV-aged	S(60) ≤ 300 MPa[1] m-value ≥ 0.30[1]	184 (at -18°C) 0.35 (at-18°C)	176 (at -12°C) 0.34 (at -12°C)	54 (at-12°C) 0.43 (at-12°C)
[1] Values correspond to testing performed at 10°C warmer than PG grade temperature					

Table 9.2: Performance Grade Results of Recovered RAP Binders

Critical Temperature	Aging Condition	Test Parameter	New York	California	Alabama
High	Unaged RTFO-aged	G*/sinδ ≥ 1.00 kPa G*/sinδ ≥ 2.20 kPa	91.1 92.0	106 108	>118 >118
Intermediate	RTFO-aged	G* x sinδ ≤ 5,000 kPa	26.6	48.3	58.2
Low	RTFO- and PAV-aged	S(60) ≤ 300 MPa[1] m-value ≥ 0.30[1]	216 (at-12ºC) 0.31 (at-12ºC)	476 (at-6ºC) 0.20 (at-6ºC)	166 (at-6ºC)[+] 0.28 (at-6ºC)[+]
[1] Values correspond to testing performed at 10°C warmer than PG grade temperature					

The high PG limit of the extracted and recovered binder from the Alabama RAP was not determined since the procedure could not be performed at temperatures higher than 120°C, the limit of the range of the dynamic shear rheometer (DSR) used in this study. The grades of the extracted binders from the three RAP sources were notably different and were therefore considered to be appropriately representative of different RAP sources, which would provide insights with regard to the influence of RAP binder source and grade on the properties of composite binders and the mixes produced with them. Studies into the influence of the chemical solvent used in the extraction process were beyond the scope of this study but that influence warrants further investigation.

Recovered RAP binders were blended with different virgin binders to simulate 25 percent and 40 percent binder replacement. The binders were then short-term aged in a rolling thin-film oven (RTFO) and tested in a DSR (25 mm parallel plate with 1 mm gap setting) to measure the influence of the RAP binder on the high PG limits of the virgin binder. RTFO aging was considered appropriate since the blending of RAP and virgin binders mostly occurs during mixing, storage, and paving operations. The following blended binders were evaluated:

- PG 64-22 binder with 25 percent RAP binder replacement (all three RAP sources)
- PG 58-28 binder with 40 percent RAP binder replacement (New York RAP source only)
- PG 76-22 PM binder with 25 percent RAP binder replacement (all three RAP sources)

Figure 9.1 shows the high PG limit of the RTFO-aged virgin and blended binders.

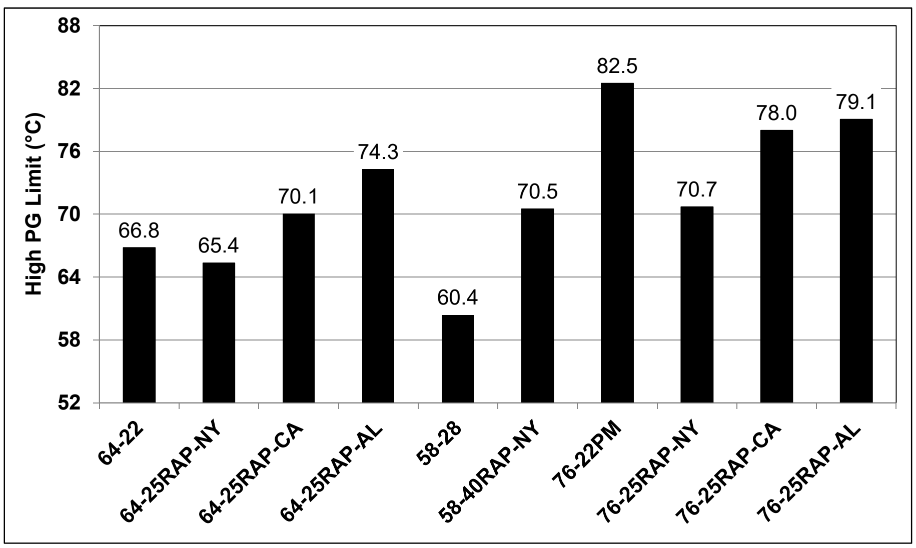


Figure 9.1: High PG limit of RTFO-aged virgin and blended binders.

The following observations were made:

- The influence of RAP binder on the high PG limit of the virgin and polymer-modified binders was inconsistent.
- Adding New York RAP binder to the PG 64-22 binder resulted in a slight reduction (1.4°C) in the high PG grade of binder, which was unexpected given that adding RAP binder to virgin binder generally results in an increase in binder stiffness. This was attributed in part to the apparent relatively unaged condition of the New York RAP (i.e., limited long-term aging of the binder) and likely lower initial PG grading of the original binder (e.g., PG 58-34).
- The high PG grade of the PG 64-22 binder increased by 3.1°C and 7.5°C with the addition of California and Alabama RAP, respectively.
- Adding New York, California, and Alabama RAP to the PG 76-22 PM binder reduced the high PG limit by 11.8°C, 4.5°C, and 3.4°C, respectively. This was also unexpected, but was attributed in part to potential "dilution" of the polymer modification by the addition of the unmodified RAP binder

and/or to potential alteration of the polymer cross-linking structure. Additional research into the compatibility of the different binders and the influence of the chemical solvents used in the RAP binder extraction was beyond the scope of this study but these warrant further investigation.

9.2.2 Asphalt Binder Shear Modulus

The RTFO-aged virgin binders, extracted RAP binders, and blended binders were tested with a DSR (8 mm parallel plate with 2 mm gap setting) to measure the shear moduli of the binders at three temperatures (4°C, 20°C, and 40°C) and a range of frequencies (0.1 to 100 Hz). The sigmoidal function parameters (Equation 4.1) and activation energy terms for the Arrhenius shift factor equation (Equation 4.3) used to plot the master curves are provided in Table 9.3.

Table 9.3: Shear Modulus Master Curve Parameters

RAP Binder Replacement (%)	Binder Identification	Master Curve Parameters				
		δ	α	β	γ	Ea (kJ/mol)
0	64-22	-2.92	8.10	-1.31	-0.41	192,136
	58-28	-4.05	9.42	-1.12	-0.37	181,941
	76-22 PM	-0.72	6.00	-0.56	-0.42	180,555
25	64-25%RAP-NY	-1.80	6.56	-1.37	-0.52	194,634
	64-25%RAP-CA	-0.79	5.39	-1.67	-0.61	200,091
	64-%RAP-AL	-1.15	5.45	-1.65	-0.60	200,103
	76-25%RAP-NY	-1.10	6.07	-0.82	-0.46	184,114
	76-25%RAP-CA	-0.43	5.16	-1.11	-0.53	191,348
	76-%RAP-AL	-3.61	8.85	-1.30	-0.31	200,288
40	58-40%RAP-NY	-1.57	6.39	-1.31	-0.48	192,941

Figure 9.2 shows the shear modulus master curves and Figure 9.3 shows the modulus curves normalized to the corresponding control binder for the 10 binders evaluated. The following observations were made:

- The modulus of the PG 58-28 virgin binder was the lowest (at frequencies ≤ 1 Hz), as expected. Adding 40 percent RAP binder from the New York source increased the stiffness considerably through most of the frequency range.
- The PG 64-22 binder with 25 percent binder replacement from the California and Alabama RAP sources had the highest moduli through most of the testing frequency range. The RAP binder from those two sources had a similar influence in terms of change of stiffness. The PG 64-22 binder with 25 percent New York RAP binder had lower moduli than the control binder, as expected based on the results of the performance grade testing.
- The PG 76-22 PM control binder was notably stiffer than the PG 64-22 and PG 58-28 control binders at lower frequencies (corresponding to higher temperatures), but merged with the PG 58-28 binder curve at intermediate and higher temperatures, as expected (i.e., the polymer increases stiffness at higher temperatures, but adds flexibility at lower temperatures).
- Adding 25 percent California and Alabama RAP binder to the PG 76-22 PM binder increased the stiffness of the binder, consistent with the results of the PG 64-22 binder. Adding RAP binder from the New York source reduced the stiffness.

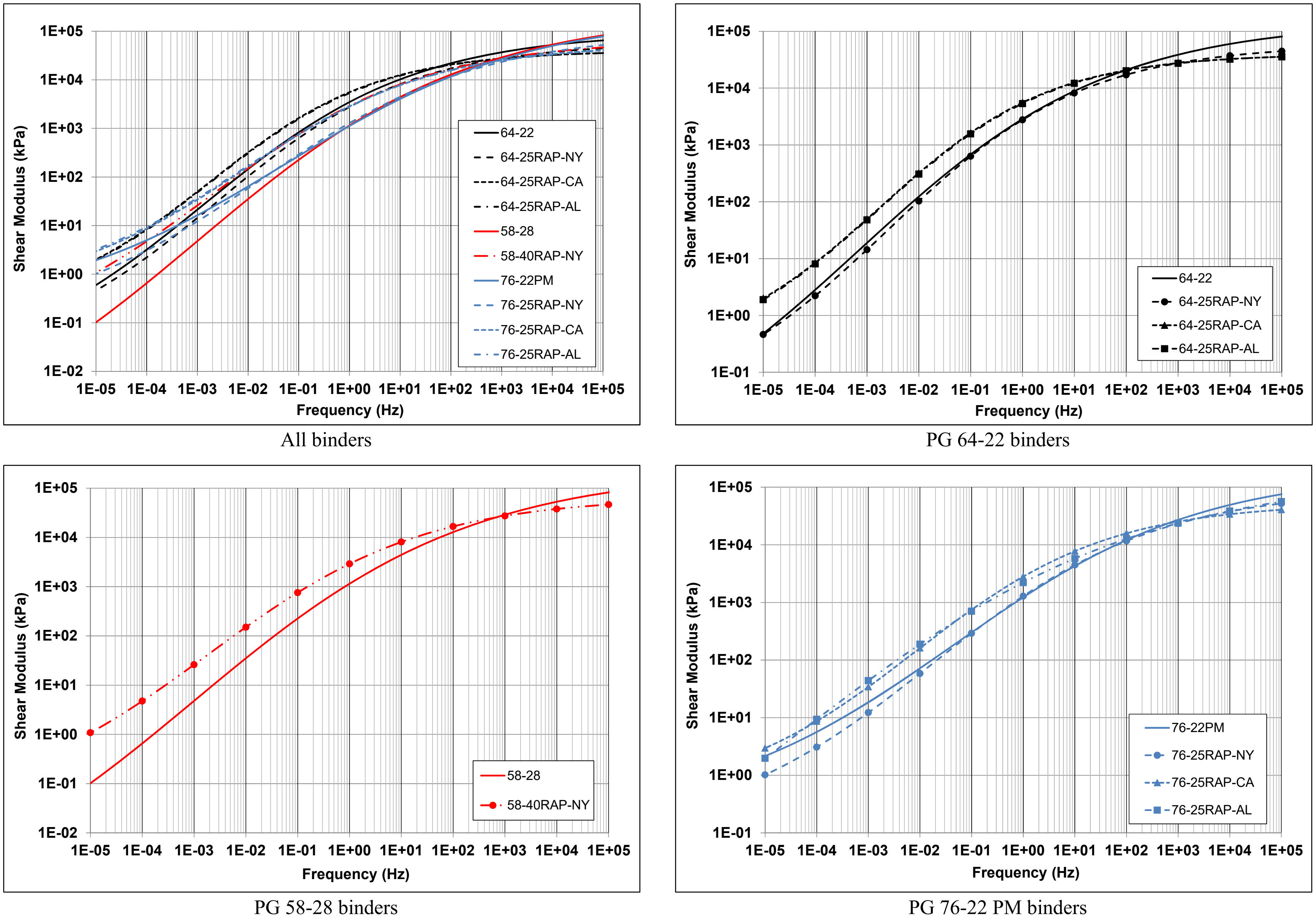


Figure 9.2: Shear moduli master curves for asphalt binders (20°C).

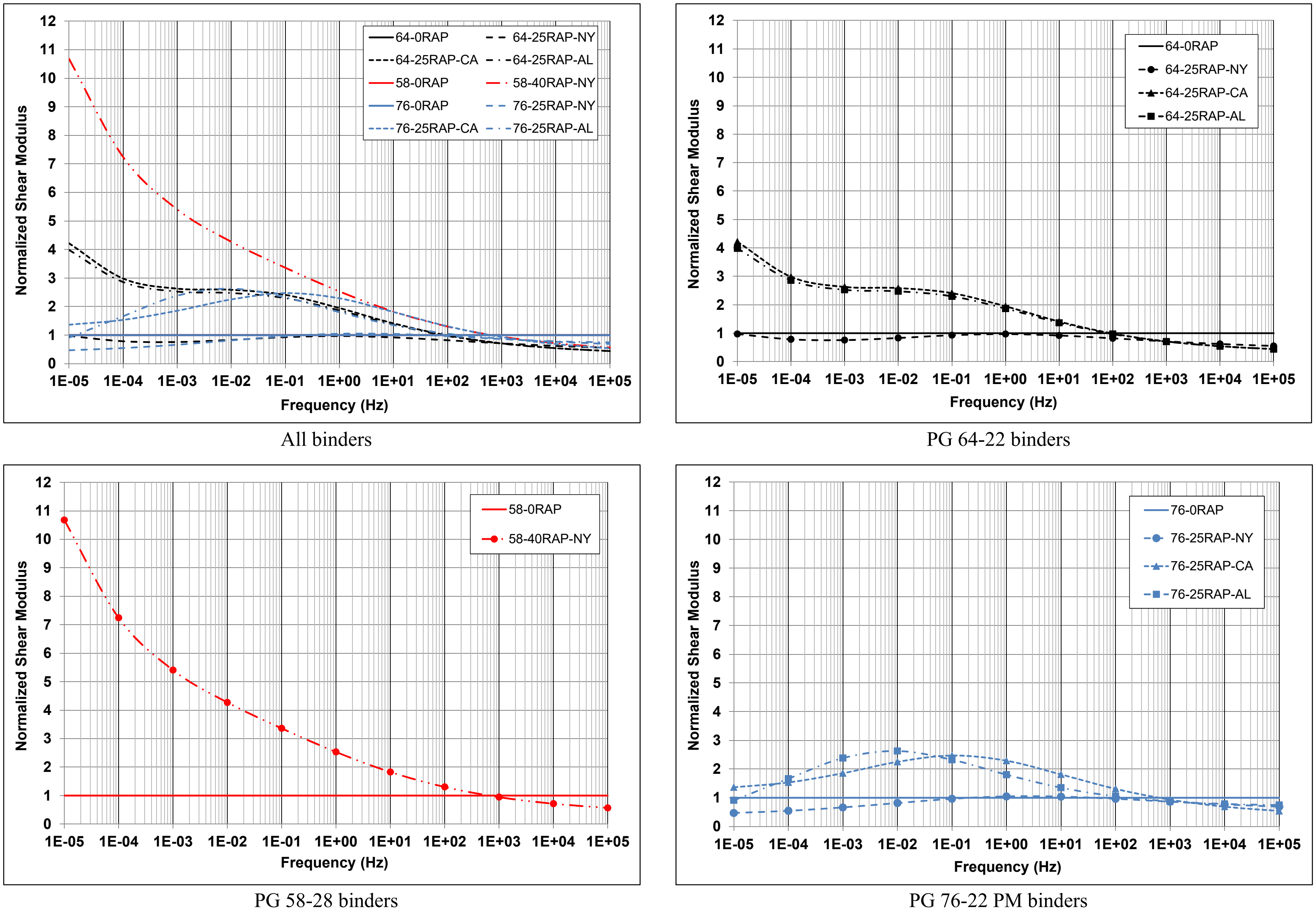


Figure 9.3: Normalized shear moduli master curves for asphalt binders (20°C).

- The master curves of all binders merged at high frequencies (> 1,000 Hz, representing colder temperatures), regardless of the virgin binder grade, RAP source, or the quantity of RAP binder added.

9.3 Fine Aggregate Matrix Mix Test Results

FAM mix specimens were prepared and tested according to the procedures described in Section 7.2 and the mix design described in Section 8.5. A total of 10 FAM mixes were evaluated.

9.3.1 Fine Aggregate Matrix Mix Air-Void Content

Air-void contents of the FAM mix specimens were determined by measuring the maximum theoretical specific gravity of the mix (AASHTO T 209) and bulk specific gravity of the saturated surface-dry specimen (AASHTO T 166). Figure 9.4 summarizes the air-void contents measured on the specimens (average of six specimens per mix). The air-void contents ranged between 9.1 and 11.8 percent, which were within the target range and considered acceptable for this study. Air-void contents were considered in all test result analyses.

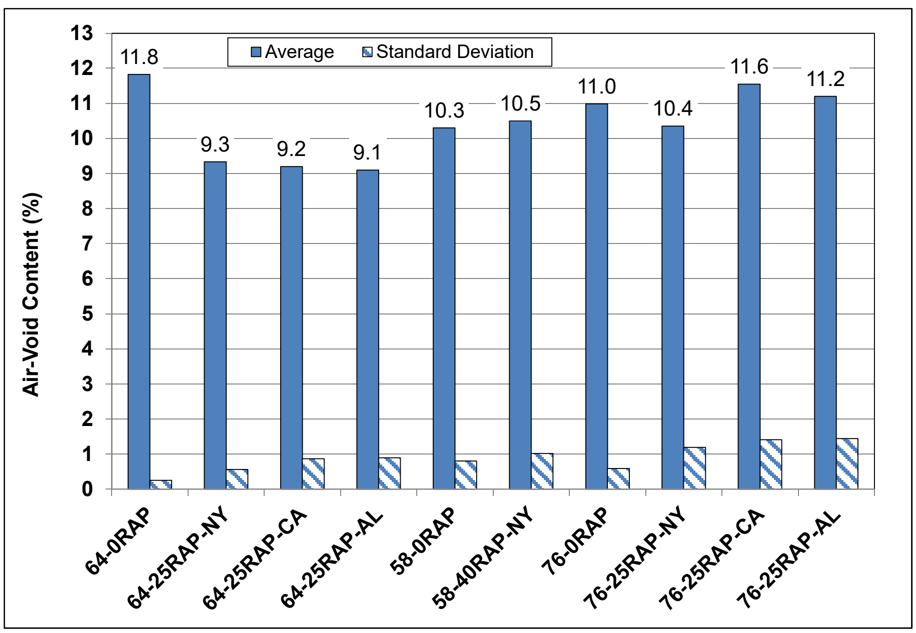


Figure 9.4: Air-void content of FAM mixes.

9.3.2 Fine Aggregate Matrix Mix Characterization

FAM mix specimens were testing using a dynamic mechanical analyzer (DMA) fitted to a DSR to measure the shear modulus (G*) at three temperatures (4°C, 20°C, and 40°C) and over a range of frequencies from 0.1 Hz to 25 Hz under strain-control conditions. A strain amplitude of 0.002 percent was selected to ensure that specimens were tested within the linear viscoelastic region of the mix. A sigmoidal function (Equation 4.1) and an Arrhenius shift factor (Equation 4.3) were used to shift the measured moduli to the reduced frequency domain and to construct shear modulus master curves for each mix. The estimated parameters are provided in Table 9.4.

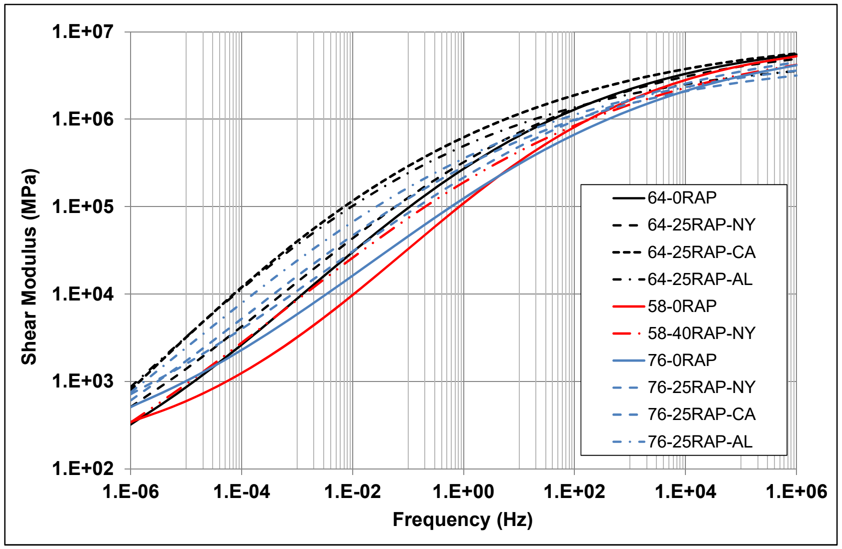
Table 9.4: FAM Mix Shear Modulus Master Curve Parameters

RAP Binder Replacement (%)	FAM Mix Identification[1]	Master Curve Parameters				
		δ	***α***	***β***	***γ***	**Ea (kJ/mol)**
0	64-22	1.11	5.85	-1.04	-0.37	204,052
	58-28	2.02	4.92	-0.46	-0.43	182,937
	76-22 PM	1.78	5.17	-0.58	-0.35	195,405
25	64-25%RAP-NY	1.13	5.77	-1.14	-0.35	207,550
	64-25%RAP-CA	-1.37	8.36	-1.79	-0.29	216,933
	64-%RAP-AL	-0.72	7.45	-1.81	-0.31	226,856
	76-25%RAP-NY	1.65	5.28	-0.83	-0.34	206,826
	76-25%RAP-CA	0.92	5.78	-1.29	-0.34	211,854
	76-%RAP-AL	-0.14	6.94	-1.51	-0.30	221,915
40	58-40%RAP-NY	0.59	6.37	-1.02	-0.31	201,955

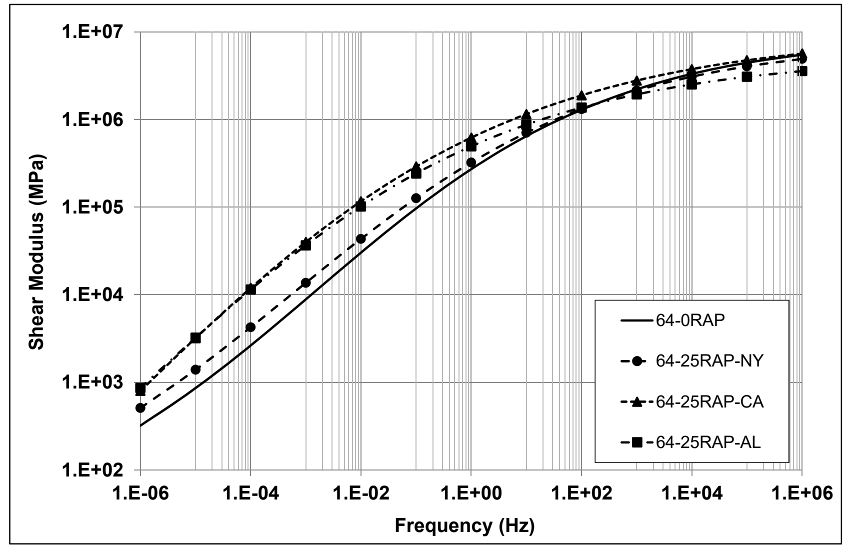
[1] Note that the mix identifications were not changed to reflect the effective 27% binder replacement rates in the California and Alabama mixes

The shear modulus master curves for the FAM mixes at different RAP binder replacement and virgin binder grades are shown in Figure 9.5. Master curves normalized to the corresponding control mixes are shown in Figure 9.6. The following observations were made:

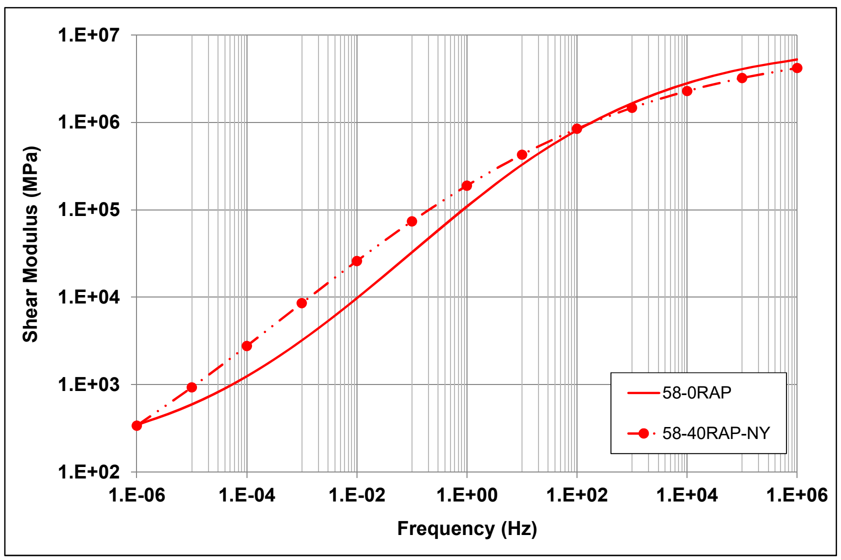
- The results were generally consistent with the observations made about the binder test results. Differences were attributed to:
  + The differences in the degree of blending between the virgin and RAP binders when mixed prior to binder testing, and the degree of blending when the virgin binder was mixed with the virgin and RAP aggregates.
  + Possible effects of the solvent on the properties of the extracted and recovered blended binder.
- The shear modulus of the PG 58-28 mix was the lowest (at frequencies ≤ 1 Hz), as expected. Adding 40 percent RAP binder from the New York source increased the stiffness of the mix up to about three times that of the control at low and intermediate frequencies.
- The PG 64-22 mixes with 25 percent binder replacement from the California and Alabama RAP sources had the highest moduli through most of the testing frequency range. The two sources had a similar influence in terms of change of stiffness (up to five times stiffer than the control mix [at about 0.0001 Hz]). The PG 64-22 mix with 25 percent New York RAP binder had similar moduli to the control binder. Although the virgin binder content was slightly lower in the California and Alabama RAP mixes than in the New York RAP mix (73 percent versus 75 percent [see discussion on binder content determination in Section 8.4]), comparison with the binder testing results (where all three binder samples were prepared with 75 percent virgin binder content) indicate that this binder content difference did not significantly influence the results and that the RAP binder properties had the biggest influence on the shear modulus.



