Title

Evaluation of the Combined Effects of Recycled Asphalt Pavement (RAP), Recycled Asphalt Shingles (RAS), and Different Virgin Binder Sources on Performance of the Blended Binder for Mixes with Higher Percentages of RAP and RAS

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List of Abbreviations

AASHTO	American Association of State Highway and Transportation Officials
AB	Assembly bill
ANOVA	Analysis of variance
BBR	Bending beam rheometer
Caltrans	California Department of Transportation
DMA	Dynamic mechanical analyzer
DSR	Dynamic shear rheometer
FAM	Fine aggregate mix
FHWA	Federal Highway Administration
G*	Dynamic shear modulus
GmB	Bulk specific gravity of the mix
Gmm	Theoretical maximum specific gravity of the mix
HMA	Hot mix asphalt
LVE	Linear viscoelastic
NCHRP	National Cooperative Highway Research Program
n-PB	Normal propyl bromide
NCST	National Center for Sustainable Transport
PAV	Pressure aging vessel
PG	Performance Grading
PPRC	Partnered Pavement Research Center
RA	Rejuvenating agent
RAP	Reclaimed or Recycled Asphalt Pavement
RAS	Reclaimed or Recycled Asphalt Shingles
RTFO	Rolling thin-film oven
SARA	Saturates, aromatics, resins, and asphaltenes
SHRP	Strategic Highway Research Program
SPE	Strategic Plan Element
SUPERPAVE	Superior Performing Asphalt Pavement
TCE	Trichloroethylene
UCPRC	University of California Pavement Research Center
WMA	Warm mix asphalt
δ	Phase angle

Test Methods Cited in the Text

AASHTO M 320	Standard Specification for Performance-Graded Asphalt Binder
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 T 30	Standard Method of Test for Mechanical Analysis of Extracted 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 269	Standard Method of Test for Percent Air-voids in Compacted Dense and Open Asphalt Mixtures
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 (DSR)
ASTM D 1856	Standard Test Method for Recovery of Asphalt from Solution by Abson Method

Conversion Factors

SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	Millimeters	mm
ft	feet	0.305	Meters	m
yd	yards	0.914	Meters	m
mi	miles	1.61	Kilometers	Km
		AREA		
in^2	square inches	645.2	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	Inches	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 inches	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 be made to comply with Section 4 of ASTM E380 (Revised March 2003)

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Executive Summary

This report summarizes the main findings from a project funded by the National Center for Sustainable Transportation (NCST) to investigate the use of higher percentages of reclaimed asphalt pavement (RAP) and reclaimed asphalt shingles (RAS) as a replacement for a percentage of the virgin binder in new asphalt mixes in California. The research focused on testing procedures that do not first require chemical extraction and recovery of the age-hardened asphalt binders from the RAP and RAS.

Five different asphalt binders covering two performance grades (PG 64-16 and PG 58-22) and sourced from three California refineries were evaluated in this study. The influence of two different percentages of RAP (25 and 40 percent by binder replacement) and one percentage of RAS (15 percent by binder replacement) were evaluated through partial factorial asphalt binder testing and full factorial fine aggregate matrix (FAM) mix testing. The effect of a petroleum-based rejuvenating agent added to selected mixes (with 40 percent RAP and 15 percent RAS) was also investigated. Testing was limited to the intermediate temperature properties of the mixes (i.e., 4°C to 40°C). Key observations and findings from this project 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 samples for testing in a dynamic shear rheometer (DSR).
- Testing procedures were developed as part of this preliminary testing phase to measure dynamic shear modulus at different temperatures and frequencies, and a method for preparing and testing FAM mix specimens was developed. Cylindrical specimens 0.5 in. (12.5 mm) in diameter cored from a Superpave gyratory-compacted FAM mix specimen were tested using a torsion bar fixture in a DSR. Preliminary testing of FAM mixes prepared with materials passing the #4, #8, or #16 (4.75 mm, 2.36 mm, or 1.18 mm) sieves indicated that this approach is repeatable and reproducible, and produces representative results for characterizing the performance related properties of composite binder at binder replacement rates up to 40 percent and possibly higher. Use of materials passing the #8 sieve (2.36 mm) is recommended.
- 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 indicated that RAP and RAS content, asphalt binder grade and source, and rejuvenating agent all had a significant influence on FAM mix stiffness, as expected.
- 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 asphalt binder and the stiffnesses of FAM mixes at testing frequencies ranging from 0.1 Hz to 10 Hz. 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. This warrants further investigation.

Based on the findings from this study, FAM mix testing is considered to be a potentially appropriate procedure 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.

1. Introduction

1.1 Background

More than 90 percent of the road and highway network in the United States is paved with asphalt concrete. These pavements require regular maintenance and periodic rehabilitation to perform effectively under heavy repetitive traffic loads and severe environmental conditions. This maintenance and rehabilitation in turn requires a continuous supply of aggregate and asphalt binder, both of which are becoming increasingly scarce and more expensive. Consequently, there is growing interest in the use of reclaimed asphalt pavement (RAP) materials in the production of new asphalt mixes to reduce costs and preserve nonrenewable resources. To encourage this change, the Federal Highway Administration (FHWA) recycling policy states that the materials originally used in the construction of pavements can be reused for their repair, reconstruction, and maintenance *(1)*.

Reclaimed asphalt roofing shingles (RAS) are another potentially valuable source of asphalt binder for use in pavement construction since they contain between 20 and 30 percent asphalt binder by weight of the shingle. The majority of RAS produced in the United States (approximately 10 million tons per year) is obtained from used roof shingles (i.e., tear-off shingles). About 1 million tons of RAS is obtained from production rejects *(2)*. 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 mixes, and although 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 and RAS stockpiles are usually highly variable in terms of binder content, binder properties, and binder condition due to the diverse sources of the materials and the methods used to reclaim them. They are also often contaminated with other construction waste, which may further influence the way they behave in new asphalt mixes.

The California Department of Transportation (Caltrans) recently increased to 25 percent the allowable percentage of reclaimed asphalt pavement (RAP) that can be used in new asphalt mixes. A Caltrans-industry task group, formed to consider recent legislation (AB 812) covering the use of RAP in new mixes, has proposed allowing an increase of up to 40 percent virgin binder replacement from a combination of RAP and RAS. These changes can reduce the amount of virgin binder required in new mixes, and road agencies and contractors can therefore potentially contribute to increased sustainability of pavements by effectively using RAP and RAS materials in new asphalt mixes. However, concerns have been raised regarding the influence that the aged binder in RAP and RAS will have on the new binder properties. The effect of these materials on the long