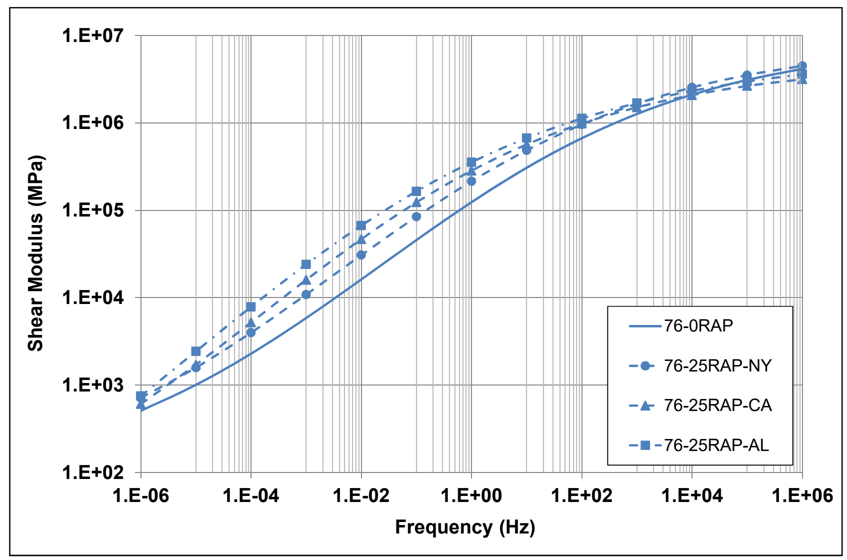
All FAM mixes



PG 64-22 FAM mixes

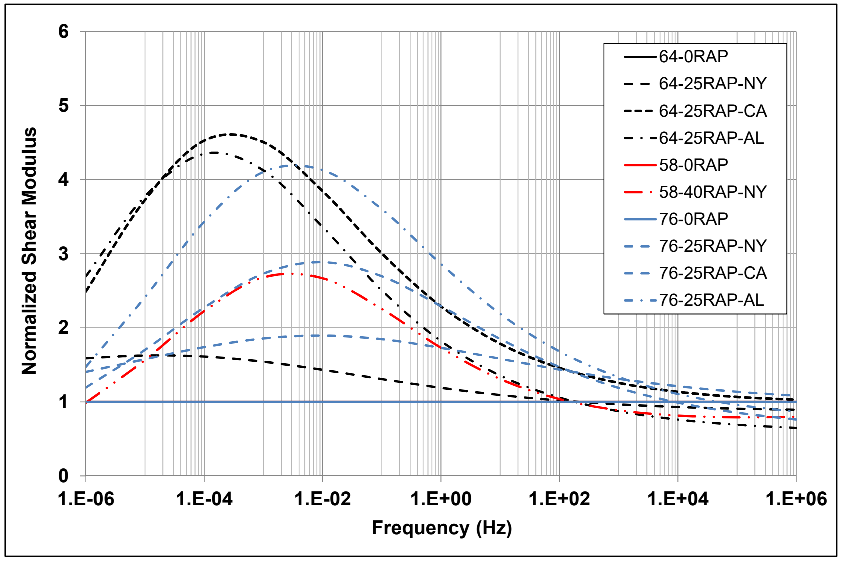


PG 58-28 FAM mixes

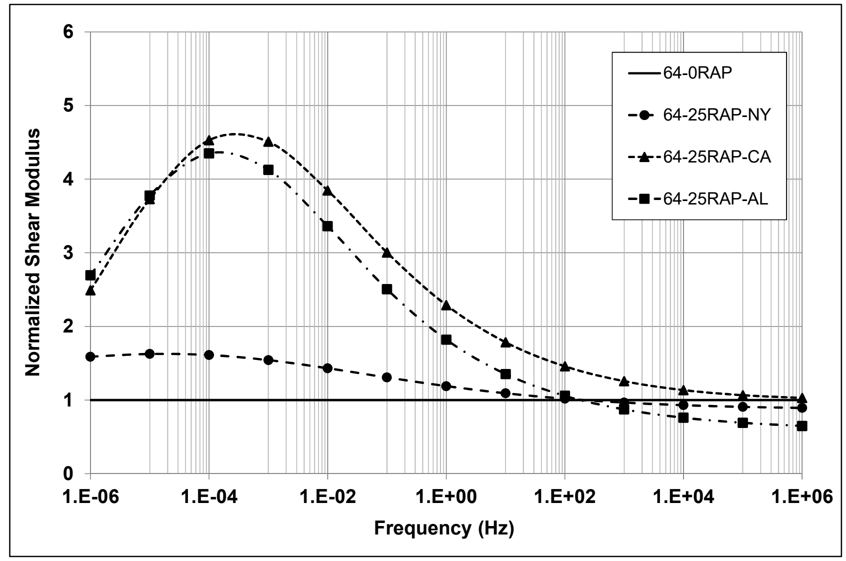


PG 76-22 PM FAM mixes

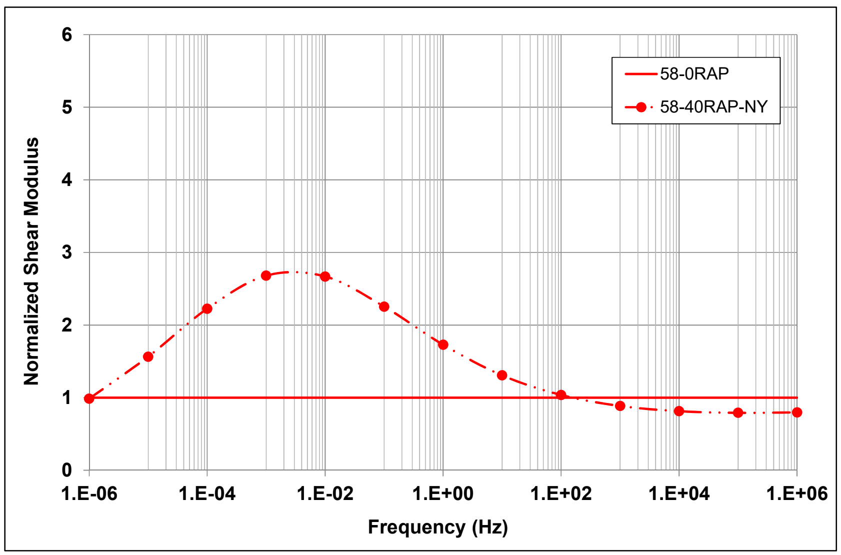
Figure 9.5: Shear moduli master curves for FAM mixes (20°C).



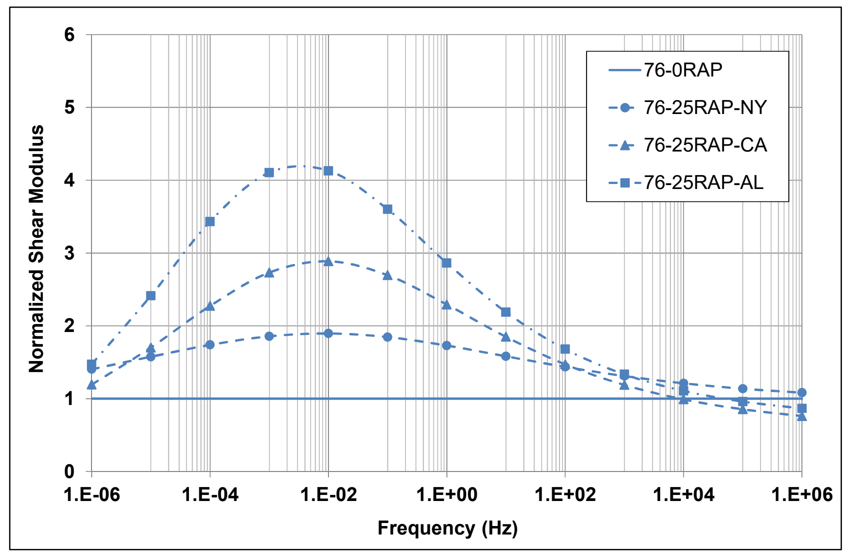
All FAM mixes



PG 64-22 FAM mixes



PG 58-28 FAM mixes



PG 76-22 PM FAM mixes

Figure 9.6: Normalized shear moduli master curves for FAM mixes (20°C).

- The PG 76-22 PM control mix was notably stiffer than the PG 64-22 and PG 58-28 mixes at lower frequencies (corresponding to higher temperatures), but merged with the PG 64-22 mix curve at an intermediate frequency (~10 Hz) and with the PG 58-28 mix curve at a higher frequency (~100 Hz) (corresponding to colder temperatures). The differences between the PG 76-22 PM mix and the PG 64-22 and PG 58-28 mixes were less distinct here than they were in the binder testing results. Adding 25 percent California and Alabama RAP binder to the PG 76-22 PM mix had only a marginal effect on mix stiffnesses. Adding RAP binder from the New York source reduced the stiffness. The same conclusions with regard to effective virgin binder content of the PG 64-22 California and Alabama RAP mixes discussed above are also relevant to the PG 76-22 PM mixes.
- The master curves of all binders merged at high frequencies (> 1,000 Hz, representing colder temperatures), regardless of the virgin binder grade, RAP source, or the quantity of RAP binder added.

9.4 Phase 1f Testing Summary

Key observations from this phase of the study include the following:

- The degree of change in PG grade after the addition of RAP binder varied depending on the virgin binder grade and the RAP source. This was attributed to various factors including but not limited to the degree of aging of the RAP binder, the original PG grade of the RAP binder, and the extent of the "dilution" of the polymer in polymer-modified binders.
- Using RAP binder to replace a portion of the virgin binder always increased the stiffness of the binder, but the degree of increase was dependent on the RAP source.
- The results from FAM mix testing were consistent with the results from binder testing. Differences were attributed to the differences in the degree of blending during preparation of the binders (stirred with a glass rod in a glass beaker) and preparation of the FAM mixes (standard laboratory mixing process), and to possible effects of the chemical solvent on the properties of the extracted and recovered binder. The slightly higher effective RAP binder contents of the California and Alabama RAP mixes did not appear to influence the results.
- The FAM mix test results further supported the use of this testing approach as an appropriate procedure for evaluating the properties of blended asphalt binder in mixes containing relatively high quantities of RAP.

10. PHASE 1g: MIX TESTING RESULTS

10.1 Introduction

This chapter summarizes the test results on full-graded mixes. Tests included air-void content, stiffness (dynamic modulus and flexural modulus), rutting performance (flow number, Asphalt Pavement Analyzer, and Hamburg Wheel-Track) and cracking performance (beam fatigue).

10.2 Experiment Design

Table 10.1 lists the test methods and brief details about the test parameters used to conduct performance-related testing on full-graded asphalt mixes in this study. The test results are discussed in the following subsections.

Table 10.1: Asphalt Mix Tests Performed

Test	Replicates	Air Voids (%)	Test Variables
Stiffness • AMPT dynamic modulus - AASHTO TP 79	2	7.0 ± 1.0	1 temperature sequence (4, 25, 40°C) 1 frequency sequence (10, 1, 0.1, 0.01 Hz) 1 stress level[1]
Stiffness • Beam flexural frequency sweep - AASHTO T 321	2	6.0 ± 0.5	3 temperatures (10, 20, 30°C) 2 strain levels (100 µstrain at 10, 20°C; 200 µstrain at 30°C)
Rutting Performance • AMPT flow number - AASHTO TP 79	2	7.0 ± 1.0	1 temperature (52°C) 1 deviator stress (600 kPa [70 psi]) 1 contact stress (30 kPa [4 psi])
Rutting Performance • Asphalt Pavement Analyzer[2] - AASHTO T 340	3	7.0 ± 1.0	1 temperature (64°C) 1 hose pressure (1,700 kPa [250 psi]) 1 wheel load (113 kg [250 lb])
Moisture Sensitivity • Hamburg Wheel-Track - AASHTO T 324	4	7.0 ± 1.0	1 temperature (50°C) 1 bath condition (with water bath)
Cracking Performance • Beam fatigue - AASHTO T 321	3	6.0 ± 0.5	1 temperature (20°C) 3 strain ranges (dependent on mix)

[1] Deviator stress controlled by software to get 75 to 125 µstrain peak-to-peak axial strain.
[2] Testing performed by FAA at National Airport Pavement and Materials Research Center.

10.3 Specimen Preparation

The following process was followed to prepare asphalt mix specimens for performance-related testing:

1. Add liquid anti-stripping agent to virgin asphalt binder at a dosage of 0.75 percent by the weight of total binder (including virgin binder and RAP binder) used in the mix.
2. Heat the aggregates, asphalt binder, and RAP to the specified mixing temperatures obtained from the viscosity-temperature charts provided by the binder supplier (150°C [302°F] for PG 64-22 and PG 58-28 asphalt binders, 165°C [329°F] for the PG 76-22 PM binder). Heat the aggregates to 15°C

(27°F) higher than the mixing temperature of the binder for four hours. Heat the RAP to 110°C (230°F) higher than the mixing temperature of the binder for one hour (use a shorter heating period to eliminate possible undesired aging of asphalt binders).

3. After heating, mix the asphalt binder, aggregates, and RAP in a mechanical mixer to achieve a uniform mix with well-coated aggregates.
4. Short-term age the loose mix at 135°C (275°F) for four hours (note that the duration of short-term aging for mix testing specimens is different from that for mix design testing, which specifies two hours at the representative compaction temperature [AASHTO R 30])
5. Increase the loose mix temperature to the compaction temperature. In this study, compaction temperatures were chosen from temperature-viscosity charts provided by the refinery (140°C [284°F] for PG 64-22 and PG 58-28 and 142°C [288°F] for PG 76-22 PM).
6. Compact the mix in a Superpave gyratory compactor to produce specimens for dynamic modulus, flow number, Hamburg Wheel-Track, and Asphalt Pavement Analyzer tests. Compact additional mix under a rolling wheel compactor to produce specimens for beam flexural stiffness and beam fatigue tests. The target air-void contents were:
   - 7 ± 1.0 percent for dynamic modulus, flow number, Hamburg Wheel-Track and Asphalt Pavement Analyzer tests
   - 6 ± 0.5 percent for beam flexural stiffness and fatigue tests
7. Core or extract and trim asphalt mix specimens from the compacted cylinders and beams to the desired dimensions for testing.
8. Measure the air-void content of the prepared specimens according to AASHTO T 269, using the bulk specific gravities of the saturated surface-dry compacted specimen (determined according to AASHTO T 166) and the theoretical maximum specific gravity of each mix (determined according to AASHTO T 209).
9. Seal and store dry samples for testing.

10.4 Effect of RAP on Mix Stiffness: Dynamic Modulus

10.4.1 Specimen Air-Void Contents

Average specimen air-void contents are summarized in Figure 10.1. Air-void contents ranged between 6.5 and 7.7 percent, with all specimens within the allowable range. There was very little variation in the air-void contents of the replicate specimens in each mix, indicating that specimen compaction was satisfactory. The mixes had fixed binder contents, as discussed in Section 8.4 (i.e., 5.5 percent for mixes containing RAP from the California and Alabama sources, and 6.0 percent for the other mixes).

10.4.2 Test Results

Table 10.2 lists the sigmoidal function parameters and activation energy term in the Arrhenius shift factor equations (Equations 4.1 to 4.3 in Section 4.2.2) that were used to develop dynamic modulus master curves.

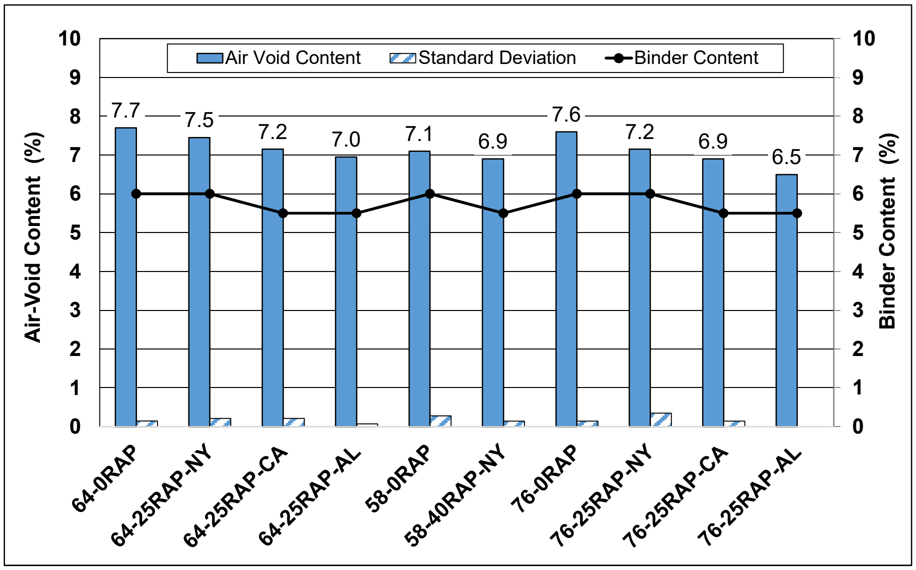


Figure 10.1: Average air-void contents of dynamic modulus specimens.

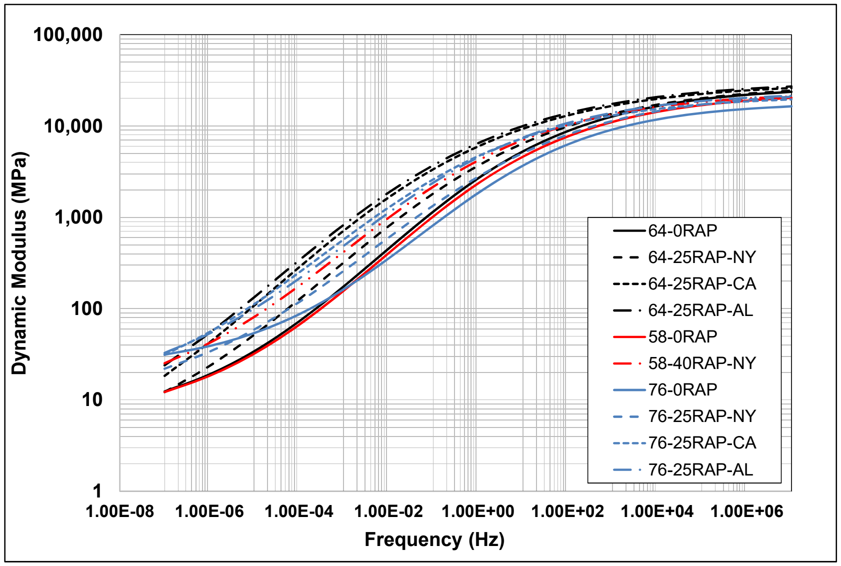
Table 10.2: Dynamic Modulus Master Curve Parameters

RAP Binder Replacement (%)	Mix Identification	Master Curve Parameters				
		δ	*α*	*β*	*γ*	Ea (kJ/mol)
0	64-0RAP	0.70	3.73	-0.99	0.45	200,000
	58-0RAP	0.73	3.64	-0.98	0.46	200,000
	76-0RAP	0.50	2.92	-0.66	0.50	200,000
25	64-25RAP-NY	0.28	4.18	-1.30	0.39	200,000
	64-25RAP-CA	-0.01	4.48	-1.68	0.37	200,000
	64-25RAP-AL	0.15	4.37	-1.68	0.37	200,000
	76-25RAP-NY	1.34	2.92	-0.66	0.50	200,000
	76-25RAP-CA	0.91	3.48	-0.99	0.42	200,000
	76-25RAP-AL	0.85	3.49	-1.44	0.42	200,000
40	58-40RAP-NY	0.88	3.48	-1.29	0.43	200,000

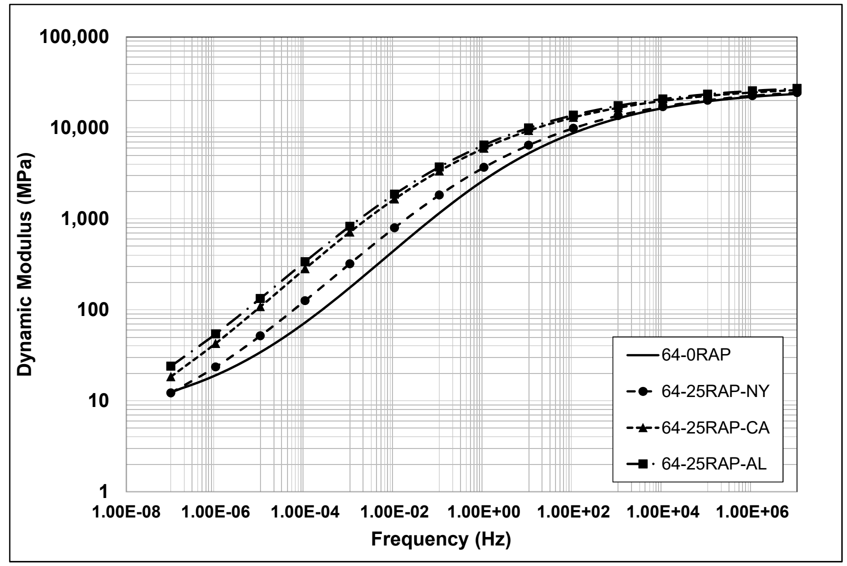
[1] Note that the mix identifications were not changed to reflect the effective 27% binder replacement rates in the California and Alabama mixes.

Figure 10.2 shows the dynamic shear modulus master curves and Figure 10.3 shows the master curves normalized to the corresponding control mix for the 10 mixes evaluated. The normalized values were obtained by dividing the stiffness of each mix with binder replacement by the corresponding value of the control mix. The following observations were made:

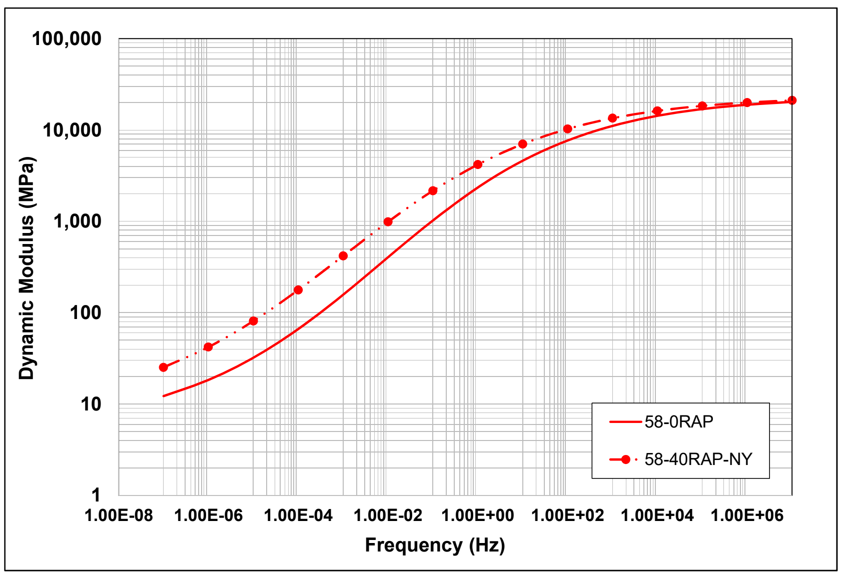
- The results were consistent with those recorded during FAM mix testing (discussed in Section 9.3.2).
- The PG 64-22 and PG 58-28 control mixes had similar stiffnesses throughout the testing frequency range. The PG 76-22 PM control mix had a notably higher stiffness than the other control mixes at testing frequencies less than 0.001 Hz, and slightly lower stiffness at higher testing frequencies.
- Incorporation of RAP into the mixes always resulted in an increase in stiffness when compared to the corresponding control mix without RAP, as expected.



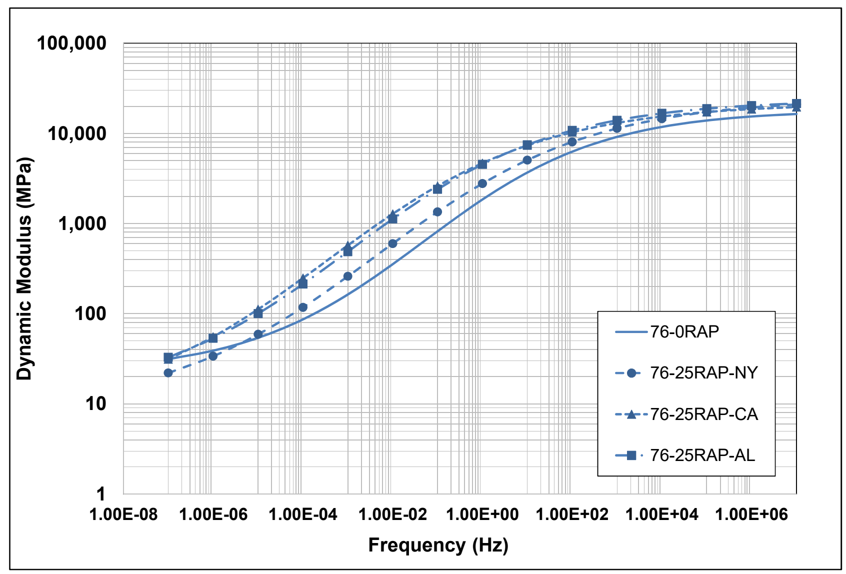
All mixes



PG 64-22 mixes

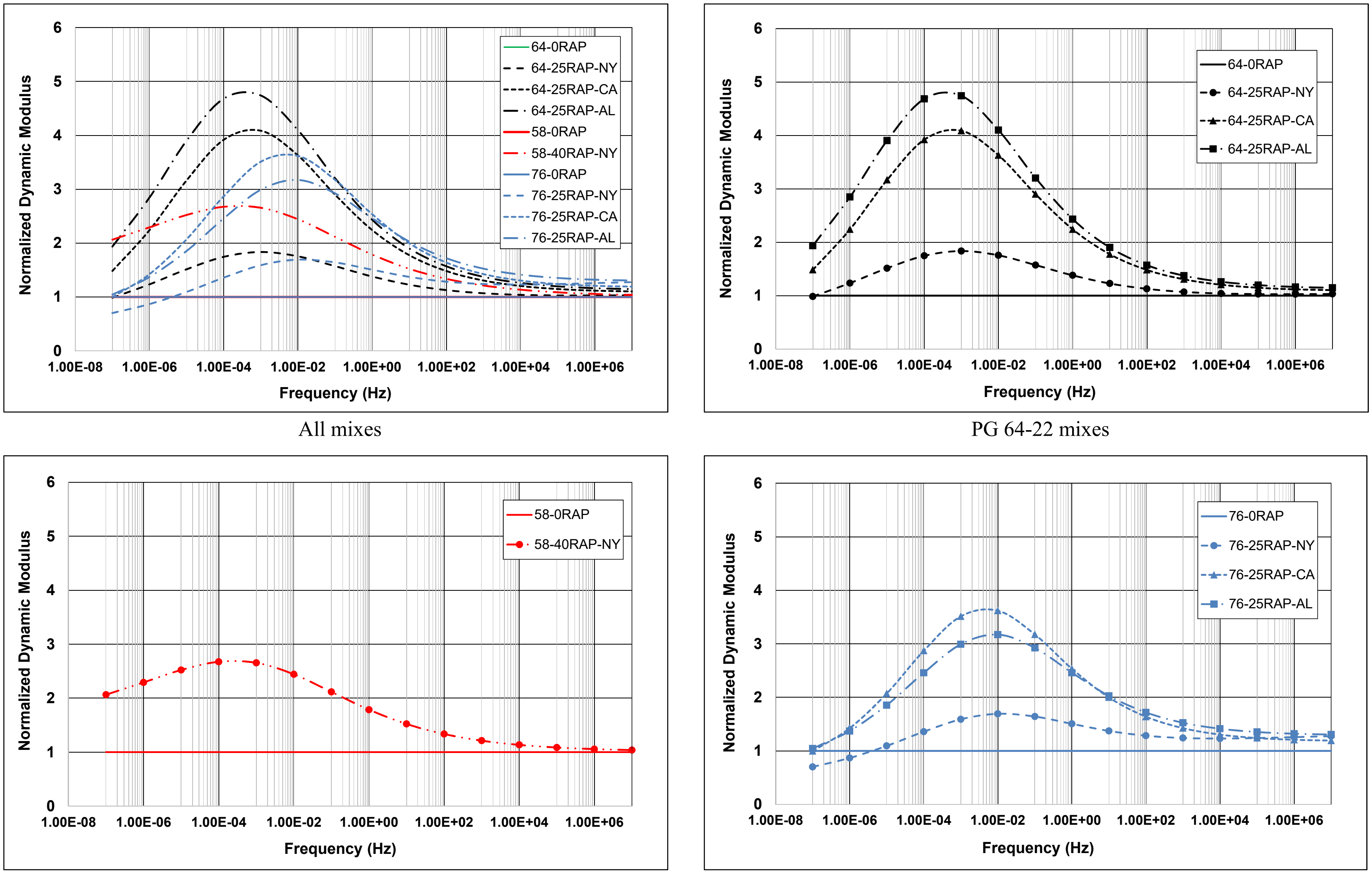


PG 58-28 mixes



PG 76-22 PM mixes

Figure 10.2: Dynamic shear modulus master curves for full-graded mixes.



All mixes

PG 64-22 mixes

PG 58-28 mixes

PG 76-22 PM mixes

Figure 10.3: Normalized dynamic shear modulus master curves for full-graded mixes.

- The normalized graphs show that the differences in modulus occurred mainly between 0.00001 Hz and 100 Hz for all mixes.
- Of the PG 64-22 mixes, those with 25 percent California and RAP were the stiffest, followed by the mix with 25 percent New York RAP. This was again attributed in part to the apparent relatively unaged condition of the New York RAP (i.e., limited long-term aging of the binder) and likely lower initial PG grading of the original binder (e.g., PG 58-34). Adding 25 percent New York, California, and Alabama RAP resulted in modulus increases up to 1.7, 4.0, and 4.8 times, respectively, over the corresponding control mixes. The largest differences were observed at frequencies around 0.001 Hz.
- Of the PG 76-22 PM mixes, those with 25 percent California and 25 percent Alabama RAP had the highest stiffnesses, followed by the mixes with 25 percent New York RAP, which is consistent with the observations for the PG 64-22 mixes. Adding 25 percent RAP from the New York, California, and Alabama sources resulted in modulus increases of up to 1.5, 3.1, and 3.5 times, respectively, over the corresponding control mixes. The largest differences were observed at frequencies between 0.005 Hz and 0.01 Hz. This difference in behavior compared to the PG 64-22 and PG 58-28 mixes was attributed mostly to the effect of the polymer modification.
- Comparing the 40 percent New York RAP mix (PG 58 binder) with the 25 percent New York RAP mixes (PG 64 and PG 76 binders) shows that the mix with 40 percent RAP had a marginally higher stiffness over the frequency range, indicating some stiffening by the RAP binder despite using the softer virgin base binder. Adding 40 percent New York RAP to the PG 58-28 mixes increased the modulus by up to 2.7 times over the control mix. The largest differences were also observed at frequencies around 0.001 Hz.
- The addition of 25 percent RAP had a larger influence on the modulus of the PG 64-22 mixes than on the PG 76-22 PM mixes, indicating the dominating effect of the polymer modification.

Figure 10.4 summarizes the dynamic modulus of the 10 mixes at three frequencies in the middle of the testing range (0.01 Hz, 1.0 Hz, and 100 Hz).

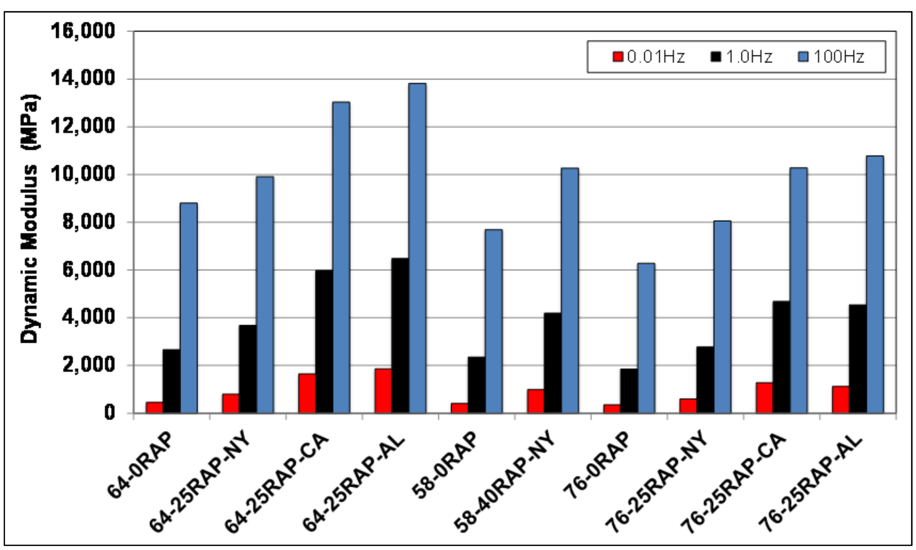


Figure 10.4: Comparison of dynamic modulus at three frequency levels at 20°C.

The following observations were made, further supporting the above discussion:

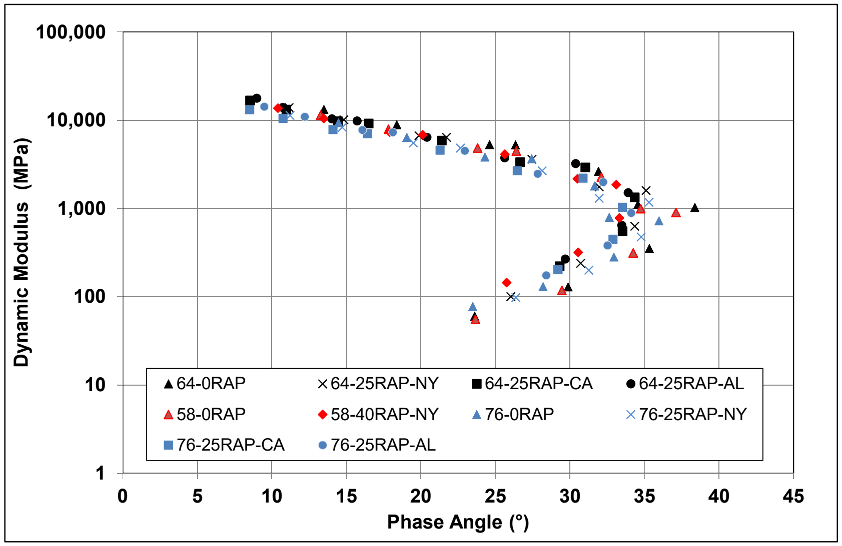
- The PG 64-22 mixes had the highest stiffnesses across the three frequencies and the PG 76-22 PM mixes had the lowest. Similar trends were observed across all the mixes.
- The effect of the addition of RAP was clearly evident at all frequencies. The California and Alabama RAP mixes were stiffer than the New York RAP mixes.
- The stiffnesses of the PG 58-28 mix with 40 percent New York RAP were similar to the PG 64-22 mix with 25 percent New York RAP, but lower than the PG 64-22 mixes with California and Alabama RAP, indicating the compensating effect of using a softer binder for the higher RAP content.
- Although the virgin binder content was slightly lower in the California and Alabama RAP mixes than in the New York RAP mix (73 percent versus 75 percent [see discussion on binder content determination in Section 8.4]), the trends in the test results were consistent with the FAM mix testing results and binder testing results (where all three binder samples were prepared with 75 percent virgin binder content), further supporting the observation that this slightly higher binder content did not significantly influence the results and that the RAP binder properties had the biggest influence.

Figure 10.5 shows Black diagrams illustrating the relationship between stiffness and phase angle for each mix for all testing temperatures and frequencies. Phase angle trends were similar across all mixes. At stiffnesses above 1,000 MPa, the phase angles of the different mixes were essentially the same. At stiffnesses below 1,000 MPa, corresponding mixes showed slightly more spread, with phase angles of the RAP mixes generally higher than those of the control mixes, indicating the less elastic behavior of the RAP mixes.

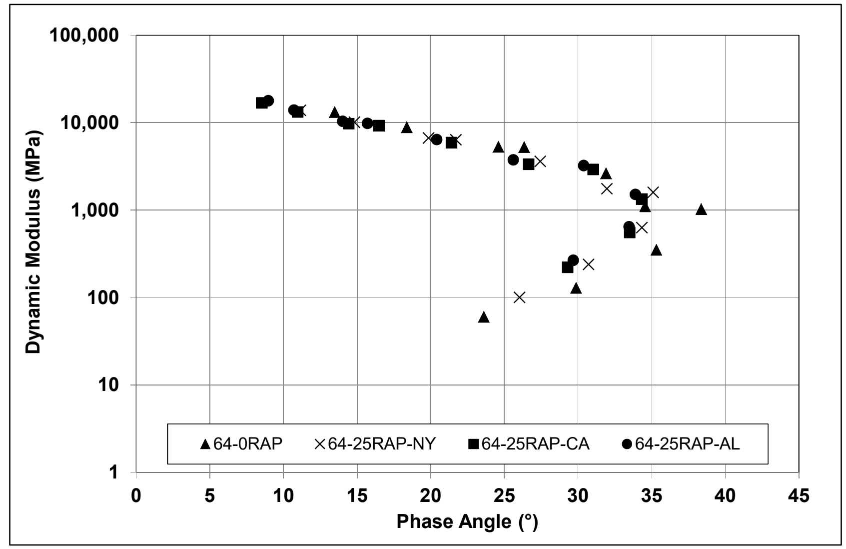
10.5 Effect of RAP on Mix Stiffness: Flexural Modulus

10.5.1 Specimen Air-Void Contents

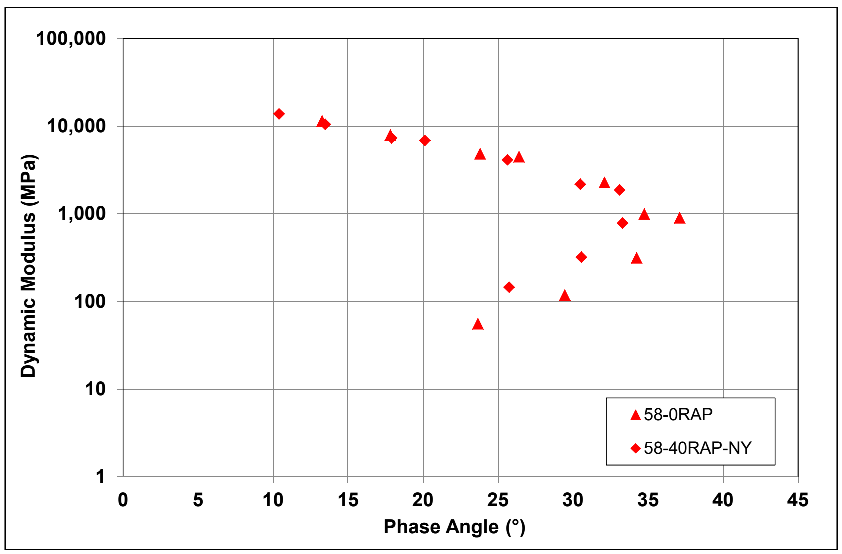
The average air-void content and standard deviation of the beams produced for each mix are summarized in Figure 10.6. Beam air-void contents in seven of the mixes were within the target range. Beam air-void contents in the remaining three mixes (i.e., 64-25RAP-AL, 76-25RAP-CA, and 76-25RAP-AL) were slightly below the target range, but a decision was made to continue with testing these beams due to the limited availability of materials and time constraints for compacting additional beams. Variation in air-void content between beams from the same mix was larger than that achieved with the gyratory-compacted specimens but was still acceptable, indicating that consistent compaction was achieved. Any potential influences of air-void content were considered during analysis of the results.



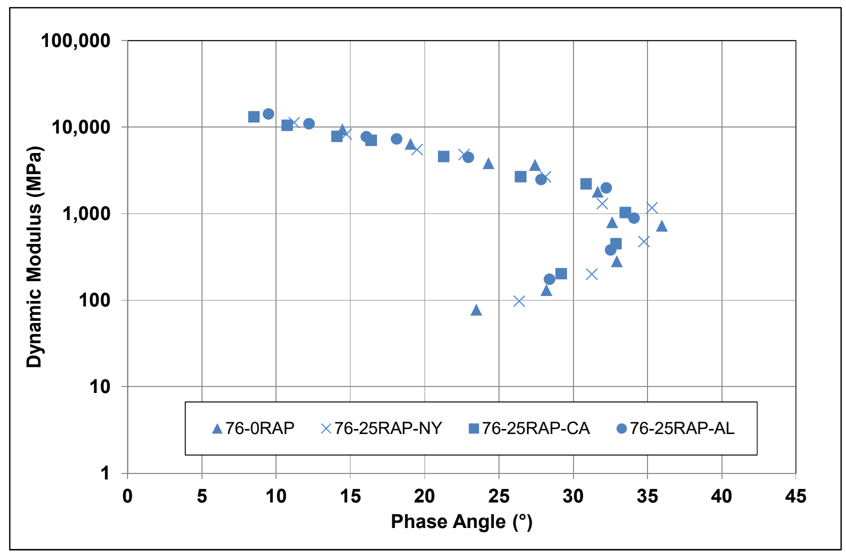
All mixes



PG 64-22 mixes



PG 58-28 mixes



PG 76-22 PM mixes

Figure 10.5: Phase angle Black diagrams for full-graded mixes.

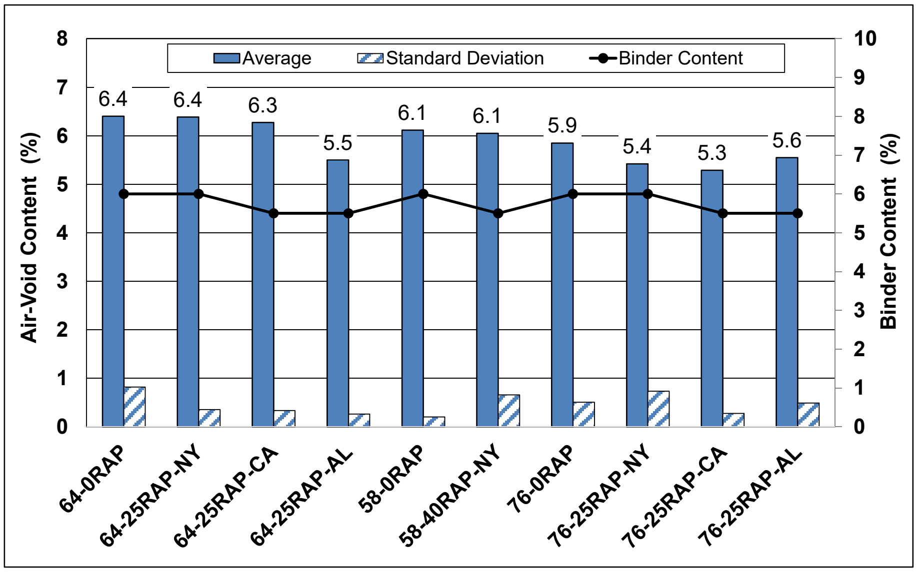


Figure 10.6: Average air-void contents of flexural frequency sweep specimens.

10.5.2 Test Results

Four-point bending frequency sweep tests were conducted to measure the stiffness (flexural modulus) of the beams under different frequencies and various loading rates. Two replicates were tested at temperatures of 10°C, 20°C, and 30°C and over frequencies of 15, 10, 5, 2, 1, 0.5, 0.2, 0.1, 0.05, 0.02, and 0.01 Hz. Tests were performed in strain-control mode. A sigmoidal function similar to that used to determine the FAM mix shear modulus and dynamic modulus was used to construct the flexural modulus master curve at a reference temperature of 20°C. The shift factor equation used for generating the master curves is shown in Equation 10.1. Table 10.3 shows the sigmoidal function parameters and the shift factor equation constant used for the evaluated mixes.

$$Log\ a_T(T) = C \times (T - T_r) \quad \textbf{(10.1)}$$

Where: C is the shift factor constant

T_r is the reference temperature and T is the testing temperature (°C)

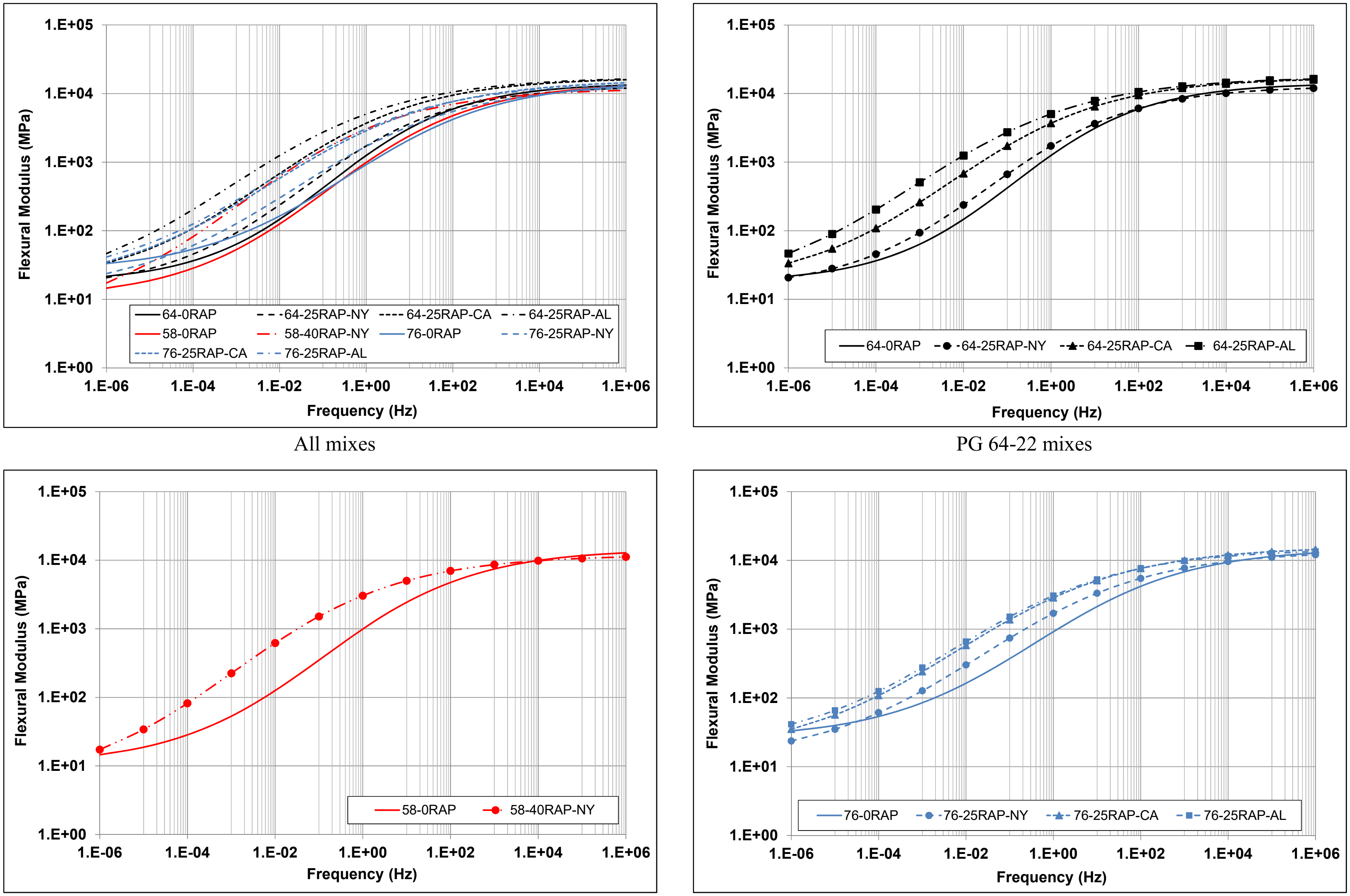
Figure 10.7 shows the flexural modulus master curves for the different mixes. Figure 10.8 shows the modulus curves normalized to those of the control mix. The normalized values were obtained by dividing the stiffness of each mix with binder replacement by the corresponding value of the control mix. The following observations were made:

- The results were consistent with the results from the AMPT dynamic modulus testing discussed in Section 10.4.2.
- The master curves of all the mixes merged at high frequencies (> 1,000 Hz, corresponding to colder temperatures).

Table 10.3: Flexural Modulus Master Curve Parameters

RAP Binder Replacement (%)	Mix Identification	Master Curve Parameters				
		δ	α	β	γ	Ea (kJ/mol)
0	64-0RAP	0.70	3.51	-0.78	-0.58	-0.12
	58-0RAP	1.23	2.79	-0.54	-0.70	-0.14
	76-0RAP	1.48	2.56	-0.33	-0.67	-0.13
25	64-25RAP-NY	1.14	2.97	-0.88	-0.61	-0.13
	64-25RAP-CA	1.18	3.06	-1.28	-0.55	-0.14
	64-25RAP-AL	1.06	3.18	-1.58	-0.51	-0.15
	76-25RAP-NY	1.08	3.06	-0.86	-0.52	-0.14
	76-25RAP-CA	1.15	3.05	-1.13	-0.51	-0.14
	76-25RAP-AL	1.24	2.93	-1.19	-0.52	-0.14
40	58-40RAP-NY	0.67	3.41	-1.56	-0.53	-0.12

- The stiffnesses of the three control mixes varied between the frequencies, as expected. At the lower frequencies, corresponding to warmer temperatures, the PG 76-22 PM mix had the highest stiffness and the PG 58-28 mix had the lowest stiffness. Mix stiffnesses were the same at a frequency of 0.1 Hz, but at higher frequencies (1.0 Hz through 1,000 Hz, corresponding to decreasing temperatures) the PG 64-22 mix had the highest stiffness and the PG 76-22 PM mix had the lowest stiffness. This is consistent with the effect of the polymer increasing stiffness at higher temperatures, but providing additional flexibility at lower temperatures.
- Adding RAP to the mixes always resulted in an increase in stiffness compared to the corresponding control mix without RAP, as expected.
- The normalized master curves show that the differences in modulus occurred mainly between 0.00001 Hz and 100 Hz, which is consistent with AMPT dynamic modulus results.
- The PG 64-22 mix with 25 percent Alabama RAP had the highest stiffness of all the mixes over the full range of frequencies, which is consistent with AMPT dynamic modulus results.
- Of the PG 64-22 mixes, the one with 25 percent Alabama RAP was the stiffest, followed by the mix with 25 percent California RAP and then the mix with 25 percent New York RAP. Adding 25 percent California and Alabama RAP increased the stiffness of the mix by up to six times and eleven times that of the control, respectively. Adding 25 percent New York RAP increased the flexural stiffness by up to 2.5 times that of the control.
- The stiffnesses of the PG 58-28 control mix and the mix with 40 percent New York RAP merged at the higher and lower frequencies, corresponding to the coldest and warmest temperatures. The stiffening effect of the RAP occurred primarily in the 0.001 Hz to 10 Hz frequency range. The greatest increase in stiffness was about six times that of the control mix, at a frequency of 100 Hz.
- Of the PG 76-22 PM mixes, those with 25 percent California and 25 percent Alabama RAP had similar high stiffnesses (up to four times that of the control) compared to the mix with 25 percent New York RAP (up to two times that of the control), which is consistent with the observations for the PG 64-22 mixes and with the AMPT dynamic modulus results. The largest differences were observed at frequencies between 0.005 Hz and 0.01 Hz. The smaller difference between the behavior of the PG 76-22 PM mixes and the PG 58-28 and PG 64-22 mixes was again attributed to the effect of the polymer modification. Results from the two PG 76-22 PM mixes with air-void contents marginally lower than the target 5.5 percent did not appear to differ from the general trend.



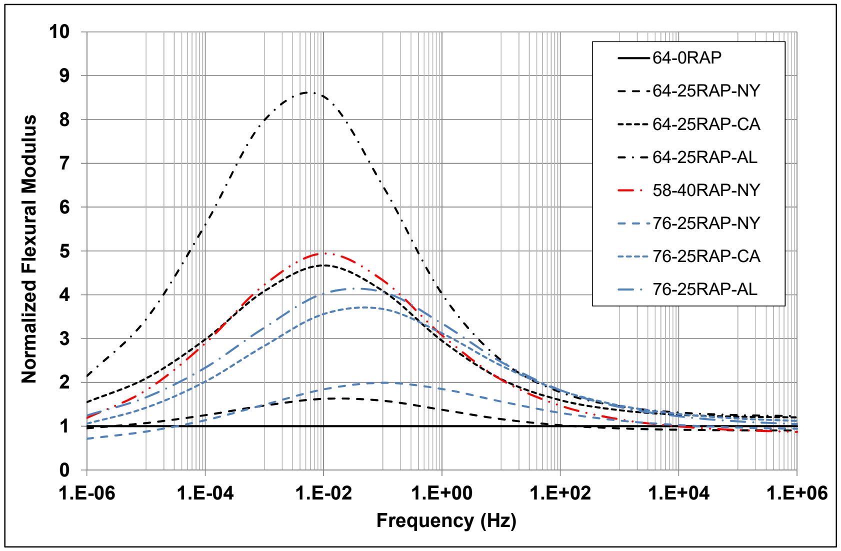
All mixes

PG 64-22 mixes

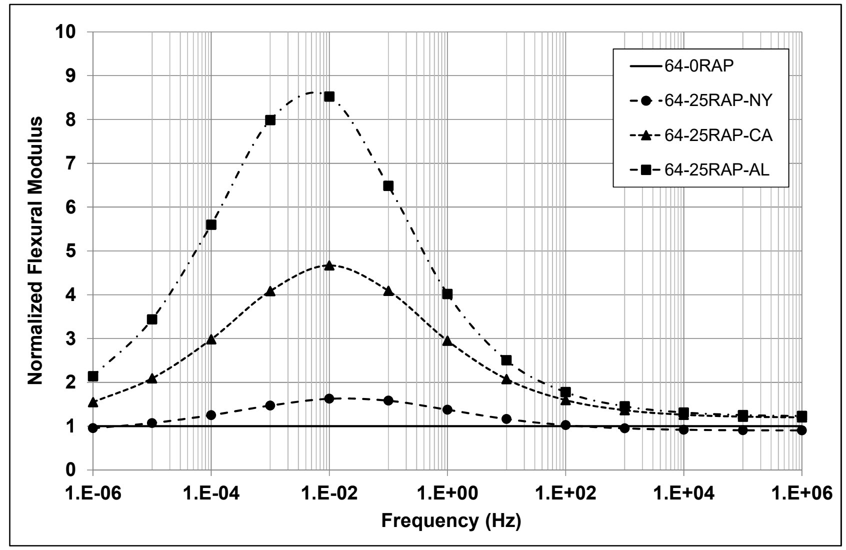
PG 58-28 mixes

PG 76-22 PM mixes

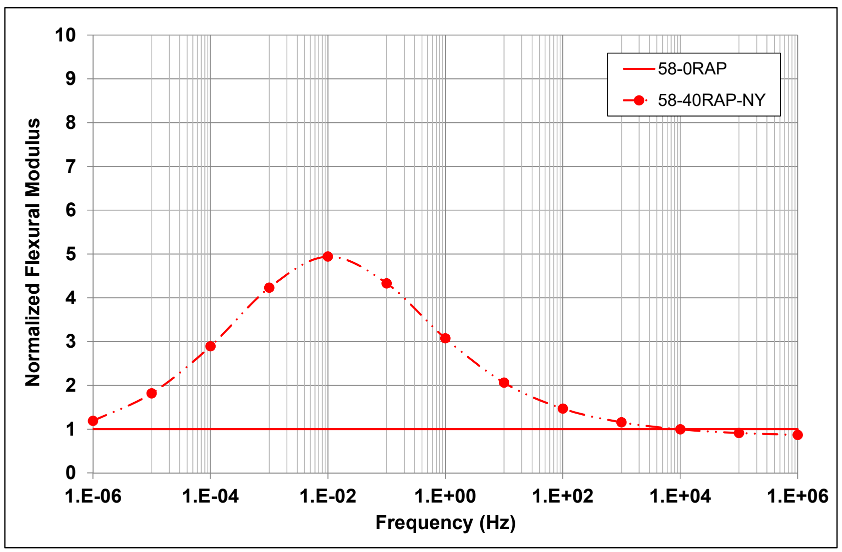
Figure 10.7: Flexural modulus master curves for full-graded mixes.



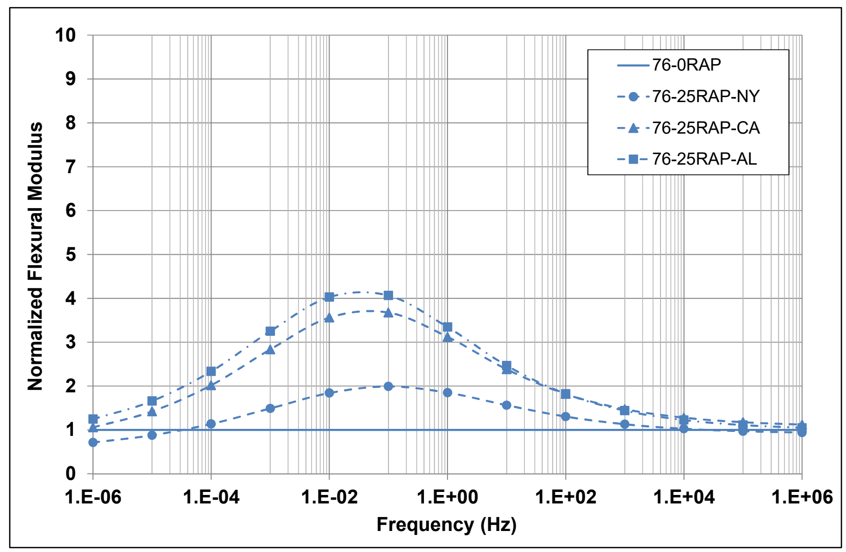
All mixes



PG 64-22 mixes



PG 58-28 mixes



PG 76-22 PM mixes

Figure 10.8: Normalized flexural modulus master curves for full-graded mixes.

- Comparing the 40 percent New York RAP mix (PG 58 binder) with the 25 percent New York RAP mixes (PG 64 and PG 76 binders) showed that the mix with 40 percent RAP had a higher stiffness over the frequency range, indicating the stiffening effect of the RAP despite using the softer binder. This observation differed from the AMPT dynamic modulus results, where the softer binder compensated somewhat for the increase in stiffness caused by the higher RAP content.

10.6 Effect of RAP on Rutting Performance: Repeated Load Triaxial

10.6.1 Specimen Air-Void Contents

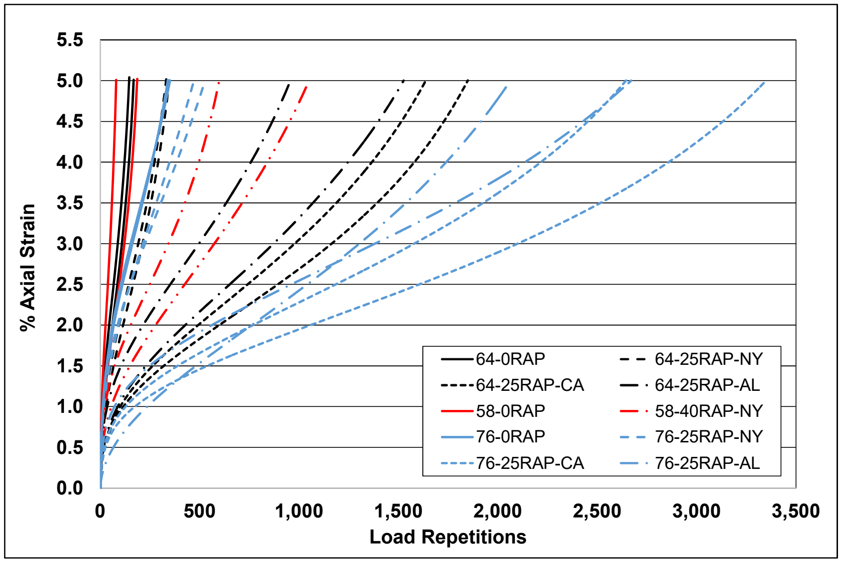
The same mix specimens used to assess dynamic modulus were also used to assess rutting performance using the flow number test setup in an asphalt mixture performance tester (AMPT). Specimen air-void contents ranged between 6.5 and 7.7 percent (see Figure 10.1), with all specimens within the allowable range.

10.6.2 Test Results

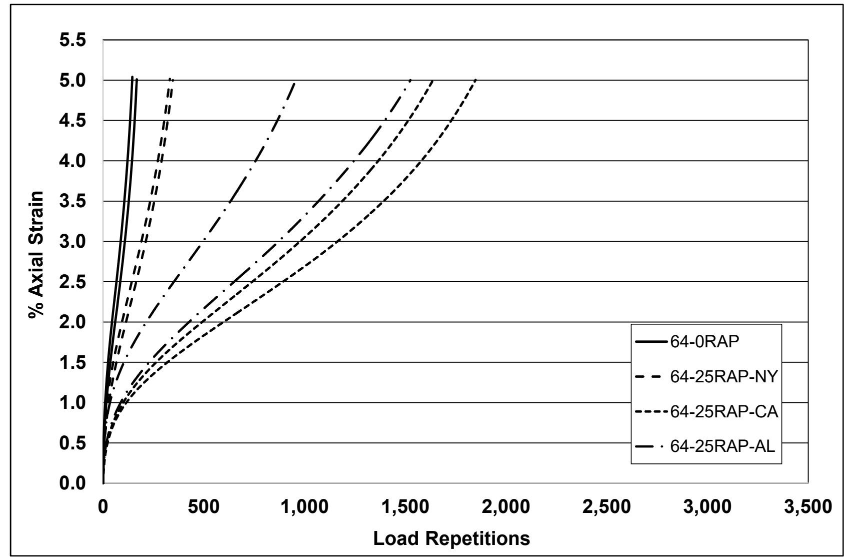
All tests were conducted at 52°C with 30 kPa contact stress and 600 kPa deviator stress in an unconfined configuration. The results were analyzed in terms of axial strain and flow number (i.e., the number of load repetitions to the start of tertiary flow as determined by the AMPT software), both of which are measures of expected cumulative permanent deformation. Figure 10.9 shows the development of axial strain versus loading cycles for both specimens in each mix. The following observations were made:

- Variability between specimens in the same mix was considered acceptable for repeated load tests. Results in terms of ranking of performance were consistent with the stiffness measurements discussed in the previous two sections.
- Adding RAP to the mixes improved the rutting resistance properties, as shown by the increase in stiffness and consequent decrease in the rate of change in permanent deformation.
- Performance varied across the different RAP sources, with the RAP sourced in California generally showing the most potential improvement in rutting performance, followed by the Alabama RAP and then by the New York RAP.
- The control mix with PG 76-22 PM binder had the lowest increase in cumulative permanent strain (the best rutting resistance) followed by the control mixes with PG 64-22 binder, as expected. The mixes with PG 58-28 binder had a much faster development of permanent deformation compared to the other control mixes. Adding 40 percent RAP to the PG 58-28 mix resulted in a notable improvement in rutting performance.

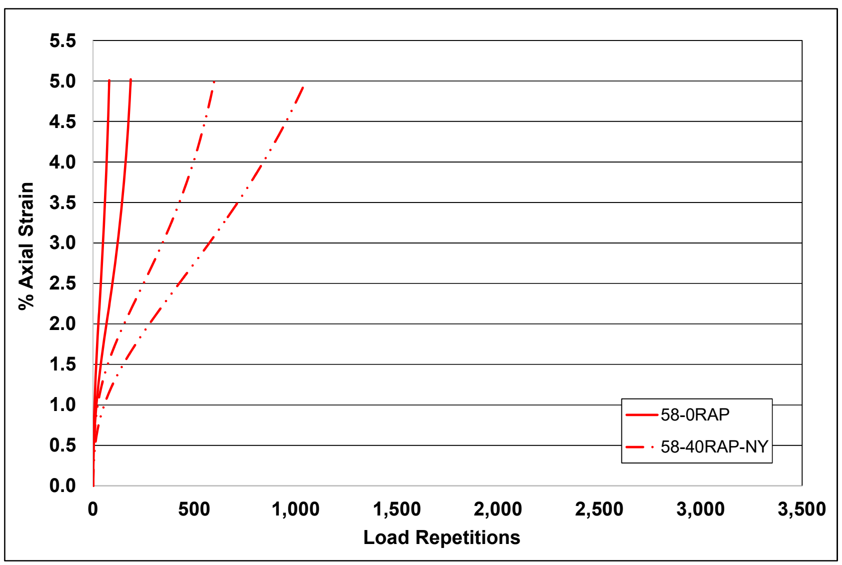
Figure 10.10 and Figure 10.11 show the average number of load repetitions required to reach three percent axial strain and the flow number, respectively, at a testing temperature of 52°C for all mixes. Error bars show the differences between the two replicates. Binder content and air-void content are shown on the plots for reference purposes. The flow numbers of the RAP mixes after normalizing to the corresponding control mixes are shown in Figure 10.12 to better illustrate the influence of the RAP on performance.



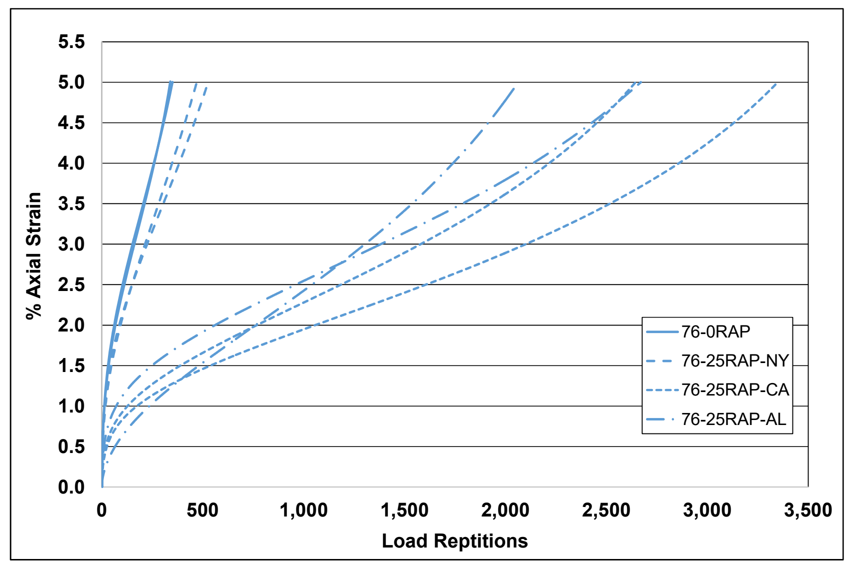
All mixes



PG 64 mixes



PG 58 mixes



PG 76 mixes

Figure 10.9: Percent axial strain vs. load repetitions.

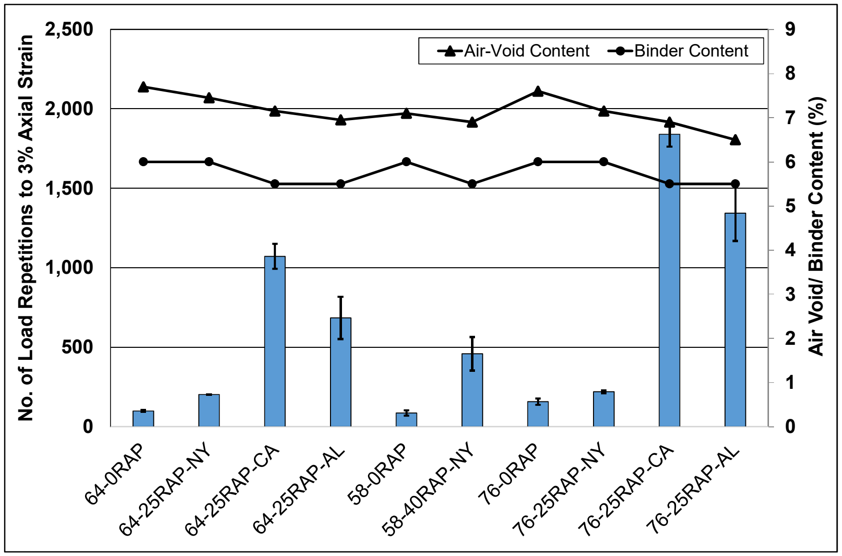


Figure 10.10: Average number of load repetitions to reach 3% axial strain at 52°C.

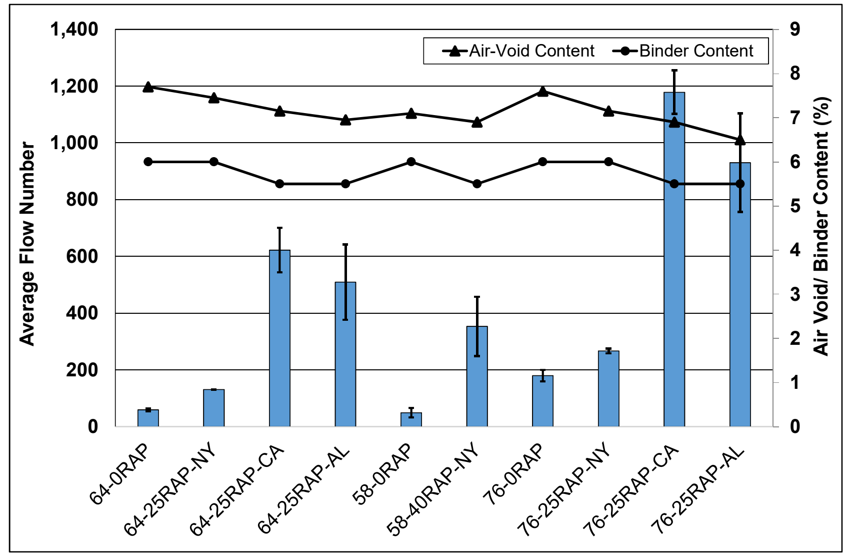


Figure 10.11: Average flow number at 52°C.

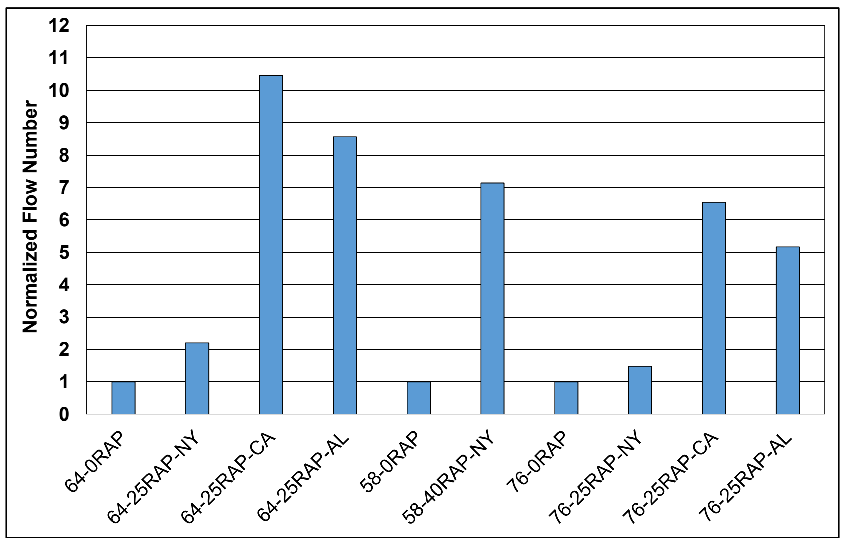


Figure 10.12: Normalized flow number.

10.7 Effect of RAP on Rutting Performance: Asphalt Pavement Analyzer

Asphalt Pavement Analyzer (APA) testing is not a requirement in the Caltrans specifications, but it is in the FAA P-401 specifications. APA testing was therefore carried out on gyratory-compacted specimens according to AASHTO T 340 as part of the FAA study at the FAA William J. Hughes Technical Center. Hose pressure was set at 250 psi (1,700 kPa) and load was set at 250 lb (113 kg). The testing temperature was maintained at 64°C (147°F). Mixes were considered to have failed if the rut depth exceeded 10 mm at 4,000 loading cycles. The results are included in this report as an additional rutting test.

10.7.1 Specimen Air-Void Contents

Specimen air-void contents ranged between 6.3 and 7.4 percent, with all specimens within the allowable range (Figure 10.13). There was very little variability between the specimens in each mix.

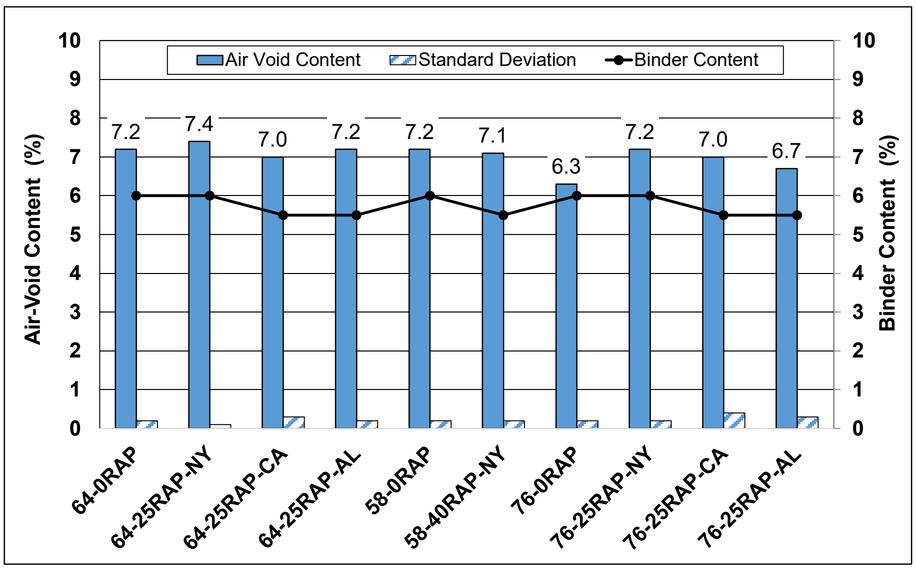
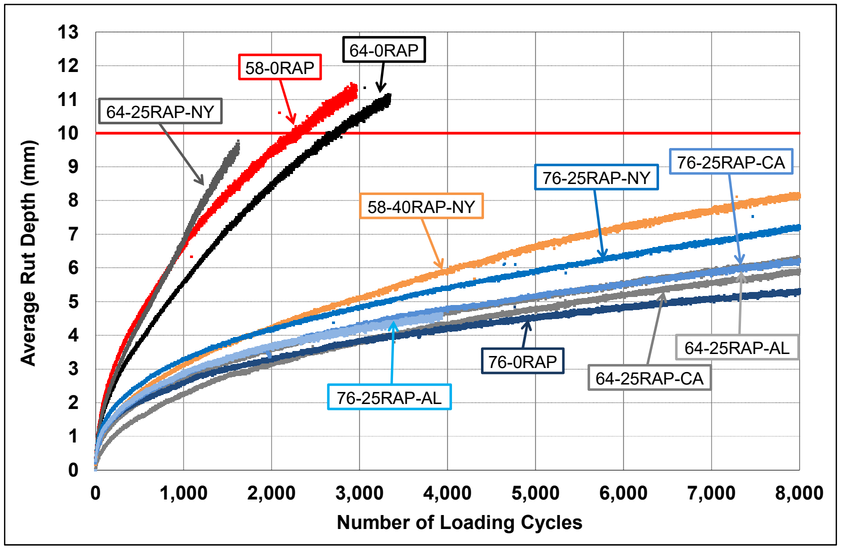


Figure 10.13: Average air-void contents of Asphalt Pavement Analyzer specimens.

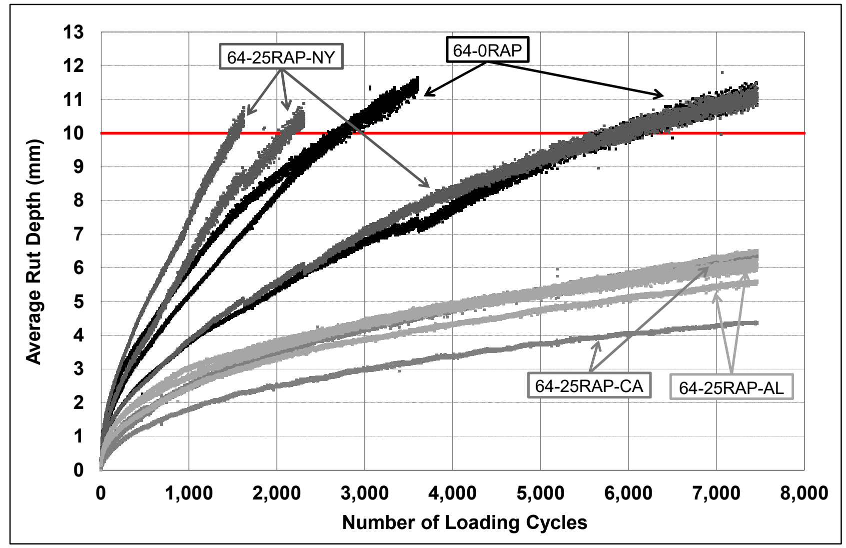
10.7.2 Test Results

The Asphalt Pavement Analyzer test results are summarized in Figure 10.14. A technical problem with the equipment resulted in the PG 76-22 PM mix with 25 percent Alabama RAP testing being terminated after approximately 4,000 loading cycles. This incident was unlikely to influence the interpretation of the results given that this was the point at which failure was assessed. The following observations were made:

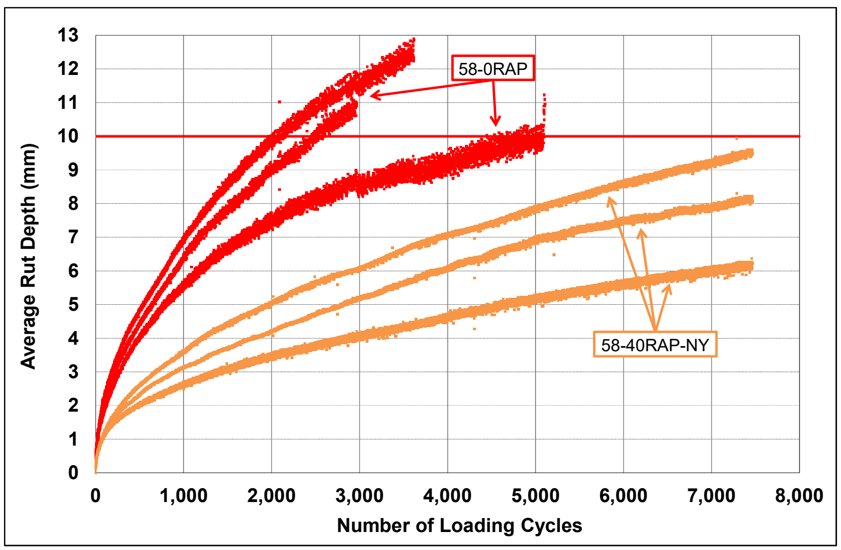
- The result trends were generally consistent with those from repeated load triaxial testing (discussed in Section 10.6.2) and Hamburg Wheel-Track Testing (discussed in Section 10.8.2), with some exceptions.
- The PG 64-22 and PG 58-28 control mixes and the PG 64-22 mix with 25 percent New York RAP did not meet the FAA P-401 specification requirements. All other mixes were well within the required limit.



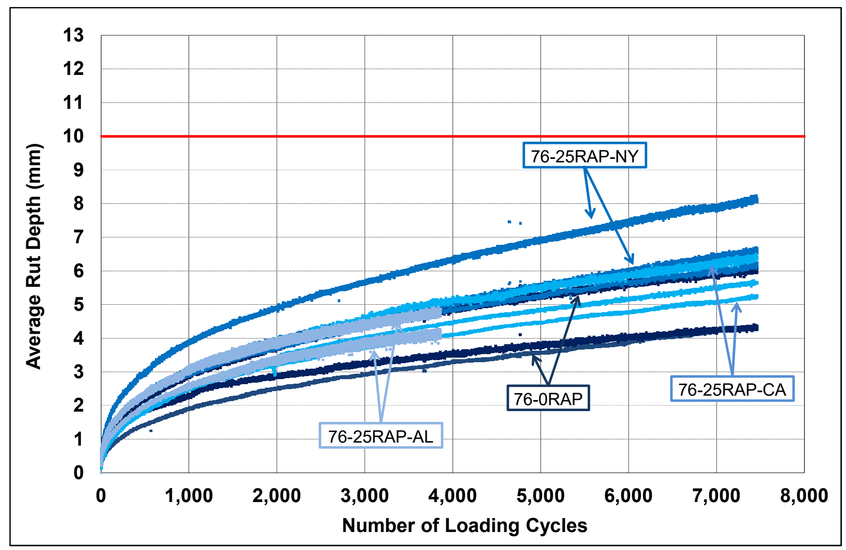
All mixes



PG 64-22 mixes



PG 58-28 mixes



PG 76-22 PM mixes

Figure 10.14: Average Asphalt Pavement Analyzer rut progression for full-graded mixes.

- Adding RAP to the PG 64-22 and PG 58-28 mixes improved rutting performance by a considerable margin. Adding RAP to the PG 76-22 PM mix appeared to have a negative effect on the rutting performance, which was inconsistent with the repeated load triaxial and Hamburg Wheel-Track Test results (see Section 10.8) for these mixes. This was attributed in part to sensitivity of the test to possible "dilution" of the polymer modification by the 25 percent unmodified binder replacement.
- The mixes containing RAP sourced in California and Alabama performed better than the mixes containing RAP sourced in New York, which is consistent with the results from the other tests.

10.8 Effect of RAP on Rutting Performance/Moisture Sensitivity: Hamburg Wheel

Hamburg Wheel-Track testing was carried out according to AASHTO T 324 on gyratory-compacted specimens. Water temperature was maintained at 50°C (122°F). The California Department of Transportation (Caltrans) specification requirements were used as a guide for interpreting the test results (Table 10.4).

Table 10.4: Caltrans Specifications for Hamburg Wheel-Track Test

PG Grade	Minimum No. of Passes at 12.5 mm Rut Depth	Minimum No. of Passes at Inflection Point
58	10,000	10,000
64	15,000	10,000
70	20,000	12,500
76	25,000	15,000

10.8.1 Specimen Air-Void Contents

Specimen air-void contents ranged between 6.5 and 7.4 percent, with all specimens within the allowable range (Figure 10.15). There was very little variability between the specimens in each mix.

10.8.2 Test Results

Figure 10.16 shows the average rut progression curves for the 10 mixes evaluated. Figure 10.17 and Figure 10.18 summarize the average and normalized maximum rut depth of each mix respectively after 10,000, 20,000, and 30,000 wheel passes. The approximate inflection points of each mix are summarized in Figure 10.19. The following observations were made, taking into consideration that a liquid anti-strip additive was used during mix preparation to limit moisture damage (see Section 8.3.4):

- There was a notable difference in rutting performance between the control mixes and the mixes containing RAP, with the control mixes having a considerably higher rate of rut depth increase than the mixes containing RAP. Adding RAP to the mix therefore appeared to improve both rutting performance and moisture resistance, which is consistent with the results from other tests.

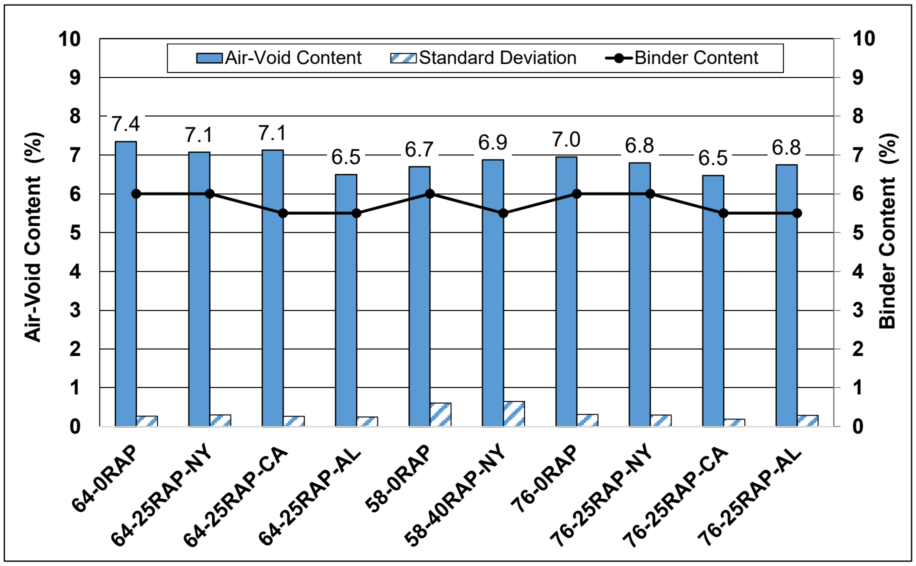
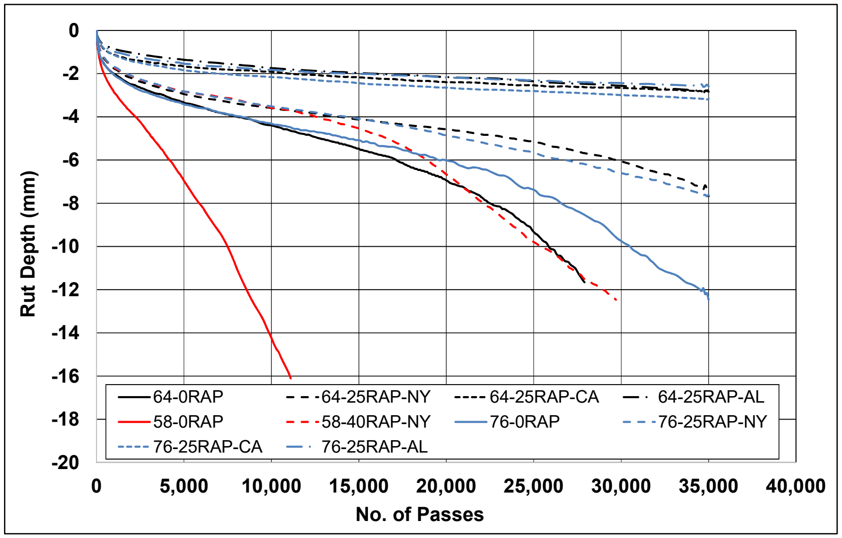
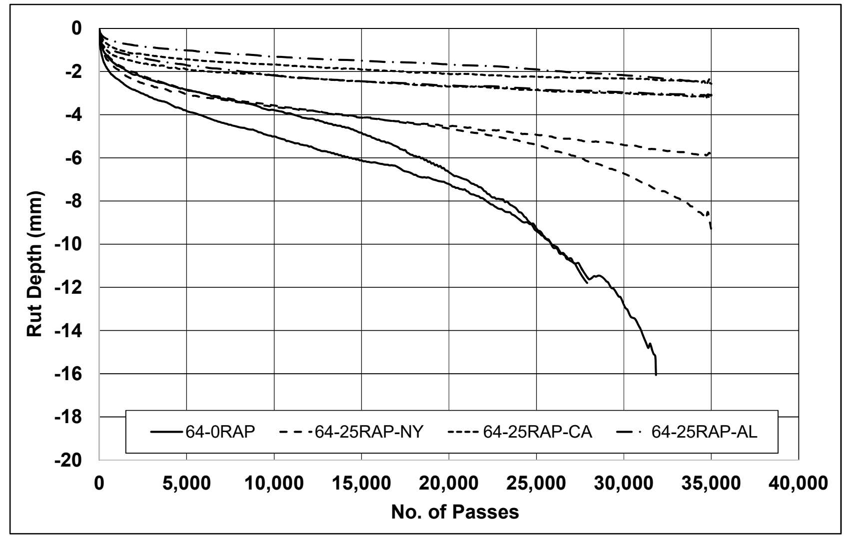


Figure 10.15: Average air-void contents of Hamburg Wheel-Track Test specimens.

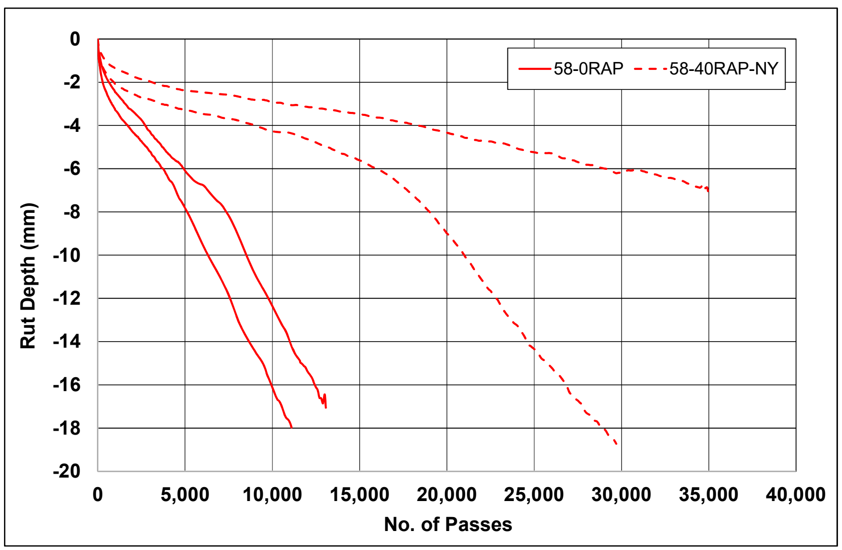
- The three control mixes showed some evidence of moisture sensitivity, with all three indicating a progression from creep slope to stripping slope. The number of wheel passes to reach the inflection point between the creep and stripping slopes differed between the mixes, with the PG 58-28 control mix being the most sensitive to moisture and the PG 76-22 PM control mix being the least sensitive. In terms of typical state department of transportation specifications, only the PG 58-28 control mix would be considered as moisture sensitive (i.e., rut depth > 12.5 mm after 10,000 wheel passes; inflection point > 10,000 wheel passes). The PG 64-22 and PG 76-22 PM control mixes exceeded minimum typical state department of transportation specification limits by a considerable margin (i.e., rut depth > 12.5 mm after 15,000 and 25,000 wheel passes respectively; inflection points > 10,000 and 15,000 wheel passes respectively).
- There was a distinct difference in rutting performance between the mixes containing New York RAP and the mixes containing California and Alabama RAP. Initial embedment on the mixes containing New York RAP was notably higher than the other mixes regardless of binder grade. This performance was consistent with other rutting performance test results. The New York RAP mixes did not show a clear inflection point (i.e., the mix was not moisture sensitive and the binder did not strip from the aggregate), but rather showed continually increasing rut depth with increasing number of wheel passes. The New York RAP mix results were, however, still well within typical state department of transportation specifications for all binder grades.
- The mixes with California and Alabama RAP performed well in all mixes, and there was very little apparent difference between the mixes with the two binder grades. Limited early embedment occurred and thereafter the rate of rut depth increase was slow, with the average maximum rut depths of each mix not exceeding 3.5 mm after 35,000 wheel passes. Analysis in terms of normalized rut depth indicate that adding RAP to the PG 64-22 mixes had a marginally greater influence on performance than adding RAP to the PG 76-22 PM mixes, especially in terms of extended testing duration (i.e., after 20,000 and 30,000 wheel passes).



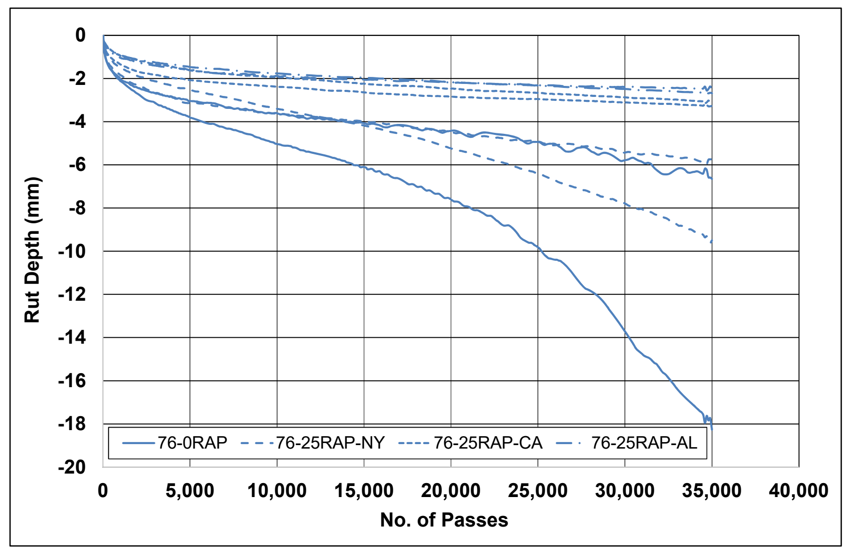
All mixes



PG 64-22 mixes



PG 58-28 mixes



PG 76-22 PM mixes

Figure 10.16: Average Hamburg Wheel-Track Test rut progression for full-graded mixes.

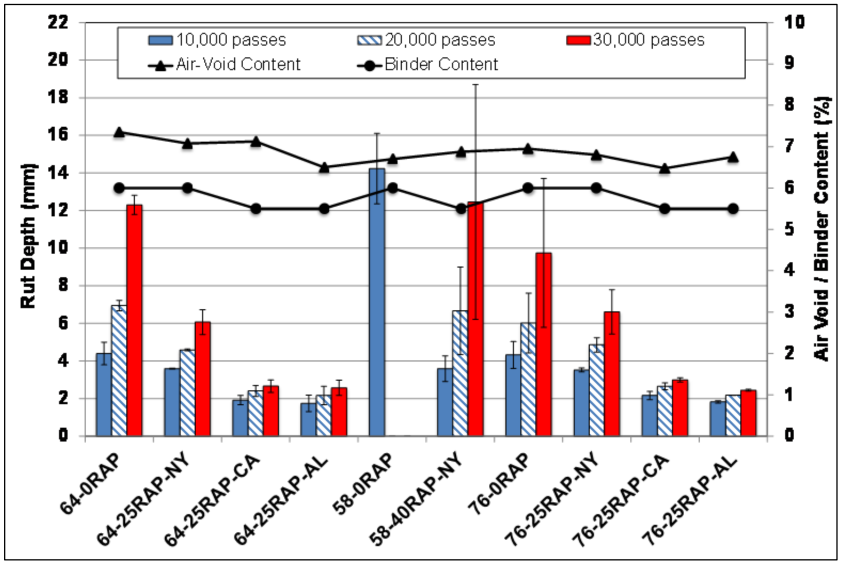


Figure 10.17: Average Hamburg Wheel-Track Test rut depth.

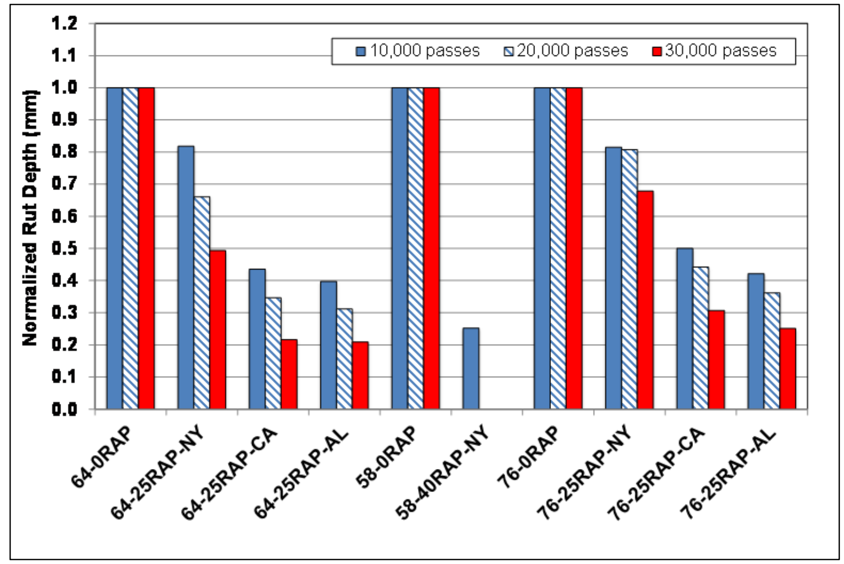


Figure 10.18: Normalized Hamburg Wheel-Track Test rut depth.

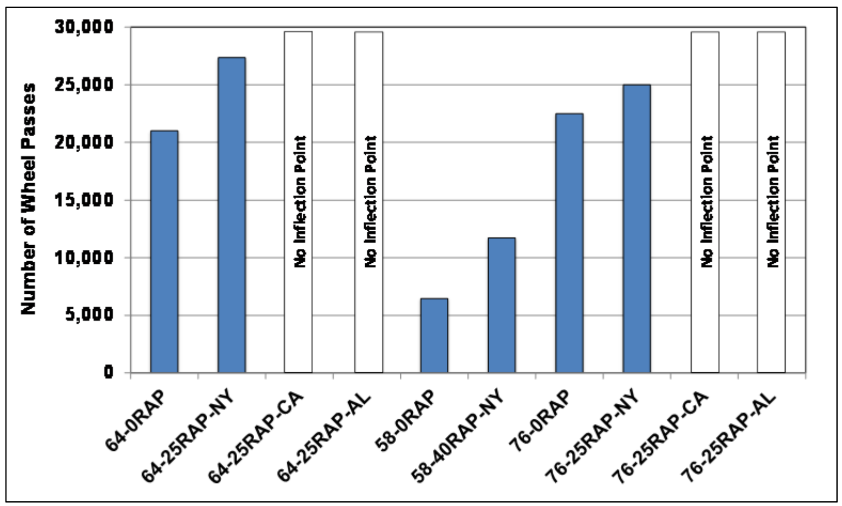


Figure 10.19: Approximate Hamburg Wheel-Track Test inflection points.

- The PG 58-28 mix with 40 percent New York RAP showed an initial embedment trend similar to those of PG 64-22 and PG 76-22 PM, but after approximately 15,000 wheel passes, the rate of rut depth of the PG 58-28 mix increased significantly, implying that stripping of the binder from the aggregate had started. The PG 58-28 mix with 40 percent New York RAP was the only RAP mix that indicated a clear inflection point.

10.9 Effect of RAP on Fatigue/Reflective Cracking Performance: Four-Point Beam

The four-point beam fatigue test provides an indication of the resistance of an asphalt mix to fatigue cracking. Beam specimens are subjected to four-point bending by applying sinusoidal loading at three different strain levels (high, intermediate, and low) at a frequency of 10 Hz and temperature of 20°C. The fatigue life at each strain level was selected as the cycle at which maximum values of stiffness multiplied by the number of cycles occurs.

In this UCPRC study, the testing approach currently specified in AASHTO T 321 was modified to optimize the quantity and quality of the data collected. Replicate specimens were first tested at high and medium strain levels to develop an initial regression relationship between fatigue life and strain (Equation 10.2), with strain levels selected, based on experience, to achieve fatigue lives between 10,000 and 100,000 load cycles and between 300,000 and 500,000 load cycles, respectively. Additional specimens were then tested at lower strain levels selected based on the initial linear relationship to achieve a fatigue life of about 1 million load repetitions. The regression relationship was then refined to accommodate the measured stiffness at the lower strain level.

$$LnN = A + B \times \varepsilon \qquad \textbf{(10.2)}$$

Where: N is fatigue life (number of cycles)
ε is the strain level (µstrain)
A and B are model parameters

10.9.1 Specimen Air-Void Contents

The average air-void content and standard deviation of the beams produced for each mix are summarized in Figure 10.20. Beam air-void contents in eight of the ten mixes were within the target range. Beam air-void contents in the remaining two mixes (i.e., 76-25RAP-NY and 76-25RAP-CA) were slightly below the target range, but as with the flexural modulus beam specimens, a decision was made to continue with testing due to the limited availability of materials and time constraints for compacting additional beams. Any potential influences of air-void content were considered during analysis of the results. Variation in air-void content between beams of the same mix was again larger than that achieved with the gyratory-compacted specimens, but was still acceptable, indicating that consistent compaction was achieved.

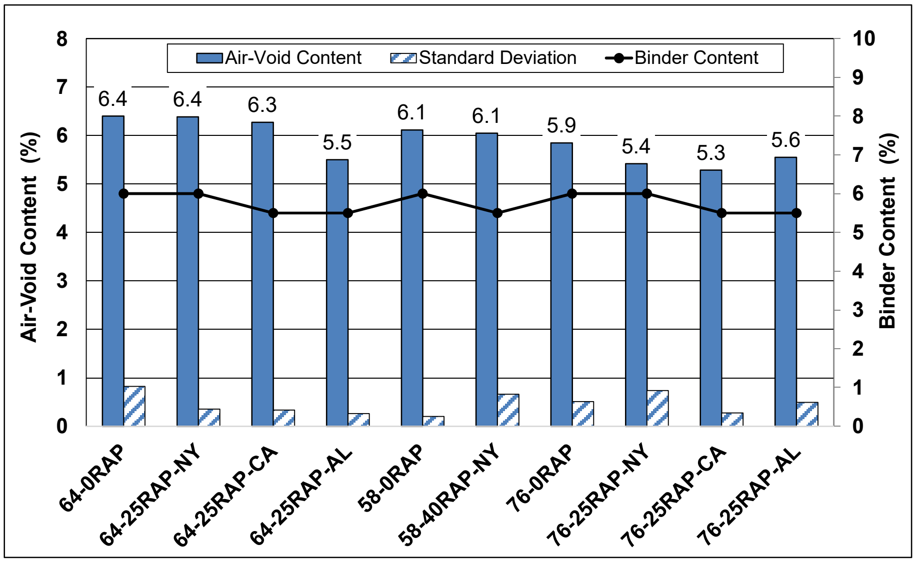
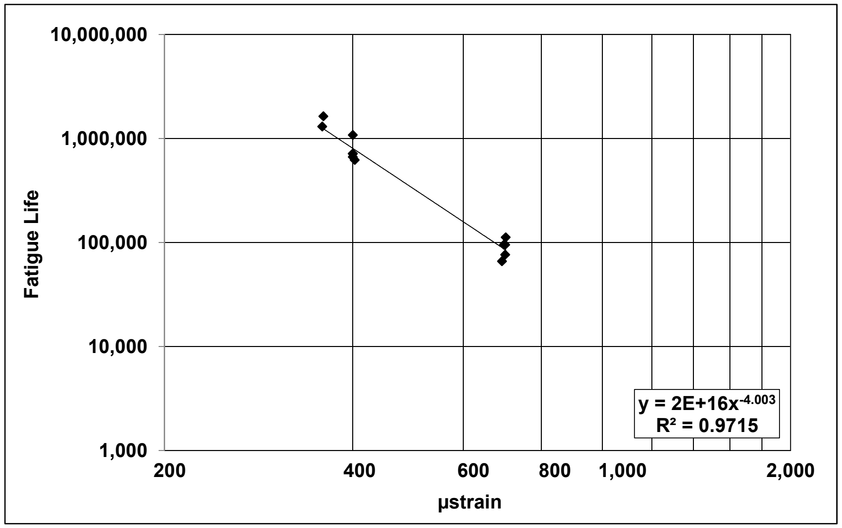


Figure 10.20: Average air-void contents of beam fatigue test specimens.

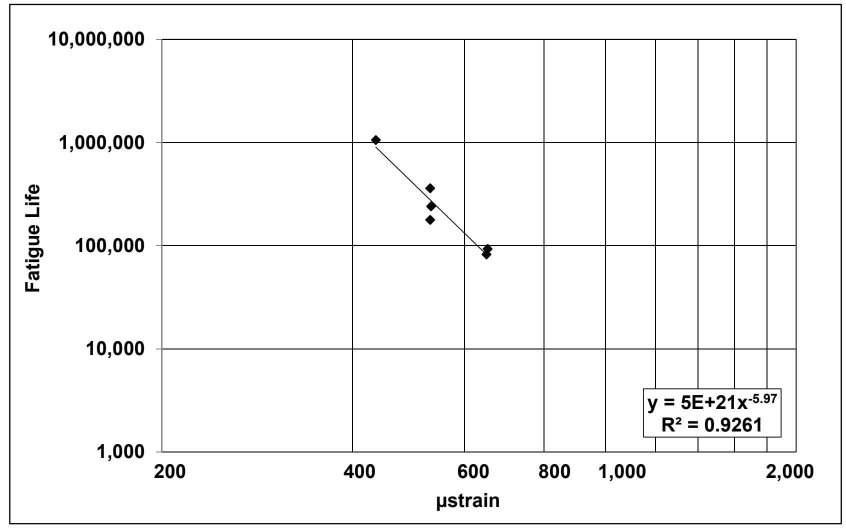
10.9.2 Test Results

Plots of the fatigue models for each binder grade are shown in Figure 10.21 through Figure 10.23. The models were considered to be appropriate based on the high R-squared values of the model fitting and repeatability of the test results at each strain level. The variability of the results for the PG 76-22 PM mixes was higher than that of the other mixes (i.e., lower r-squared values), which was attributed to testing at higher initial strain levels compared to the unmodified PG 64-22 and PG 58-28 mixes. Calculated fatigue lives at 200 µstrain, 400 µstrain, and 600 µstrain of all the mixes are compared in Figure 10.24. Note that no mixes were tested at 200 µstrain and that fatigue life at this strain level was extrapolated. The following observations were made:

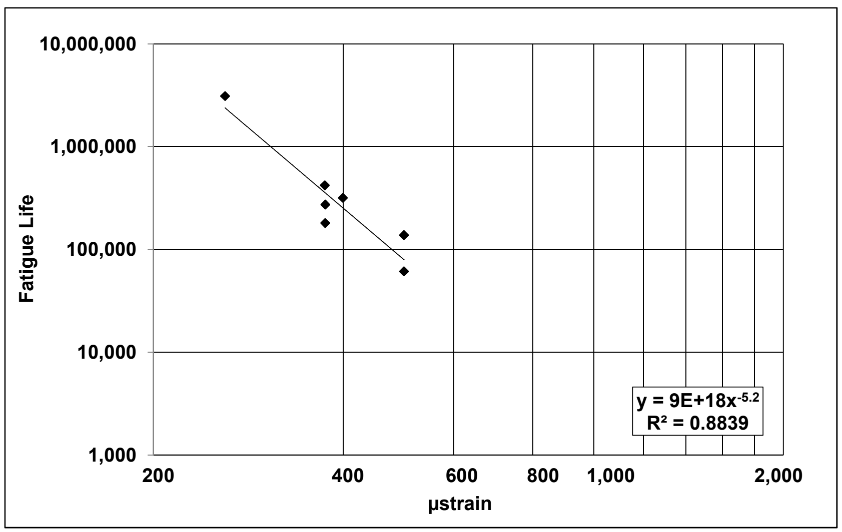
- The PG 76-22 PM control mix had the highest fatigue life and was therefore potentially considerably less susceptible to fatigue or reflective cracking than the other mixes. Adding 25 percent RAP to the mix reduced the fatigue life considerably, with the degree of reduction dependent on the RAP source. RAP from the New York source had the lowest impact, as expected, based on the results of the stiffness and rutting performance tests. RAP from the California and Alabama sources had the highest impact on fatigue life, which is consistent with other test results. Mixes prepared with the California and Alabama RAP had similar fatigue life performance.
- The PG 64-22 mixes had the lowest fatigue lives of the 10 mixes. Mixes containing RAP from the California and Alabama sources had the poorest performance, followed by the control mix and the mix prepared with RAP from the New York source. These results were again consistent with the results from the other tests (i.e., the PG 64-22 mixes with the best rutting performance had the lowest fatigue lives).
- The PG 58-28 control mix had slightly better fatigue life properties than the PG 64-22 control mix, as expected. Adding RAP from the New York source to the PG 58-28 mix appeared to improve performance at lower strain levels, but reduced the fatigue life at higher strain levels.



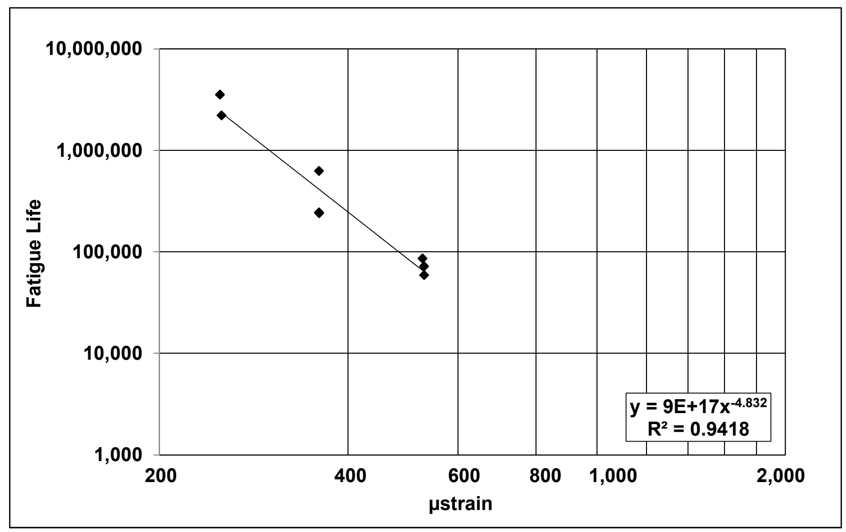
PG64-0RAP



PG64-25RAP-NY

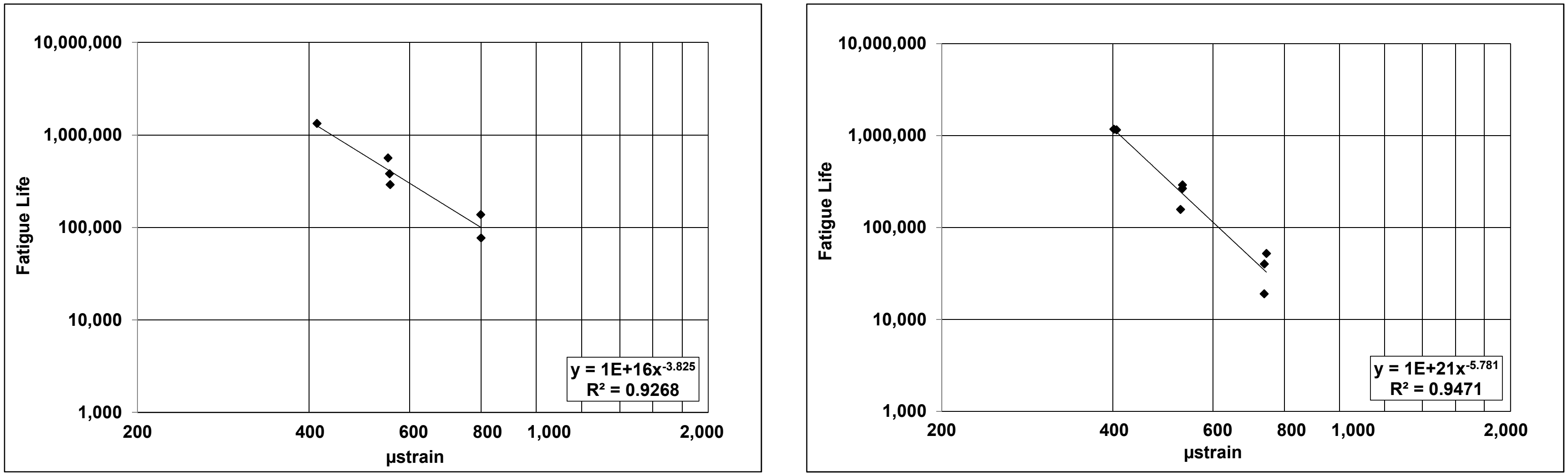


PG64-25RAP-CA



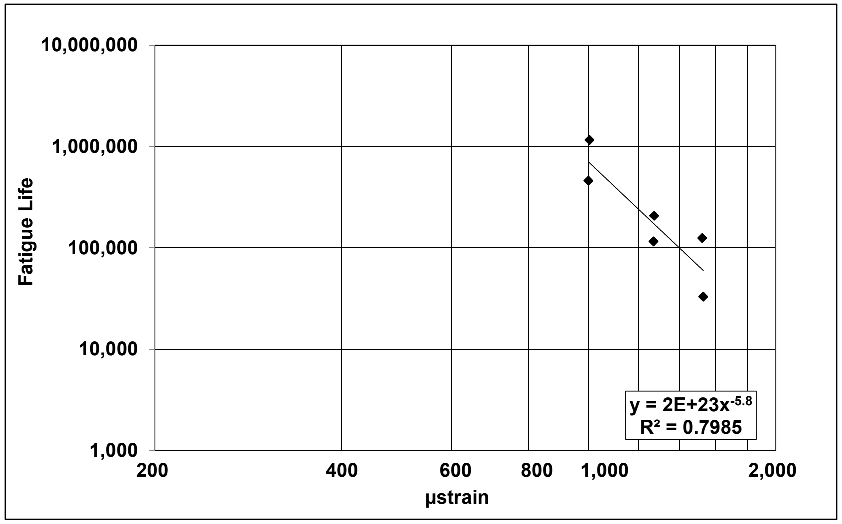
PG64-25RAP-AL

Figure 10.21: Fatigue models for PG 64-22 mixes.

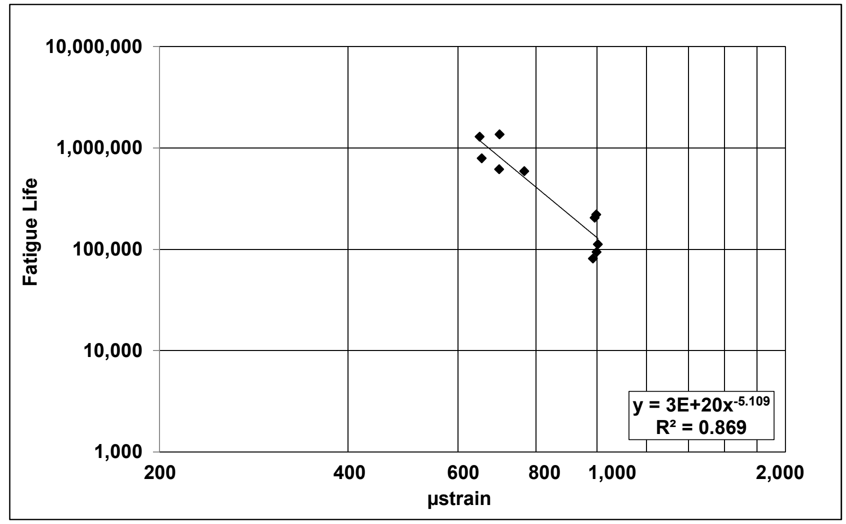


PG58-0RAP PG58-40RAP-NY

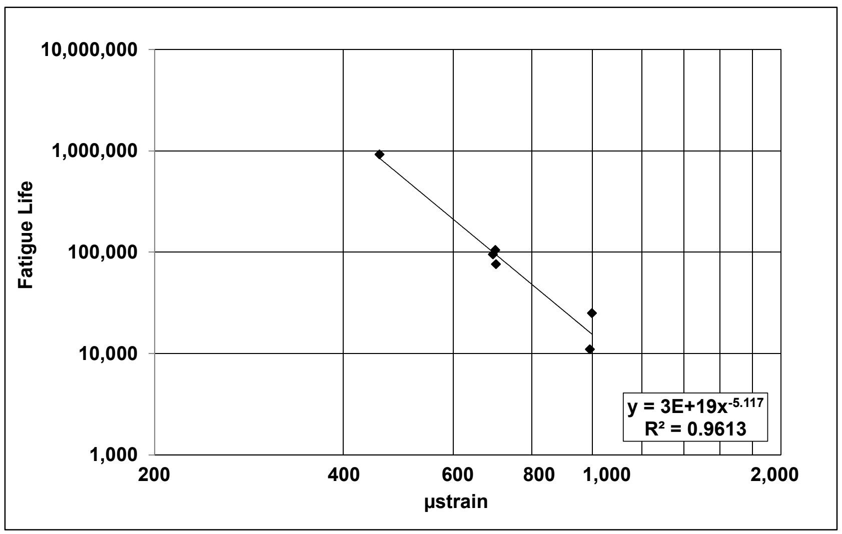
Figure 10.22: Fatigue models for PG 58-28 mixes.



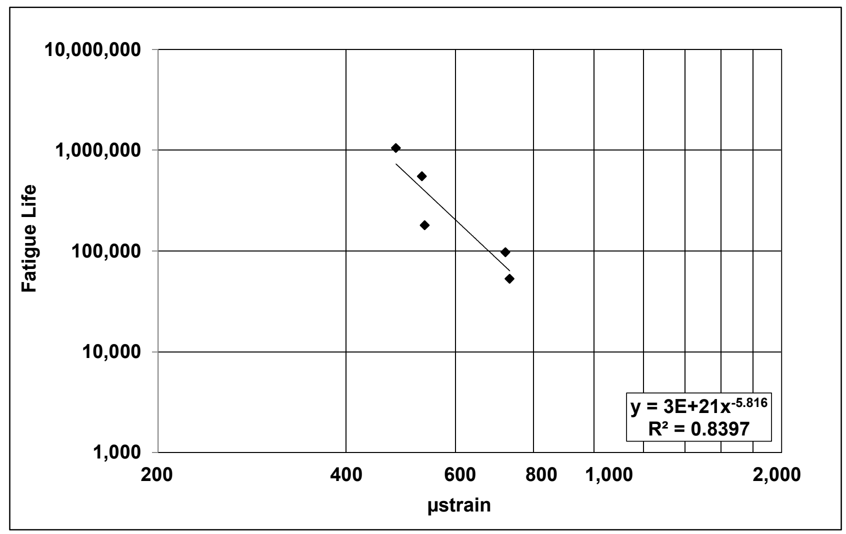
PG76-0RAP



PG76-25RAP-NY

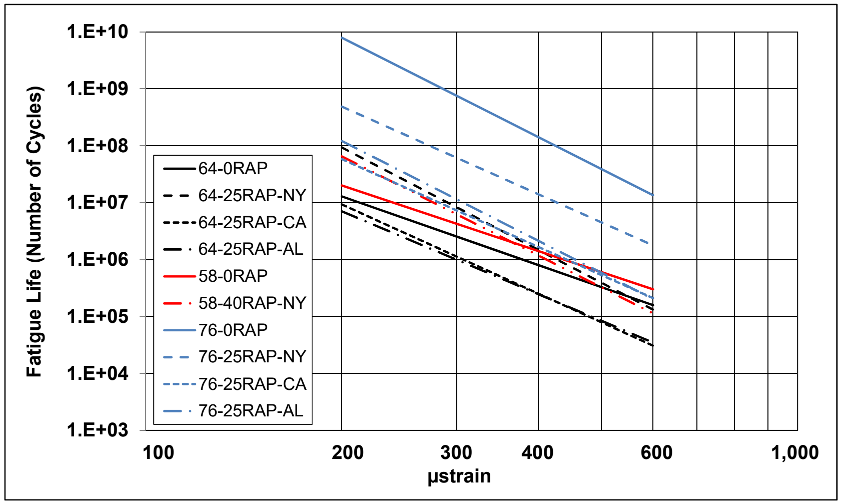


PG76-25RAP-CA

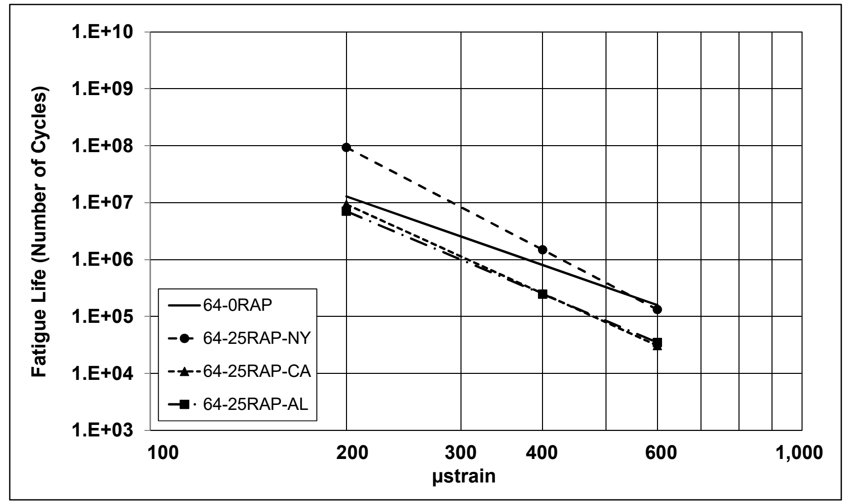


PG76-25RAP-AL

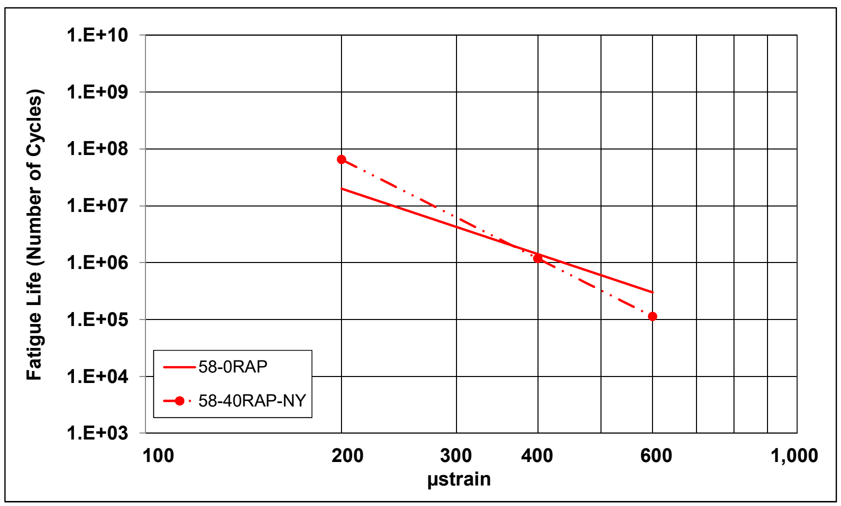
Figure 10.23: Fatigue models for PG 76-22 PM mixes.



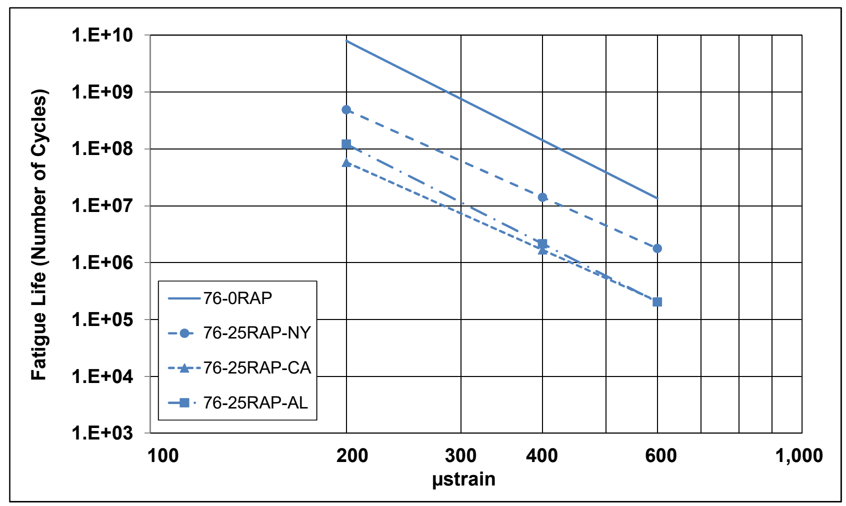
All mixes



PG 64-22 mixes



PG 58-28 mixes



PG 76-22 mixes

Figure 10.24: Calculated fatigue life at 200, 400, and 600 µstrain.

- The effect of increased strain level on the behavior of the PG 58-28 and PG 64-22 control mixes was notably different than that of the other mixes, with increasing strain level having less impact than on the mixes containing RAP. The effect of increasing strain level on the PG 76-22 PM mixes could not be distinguished, indicating that the polymer modification compensated for the potential stiffening effect of the RAP.

10.9.3 Mechanistic Analysis of Fatigue Performance

The above observations were verified with a mechanistic analysis. The fatigue performance of an asphalt mix is a function of many factors including but not limited to the pavement structure, mix stiffness, mix strength, ambient temperature, wheel load, wheel configuration, and tire pressure. The maximum tensile strength at the bottom of the asphalt concrete layers (or at the bottom of individual asphalt concrete layers if debonding has occurred) is the critical pavement response for fatigue cracking. Therefore, to obtain a realistic evaluation of fatigue performance, the critical pavement responses must be calculated based on known asphalt stiffness and traffic load configurations. Two examples are provided, one for highway pavements and one for airfield pavements (undertaken as part of the FAA study, but included to illustrate the influence of higher wheel loads and tire pressures and how these can affect the analysis outcome).

<u>Example California Pavement Structures</u>

Two pavement structures (Table 10.5) with two different asphalt layer thicknesses were considered, a thin 60 mm (0.2 ft) asphalt concrete overlay over 210 mm (0.7 ft) of old asphalt and 300 mm (1.0 ft) aggregate base, and 120 mm [0.4 ft] asphalt concrete on 300 mm (1.0 ft) aggregate base. A truck with a 40 kN single axle load and 700 kPa (101 psi) tire pressure travelling at 80 km/h (50 mph) was used for the analysis.

Table 10.5: Highway Pavement Structures Used in the Fatigue Performance Analysis

Layer	Thickness (mm)				Stiffness (MPa)				Poisson's Ratio		
	AC	Old AC	Base	SG	AC	Old AC	Base	SG	AC	Base	SG
Structure #1 (Thin AC)	60	210	300	infinite	Calc.	600	300	100	0.4	0.3	0.4
Structure #2 (Thick AC)	120	0	300	infinite	Calc.	-	300	100	0.4	0.3	0.4
AC = asphalt concrete			SG = subgrade				Calc. = calculated				

Loading time was calculated using Equation 10.3.

$$\textit{Loading time} = 2 \times \textit{radius of wheel loading area} \times \textit{AC thickness} \quad \textbf{(10.3)}$$

The inverse of the loading time was used as the loading frequency (in radian frequency [$\omega = 2\pi \times f\ (Hz)$]). The loading frequencies were determined to be 14.11 Hz for Structure #1 and 11.38 Hz for Structure #2. Mix stiffnesses at a pavement temperature of 20°C were selected from the flexural stiffness master curves (Figure 10.7).

The *Openpave*™ software program was used to calculate the maximum principal tensile strains at the bottom of the asphalt concrete layers. The responses were calculated under the center point of one tire where the maximum principal strain typically occurs. This calculated critical strain at the bottom of the asphalt concrete layer for each overlay was used with the respective fatigue models discussed in Section 10.9.2. Table 10.6 summarizes the critical maximum principal tensile strains and fatigue lives for the different mixes for both overlay thicknesses. Table 10.7 provides the results by ranked performance (best to poorest).

Table 10.6: Tensile Strains and Corresponding Fatigue Lives for Highway Pavements

Mix ID	Structure #1: Thin AC Overlay (60 mm)			Structure #2: Thick AC Layer (120 mm)		
	Max. Tensile Strain	Fatigue Life (Nf)	% Change from Control	Max. Tensile Strain	Fatigue Life (Nf)	% Change from Control
64-0RAP	182	1.9E+07	0	162	3.0E+07	0
64-25RAP-NY	159	1.9E+08	-900	185	1.5E+08	-400
64-25RAP-CA	135	4.9E+07	-158	198	9.8E+06	67
64-25RAP-AL	145	4.7E+07	-147	149	2.9E+07	3
58-0RAP	193	2.3E+07	0	105	2.4E+08	0
58-40RAP-NY	176	2.0E+08	-770	93	5.5E+09	-2,192
76-0RAP	198	8.4E+09	0	157	3.3E+10	0
76-25RAP-NY	180	8.3E+08	90	122	6.0E+09	82
76-25RAP-CA	160	2.3E+08	97	120	8.0E+08	98
76-25RAP-AL	157	4.9E+08	94	124	2.0E+09	94

Table 10.7: Ranked Tensile Strains and Corresponding Fatigue Lives for Highway Pavements

Rank	Structure #1: Thin AC Overlay (60 mm)			Structure #2: Thick AC Layer (120 mm)		
	Mix ID	Max. Principal Tensile Strain	Fatigue Life (Nf)	Mix ID	Max. Principal Tensile Strain	Fatigue Life (Nf)
1	76-0RAP	198	8.4E+09	76-0RAP	157	3.3E+10
2	76-25RAP-NY	180	8.3E+08	76-25RAP-NY	122	6.0E+09
3	76-25RAP-AL	157	4.9E+08	58-40RAP-NY	93	5.5E+09
4	76-25RAP-CA	160	2.3E+08	76-25RAP-AL	124	2.0E+09
5	58-40RAP-NY	176	2.0E+08	76-25RAP-CA	120	8.0E+08
6	64-25RAP-NY	159	1.9E+08	58-0RAP	105	2.4E+08
7	64-25RAP-AL	145	4.9E+07	64-25RAP-NY	185	1.5E+08
8	64-25RAP-CA	135	4.7E+07	64-0RAP	162	3.0E+07
9	58-0RAP	193	2.3E+07	64-25RAP-AL	149	2.9E+07
10	64-0RAP	182	1.9E+07	64-25RAP-CA	198	9.8E+06

The following observations were made:

- The ranking of the mixes based on fatigue performance was dependent on the pavement structure, with fatigue performance increasing with increasing pavement thickness, as expected.
- As noted previously, the RAP from the New York source appeared to be relatively unaged and the binder extracted from it tested softer than those of the other RAP sources. This appears to have had a positive effect on fatigue performance in all the mixes, as expected.
- Adding RAP to the PG 76-22 PM mixes had a negative effect on the fatigue performance of the mixes. This implies that adding RAP to mixes with polymer-modified binders could significantly reduce the benefits of the polymer in terms of cracking resistance.

- Adding 40 percent RAP to the PG 58-28 mix improved the fatigue performance of the mix on both pavement structures. The RAP mix ranked better in fatigue performance on Structure #2, and this was attributed to increases in the initial stiffness of the mix. This result supports other work in the literature suggesting that selecting a binder one performance grade lower than the design grade for high RAP-content mixes can compensate for the stiffening effect of the RAP, and also corresponds to the results shown in Section 10.9.2, which indicated that the fatigue life of the RAP mix at strain levels less than 400 µstrain was higher than that of the corresponding control mix without RAP. However, the slope of the fatigue model was greater for the RAP mix than the control mix, indicating a potentially higher sensitivity to strain level, which implies that although the RAP mix has higher resistance to fatigue cracking it could also be more susceptible to faster crack propagation once a crack has initiated. It is also not clear if these results are indicative of long-term performance given that the beam fatigue tests were undertaken on newly prepared and compacted specimens.
- The fatigue lives of the mixes with PG 64-22 binder and 25 percent RAP were higher than their corresponding control mix without RAP on the overlay structure, but generally lower (with the exception of the mix containing New York RAP) on the structure with the thicker new asphalt layer. The fatigue lives for the PG 64-22 mixes shown in Figure 10.21 tend to merge at the 200 µstrain level, and if the models are further extrapolated to lower strain levels (as calculated), the fatigue lives of the RAP mixes improve over that of the control mix. As with the PG 58-28 RAP mixes, the PG 64-22 RAP mixes are also expected to be susceptible to higher rates of crack propagation than mixes without RAP once a crack has initiated. It is also not clear if these result are indicative of long-term performance given that the beam fatigue tests were undertaken on newly prepared and compacted specimens.

Example Airfield Pavement Structures

The second analysis, completed as part of the FAA study, used Boeing 737-800 and Boeing 777F aircraft for the calculations. The wheel-gear footprints are shown in Figure 10.25 and Figure 10.26, respectively. Three airfield pavement structures were used and are detailed in Table 10.8. The design loads per main gear strut were set at 37,250 kg (82,140 lb) and 159,900 kg (352,500 lb) for the 737-800 and 777F, respectively (information sourced from the Boeing website). The tire pressures of the main gear wheels were set at 1.4 MPa (204 psi) and 1.5 MPa (218 psi), respectively. One aircraft speed (50 km/h [31 mph]) was considered.

Table 10.8: Pavement Structures Used in the Fatigue Performance Analysis

<table>
<tr><th rowspan="2">Layer</th><th colspan="3">Thickness (mm)</th><th colspan="3">Stiffness (MPa)</th><th colspan="3">Poisson's Ratio</th></tr>
<tr><th>AC</th><th>Base</th><th>SG</th><th>AC</th><th>Base</th><th>SG</th><th>AC</th><th>Base</th><th>SG</th></tr>
<tr><td>Structure #1
(Thin AC/thick base)</td><td>125</td><td>300</td><td>Infinite</td><td rowspan="3">Calc.</td><td rowspan="3">300</td><td rowspan="3">100</td><td rowspan="3">0.4</td><td rowspan="3">0.3</td><td rowspan="3">0.4</td></tr>
<tr><td>Structure #2
(Thick AC/thin base)</td><td>250</td><td>200</td><td>Infinite</td></tr>
<tr><td>Structure #3
(Thick AC/thick base)</td><td>250</td><td>300</td><td>Infinite</td></tr>
<tr><td colspan="10">AC = asphalt concrete SG = subgrade Calc. = calculated</td></tr>
</table>

The inverse of the loading time, calculated using Equation 10.3, was used as the loading frequency (in radian frequency [$\omega = 2\pi \times f\,(Hz)$]). The loading frequency was determined to be 0.3 Hz for Structure #1, and 0.4 Hz for Structure #2 and Structure #3. Mix stiffnesses at a pavement temperature of 20°C were selected from the flexural stiffness master curves (Figure 10.7).

The *Openpave* software program was again used to calculate maximum principal strains at the bottom of the asphalt concrete layers. The responses for the 737-800 were calculated under the center point of one tire and at the midpoint between one set of dual tires. The same responses plus the response at the midpoint between two of the main gear axles were calculated for the 777F. The maximum principal strain occurred under the center point of one tire for both aircraft. This calculated critical strain at the bottom of the asphalt concrete layer for each mix type was substituted into the respective fatigue models discussed in Section 10.9.2 to estimate the fatigue life. Table 10.9 and Table 10.10 summarize the critical maximum principal tensile strains and fatigue lives for the different mixes under 737-800 and 777F loading conditions. Table 10.11 ranks the different mixes in terms of fatigue life under 737-800 loading.

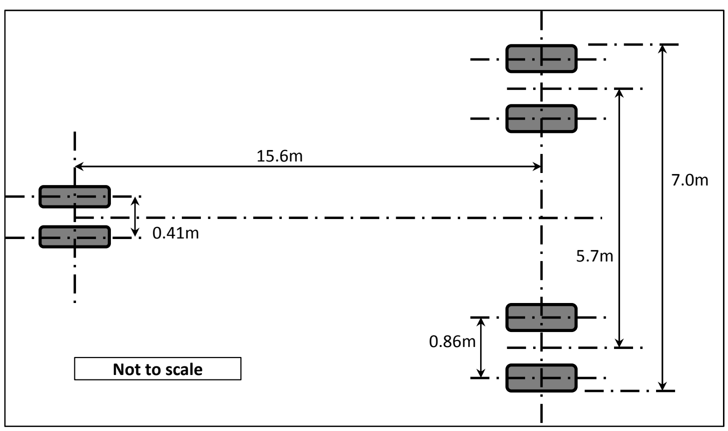


Figure 10.25: Boeing 737-800 gear footprint.

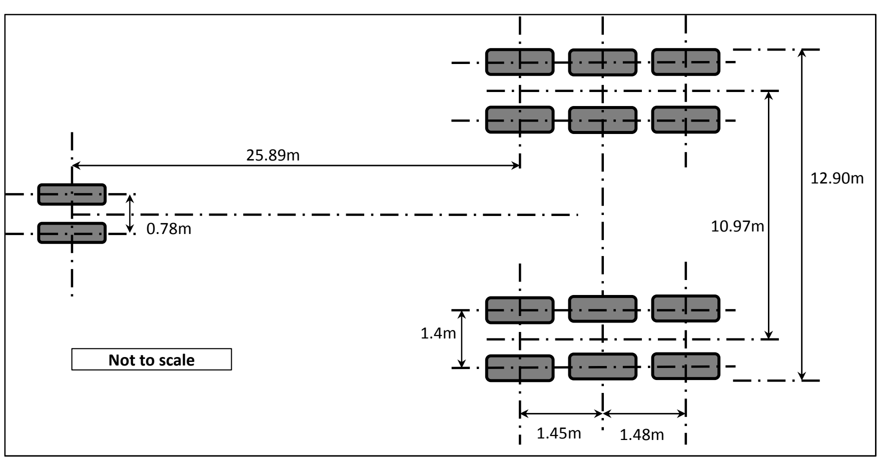


Figure 10.26: Boeing 777F gear footprint.

Table 10.9: Tensile Strains and Corresponding Fatigue Lives for 737-800 Loading

Mix ID	Structure #1 (Thin AC/Thick Base)			Structure #2 (Thick AC/Thin Base)			Structure #3 (Thick AC/Thick Base)		
	Max. Tensile Strain	Fatigue Life (Nf)	% Change from Control	Max. Tensile Strain	Fatigue Life (Nf)	% Change from Control	Max. Tensile Strain	Fatigue Life (Nf)	% Change from Control
64-0RAP	713	8.0.E+04	0	570	1.9.E+05	0	528	2.6.E+05	0
64-25RAP-NY	680	6.3.E+04	21	629	1.0.E+05	49	581	1.6.E+05	39
64-25RAP-CA	554	4.6.E+04	42	655	2.0.E+04	90	604	3.0.E+04	89
64-25RAP-AL	506	8.0.E+04	0	516	7.3.E+04	67	479	1.0.E+05	61
58-0RAP	742	1.3.E+05	0	366	2.0.E+06	0	345	2.5.E+06	0
58-40RAP-NY	603	1.1.E+05	17	318	4.4.E+06	-124	301	6.1.E+06	-145
76-0RAP	751	3.7.E+06	0	530	2.8.E+07	0	492	4.3.E+07	0
76-25RAP-NY	691	8.7.E+05	76	421	1.1.E+07	61	394	1.5.E+07	64
76-25RAP-CA	606	2.0.E+05	95	409	1.5.E+06	95	384	2.1.E+06	95
76-25RAP-AL	596	2.1.E+05	94	415	1.7.E+06	94	389	2.5.E+06	94

Table 10.10: Tensile Strains and Corresponding Fatigue Lives for 777F Loading

Mix ID	Structure #1 (Thin AC/Thick Base)			Structure #2 (Thick AC/Thin Base)			Structure #3 (Thick AC/Thick Base)		
	Max. Tensile Strain	Fatigue Life (Nf)	% Change from Control	Max. Tensile Strain	Fatigue Life (Nf)	% Change from Control	Max. Tensile Strain	Fatigue Life (Nf)	% Change from Control
64-0RAP	741	6.8.E+04	0	594	1.7.E+05	0	556	2.1.E+05	0
64-25RAP-NY	712	4.7.E+04	21	657	7.7.E+04	49	613	1.2.E+05	46
64-25RAP-CA	587	3.4.E+04	42	684	1.6.E+04	90	637	2.3.E+04	89
64-25RAP-AL	534	6.1.E+04	0	534	6.1.E+04	63	503	8.2.E+04	62
58-0RAP	763	1.2.E+05	0	379	1.7.E+06	0	360	2.1.E+06	0
58-40RAP-NY	636	8.1.E+04	17	330	3.6.E+06	-124	315	4.7.E+06	-121
76-0RAP	771	3.2.E+06	0	549	2.3.E+07	0	516	3.3.E+07	0
76-25RAP-NY	721	6.9.E+05	76	434	9.3.E+06	61	411	1.2.E+07	62
76-25RAP-CA	640	1.5.E+05	95	422	1.3.E+06	95	400	1.7.E+06	95
76-25RAP-AL	630	1.5.E+05	94	428	1.4.E+06	94	406	2.0.E+06	94

Table 10.11: Ranked Fatigue Life for 737-800 Loading

Rank	Structure #1		Structure #2		Structure #3	
	Mix ID	Fatigue Life (Nf)	Mix ID	Fatigue Life (Nf)	Mix ID	Fatigue Life (Nf)
1	76-0RAP	3.7.E+06	76-0RAP	2.8.E+07	76-0RAP	4.3.E+07
2	76-25RAP-NY	8.7.E+05	76-25RAP-NY	1.1.E+07	76-25RAP-NY	1.5.E+07
3	76-25RAP-AL	2.1.E+05	58-40RAP-NY	4.4.E+06	58-40RAP-NY	6.1.E+06
4	76-25RAP-CA	2.0.E+05	58-0RAP	2.0.E+06	58-0RAP	2.5.E+06
5	58-0RAP	1.3.E+05	76-25RAP-AL	1.7.E+06	76-25RAP-AL	2.5.E+06
6	58-40RAP-NY	1.1.E+05	76-25RAP-CA	1.5.E+06	76-25RAP-CA	2.1.E+06
7	64-0RAP	8.0.E+04	64-0RAP	1.9.E+05	64-0RAP	2.6.E+05
8	64-25RAP-AL	8.0.E+04	64-25RAP-NY	1.0.E+05	64-25RAP-NY	1.6.E+05
9	64-25RAP-NY	6.3.E+04	64-25RAP-AL	7.3.E+04	64-25RAP-AL	1.0.E+05
10	64-25RAP-CA	4.6.E+04	64-25RAP-CA	2.0.E+04	64-25RAP-CA	3.0.E+04

The following observations were made:

- The fatigue behavior in the airfield pavement analysis was notably different than that determined in the highway pavement analysis, which was expected given the different pavement structures and different wheel loads. The rankings of performance were also different.
- Fatigue performance increased with increasing pavement thickness, as expected.
- The fatigue behavior of the mixes followed similar trends under both aircraft loading conditions, with the PG 76-22 PM mixes performing better than the PG 58-28 mix, which in turn performed better than the PG 64-22 mixes.
- The ranking of the mixes based on fatigue performance was generally independent of the pavement structure.
- The PG 76-22 PM control mix had the best performance and the PG 64-22 mix with 25 percent RAP from the California source had the poorest performance, which is consistent with the laboratory test results.
- Adding RAP to the mixes significantly reduced the fatigue life of the mix in all but one of the mixes tested (PG 58-28). The effect was more severe on pavements with thicker asphalt concrete surfacings. In most cases, the RAP from the New York source had the least effect on fatigue life, while the RAP from the California source had the largest impact on fatigue life.
- Adding RAP to the mixes had a larger negative impact on the fatigue performance of the PG 76-22 PM mixes (i.e., percent change in fatigue performance compared to the control mix) than on the performance of the PG 64-22 binder mixes, which is consistent with the results for the highway pavement structures and implies that adding RAP to mixes with polymer-modified binders could significantly reduce the benefits of the polymer in terms of cracking resistance.
- Adding 40 percent RAP to the PG 58-28 mix improved the fatigue performance of the mix on the pavements with thicker asphalt concrete surfacings, which is consistent with the results for the highway pavements and is also attributable to increases in the initial stiffness of the mix.

10.10 Phase 1g Testing Summary

Key observations from testing on full-graded mixes include the following:

- The test methods used in this phase of the study were sufficiently sensitive to distinguish the behavior of the different mixes and to consistently distinguish the differences in performance between the mixes containing no RAP (i.e., control mixes) and mixes containing RAP. However, all testing was undertaken on newly prepared laboratory specimens, and consequently do not necessarily reflect long-term performance of the mixes or the longer-term effects of the RAP binder on the rate of aging of the virgin binder.
- Adding RAP increased the stiffness of the mixes, which in most instances improved the mixes' rutting resistance properties, but it had differing impacts on their cracking resistance properties. The addition of RAP clearly influenced the results for beam fatigue tests. However, when considered in a mechanistic analysis, the results indicated potentially better performance than the control mixes, although it is not clear if these result are indicative of long-term performance given that the flexural modulus and beam fatigue tests were undertaken on newly prepared and compacted specimens.
- The degree of change in rutting and cracking resistance was dependent on the RAP source, with test results for each source ranking consistently across the different tests (i.e., the RAP from the New York source consistently had the least effect on mix performance, while the RAP from the California and Alabama sources consistently had the largest effect). This implies that RAP cannot be considered as a generic material with consistent properties.
- Adding RAP to mixes with polymer-modified binders appears to have a limited effect in terms of improving rutting performance but a significant effect in terms of reducing fatigue life. This implies that the known benefits of adding polymer to asphalt binders may be compromised by replacing some of the virgin binder with binder from RAP.
- The use of a softer binder to compensate for the stiffening effect of high RAP binder replacement rates (i.e., above 25 percent) appears to be justified.

11. CONCLUSIONS AND PRELIMINARY RECOMMENDATIONS

11.1 Summary

Road agencies are increasingly allowing the use of reclaimed asphalt pavement (RAP) and reclaimed asphalt shingles (RAS) in new mixes placed on highways. This report describes a study that investigated the potential implications of using relatively high reclaimed asphalt contents (up to 40 percent virgin binder replacement) in new asphalt concrete. The study included a literature review, preliminary testing to develop alternative methods for assessing the properties of virgin binders blended with RAP, the development of mix designs for mixes containing varying reclaimed asphalt contents, and the testing of the properties of the blended binders, fine aggregate matrix mixes, and full-graded mixes.

Key points from the literature review include the following:

- The asphalt binder in RAP and RAS can blend appreciably with virgin binder in new mixes. The level of blending between the aged and new binders depends on numerous factors including the chemical composition of the individual binders. To ensure the optimal performance of asphalt mixes containing high proportions of reclaimed asphalt, the compatibility of reclaimed and virgin asphalt binders from different sources and with different performance grades (PG) needs to be well understood.
- Appropriate methods for extracting aged binder from reclaimed asphalt materials are still being developed; these development efforts are focused on reducing the effects of extraction solvents on the properties of recovered binders. The solvents in current use are considered to be aggressive enough to fully blend the binders extracted from new mixes containing aged and virgin binders, and thereby provide potentially misleading binder replacement values and nonrepresentative performance gradings of the blended binders. Alternative methods to the use of extraction and recovery are also being explored to better characterize the performance properties of blended virgin and RAP and/or RAS binders. Tests on mortar and FAM mixes warrant further investigation in this regard.
- Adding RAP to a new asphalt mix can alter the volumetrics and performance of the mix. However, volumetric requirements can still be met with relatively high RAP contents (i.e., up to 25 percent). Compared to equivalent mixes without RAP, rutting performance was generally improved by the addition of RAP, but cracking performance was generally worse. Conflicting results with regard to laboratory test performance were reported.
- Given that the use of RAP as binder replacement and not just as aggregate replacement is a relatively new practice, there is limited knowledge on the long-term field performance of mixes containing high RAP contents (i.e., above 25 percent binder replacement), specifically with regard to the rate of binder aging and its effect on stiffness and susceptibility to cracking. Conventional laboratory aging procedures have not been verified for high RAP mixes.

Preliminary laboratory testing to investigate the properties of binders recovered from RAP and RAS samples and simulated RAP binders prepared in the laboratory revealed the following:

- Asphalt binder extracted and recovered from RAS could not be tested due to its very high stiffness. The RAS binder was not sufficiently workable to mold samples for testing in a dynamic shear rheometer (DSR) or bending beam rheometer (BBR).
- The guidelines recommended in NCHRP 9-12 for determining the performance grade of binders recovered from RAP samples were considered to be appropriate for this UCPRC study. Recovered binders from three different RAP sources were tested according to these guidelines.
- Initial attempts to synthesize a simulated RAP binder with performance properties comparable to recovered binders provided mixed results. Various pressure aging vessel (PAV) test scenarios were considered, but only the high critical temperature of the simulated binder was similar to the recovered binders. The low critical temperatures were significantly different. It is not clear whether this was attributable to the aging procedure or to the effect of the extraction chemicals.

Preliminary laboratory testing to investigate the properties of asphalt mortars prepared in the laboratory revealed the following:

- Mortar samples with binder replacement rates of up to 25 percent were sufficiently workable to fabricate specimens that could be tested in a DSR. Samples with binder replacement rates greater than 25 percent were generally unworkable and specimens could not be fabricated satisfactorily.
- Although the mortar test deserves further investigation, it may not be appropriate for testing samples with high binder replacement rates (i.e., >25 percent). Given that this UCPRC study focused on investigating the influence of binder replacement rates of up to 40 percent on the performance properties of the blended binders, the use of mortar testing was not considered for the remainder of the study.

Supplementary laboratory testing to investigate the blending between virgin and RAP binders revealed the following:

- The wafer composite-binder testing method using a DSR was shown to be an effective approach for examining the level of blending between new and age-hardened binders. The sample preparation and test procedure is straightforward and applicable for both practitioners and researchers.
- The diffusion mechanism in the blending process was shown to be temperature and time dependent:
  - The 153 minutes for the hot mix asphalt (HMA) time-temperature path resulted in nearly complete blending of the new and simulated RAP binders.
  - The 153 minutes for the warm mix asphalt (WMA) time-temperature path resulted in only partial blending.
  - The diffusion coefficient increased with temperature.
- The representative constant diffusivity for wafer composite specimens under a hot mix asphalt production temperature path can be successfully estimated using a finite control volume approach to numerically solve Fick's law of diffusion.
- The predicted complex modulus values of the wafer specimens following a warm mix asphalt production path for longer than 63 minutes conditioning time were found to be higher than the

actual measured values and were close to the values corresponding to the fully blended binder specimen.

Key observations and findings from preliminary testing on fine aggregate matrix (FAM) mixes include the following:

- Asphalt binder extracted and recovered from RAS could not be tested due to its very high stiffness. The RAS binder was not sufficiently workable to mold specimens for testing in a DSR or in a BBR.
- Preliminary testing of FAM mixes (prepared with materials passing the 2.36 mm [#8] sieve) indicated that this approach appears to be repeatable (consistent results on multiple specimens by the same operator) and reproducible (consistent results by different operators), and produces representative results for characterizing the performance-related properties of composite binder at binder replacement rates up to 40 percent and possibly higher.
- The effect of RAP in increasing the stiffness of blended binders was dependent primarily on the asphalt binder grade and, to a lesser extent, on the source of the asphalt binder.
- The FAM mixes containing RAS showed similar stiffnesses to the corresponding control mixes (i.e., containing no reclaimed materials), suggesting that the RAS binder did not effectively blend with the virgin binder at the temperatures and mixing durations used in this study. Based on these results, RAS was not included in further phases of this UCPRC study.
- The influence of rejuvenating agent on reducing the blended binder and FAM mix stiffnesses was evident. Additional testing (beyond the scope of this study) is required to evaluate the long-term behavior of mixes produced with rejuvenating agents to determine whether the benefits are limited to production and early life, or whether they extend through the design life of the layer.
- Reasonable correlations were observed between the stiffness of asphalt binder and the stiffness of FAM mixes. Discrepancies between the two measured stiffnesses may indicate that complete blending of the virgin and reclaimed asphalt binders was not achieved in the FAM mix, but was forced during the chemical extraction and recovery. The specific chemical solvent used in the extraction process also may have influenced the RAP binder properties. These factors warrant further investigation.

Key observations from the mix design phase of the study include the following:

- Grading and volumetric property specification requirements were difficult to meet when RAP binder replacement rates exceeded 25 percent.
- RAP source had a notable influence on the volumetric properties, which implies that RAP cannot be considered as a generic material with consistent properties, even when only using the fine fractions (i.e., material passing the 4.75 mm [#4] sieve).

Key observations from the binder and FAM mix testing phase of the study include the following:

- The degree of change in PG grade after the addition of RAP binder varied depending on the virgin binder grade and the RAP source. This was attributed to various factors including but not limited to the degree of aging of the RAP binder, the original PG grade of the RAP binder, and the extent of the “dilution” of the polymer in virgin polymer-modified binders.

- Using RAP binder to replace a portion of the virgin binder always increased the stiffness of the binder, but the degree of increase was dependent on the RAP source.
- Results from FAM mix testing were consistent with the results from binder testing. Differences were attributed to the differences in the degree of blending during preparation of the binders (stirred with a glass rod in a glass beaker) and preparation of the FAM mixes (standard laboratory mixing process), and to possible effects of the chemical solvent on the properties of the extracted and recovered binder.
- The FAM mix test results further supported the use of this testing approach as an appropriate procedure for evaluating the properties of blended asphalt binder in mixes containing relatively high quantities of RAP.

Key observations from testing on full-graded mixes include the following:

- The test methods used in this phase of the study were sufficiently sensitive to distinguish the behavior of the different mixes and to consistently distinguish the differences in performance between the mixes containing no RAP (i.e., control mixes) and mixes containing RAP. However, all testing was undertaken on newly prepared laboratory specimens, and consequently do not necessarily reflect long-term performance of the mixes or the longer-term effects of the RAP binder on the rate of aging of the virgin binder.
- Adding RAP increased the stiffness of the mixes, which in most instances improved the mixes' rutting resistance properties, but it had differing impacts on their cracking resistance properties. The addition of RAP clearly influenced the results for beam fatigue tests. However, when considered in a mechanistic analysis, the results indicated potentially better performance than the control mixes, although it is not clear if these results are indicative of long-term performance since the flexural modulus and beam fatigue tests were undertaken on newly prepared and compacted specimens.
- The degree of change in rutting and cracking resistance was dependent on the RAP source, with test results for each source ranking consistently across the different tests (i.e., the RAP from the New York source consistently had the least effect on mix performance, while the RAP from the California and Alabama sources both consistently had the largest effects). Given that the mixes had the same gradation and binder content and similar volumetric properties, the results support an earlier observation that RAP cannot be considered as a generic material with consistent properties.
- Adding RAP to mixes with polymer-modified binders appears to have limited effect in terms of improving rutting performance but a significant effect in terms of reducing fatigue life. This implies that the known benefits of adding polymer to asphalt binders may be compromised by replacing some of the virgin binder with binder from RAP.
- The use of a softer binder to compensate for the stiffening effect of high RAP binder replacement rates (i.e., above 25 percent) appears to be justified.

11.2 Conclusions

The following conclusions are made based on the test results summarized above:

- There is considerable interest in the use of reclaimed asphalt in new asphalt concrete mixes, primarily due to the cost savings and environmental benefits associated with substituting some of the virgin binder with the binder from the reclaimed asphalt. However, the laboratory testing in this study, which was all undertaken on unaged specimens, has clearly shown that although adding reclaimed asphalt (from RAP) to new mixes is likely to increase the stiffness of the mix, which in most instances will potentially improve the rutting resistance properties of the mix, the cracking resistance properties could be worse. Therefore, before use of reclaimed asphalt in new mixes is implemented, further testing on appropriately aged specimens is proposed to better understand the implications of using this process.

- Preliminary findings from this study indicate that the asphalt binder in reclaimed asphalt shingles may not effectively mobilize and blend with virgin asphalt. Using this reclaimed asphalt as a binder replacement could reduce the actual effective binder content in the mix, which could in turn lead to early cracking and raveling.
- Test results collected on the properties of blended virgin and reclaimed asphalt binders can be influenced by the chemistry of the solvents used to extract and recover the binders. Fine aggregate matrix (FAM) mix testing is considered to be a potentially appropriate alternative procedure for evaluating the properties of blended asphalt binder in mixes containing relatively high quantities of reclaimed asphalt.
- Although considerable laboratory testing has been undertaken to evaluate the performance of mixes in which reclaimed asphalt binders are a partial replacement for virgin binders, only limited longer-term full-scale field testing, with associated laboratory testing, has been undertaken. Consequently, any potential effects of accelerated aging of these mixes caused by the presence of the aged RAP binder are not fully understood.
- RAP, and the binder in it, cannot be considered as a generic material with consistent properties, and some form of mix performance testing (FAM or full-grading) will need to be undertaken as part of the project mix design process to assess the influence of the RAP binder replacement on longer-term performance.
- The known benefits of adding polymer to asphalt binders may be compromised by replacing some of the virgin binder with binder from RAP.
- The use of a softer virgin binder to compensate for the stiffening effect of high RAP binder replacement rates (i.e., above 25 percent) appears to be justified. For example, in an area where PG 64-22 binders are typically used, a PG 58-28 mix with 40 percent RAP would probably have generally similar performance to a PG 64-22 mix with 25 percent RAP. Performance properties will always need to be confirmed, however.

11.3 Recommendations

The following recommendations are made based on the findings from this study:

- Given the interest in using reclaimed asphalt for partial binder replacement in new mixes, the benefits and risks of the process should be further quantified in additional laboratory testing on appropriately aged specimens, and in controlled full-scale field studies with associated laboratory testing. Accelerated loading tests are proposed as part of this research.
- Any future research phases should also include assessments of the following:
    + The effects of reclaimed asphalt on the aging properties of the mix over time, and the effects of this on cracking performance over time.

  + The effects of reclaimed asphalt on the low-temperature properties of the mix.
  + The influence of different rejuvenating agents on mix properties and on short-, medium-, and long-term performance.
  + The influence of warm mix additives and the implications of producing mixes containing RAP at warm mix temperatures.
- Given the interest in using RAS in conjunction with RAP, further studies on the effective blending of virgin and RAS binders during mix production, transport, and placement, and the effect of RAS binders on long-term mix performance is warranted. Studying only binders chemically extracted from mixes is not recommended given that forced blending between virgin and reclaimed binders during the extraction process is likely.

12. PROPOSED PHASE 2 EXPERIMENTAL PLAN

12.1 Introduction

The preliminary laboratory testing discussed in the previous chapters indicates that adding reclaimed asphalt pavement (RAP), and potentially adding reclaimed asphalt shingles (RAS), to new asphalt mixes to partially replace virgin aggregate and asphalt binder can affect the properties of the blended binder and the properties and performance of the mix. The test results show that adding RAP appears to improve rutting performance but could worsen cracking performance, depending on the pavement design. However, it should be noted that all testing was undertaken on newly prepared laboratory specimens, and consequently the test results do not necessarily reflect long-term performance of the mixes or the longer-term effects of the RAP binder on the rate of aging of the virgin binder. Further, the study only evaluated fatigue cracking, and it is believed that low-temperature cracking performance is also likely to be affected. Given the increasing interest in the use of reclaimed asphalt to replace some virgin binder in new mixes, additional focused laboratory testing, accelerated load tests, monitoring of full-scale field performance on pilot projects, and additional laboratory testing associated with the field tests are warranted to better understand the benefits and consequences of this practice. It is recommended that subsequent testing be conducted in a continued phased study, given that numerous variables will need to be considered to address all possible concerns. Research in later phases should be planned based on the results of completed phases.

12.2 Phase 2: Additional Laboratory Testing

This phase of the project would further assess the effect of RAP content on the rutting, fatigue cracking, and low-temperature cracking performance of asphalt surface mixes in the laboratory. Key issues to be investigated include, but are not limited to:

- The effects of reclaimed asphalt on the aging properties of the mix over time, and the effects of this on cracking performance over time
- Validation of the Caltrans blending charts in terms of the effect on rutting and cracking performance
- Literature review and preliminary laboratory evaluation of the effect of rejuvenators using fine aggregate matrix mix tests
- The influence of warm mix additives and the implications of producing mixes containing RAP at warm mix temperatures
- Additional testing as identified by Caltrans and Industry Working Groups
- Design of a test track for accelerated pavement testing (Phase 3), based on the findings from these investigations

12.3 Phase 3: Accelerated Pavement and Pilot Study Testing

This phase of the project would assess the performance of mixes containing RAP in full-scale field studies (accelerated pavement testing and pilot studies) and should include, but not be limited to the following:

- Accelerated pavement testing
  - Mix design with no RAP, and with 15 percent, 25 percent, and 40 percent RAP binder replacement. A single RAP source would be used. Binder grade would be selected based on current Caltrans specification requirements. A rejuvenator would be selected based on the results of the Phase 3 testing for inclusion in the testing.
  - Construction of a test track at the UCPRC with four lanes to assess the different mixes. On the RAP mixes, half the lane would be paved with mixes containing a rejuvenator, the other half without.
  - Testing with a Heavy Vehicle Simulator (HVS) following a standard testing protocol. Testing would be conducted on unaged and artificially aged test sections.
  - Laboratory testing on binder sampled during mix production, on specimens prepared in the laboratory from loose mix sampled during construction, and on specimens cored and sawn from the test track. Tests would be conducted on binder, fine aggregate matrix (FAM) mixes, and full-graded mixes following a testing plan similar to that described in this report. The testing plan would be prepared once the project has been finalized, but tests would include, but not be limited to, those for determining binder grades and binder properties, mix stiffness (dynamic modulus and flexural modulus), rutting performance (repeated load triaxial, Hamburg Wheel-Track), cracking performance (fatigue and low-temperature cracking), and moisture sensitivity (indirect tensile strength and Hamburg Wheel-Track).
  - If time and budget permit, additional laboratory tests would be conducted on specimens prepared in the laboratory with aggregate and RAP sampled during mix production to assess the effects of using different binder grades, higher RAP contents (if feasible in terms of meeting current volumetric specifications), binder replacement from asphalt shingles, rejuvenating agents, warm mix additives, and mix production at warm mix temperatures. The results from this additional testing would be used to decide whether further phases of accelerated testing are justified.
- Monitoring and evaluation of pilot studies with limited associated laboratory testing on specimens prepared from loose mix sampled either at the asphalt plant or on the project, as described above.
- Analysis using appropriate mechanistic-empirical procedures.
- A report and recommendations for further testing, if warranted. The report would include preliminary recommendations on the use of RAP and suggested changes to mix design procedures and specifications to accommodate RAP, if justified.

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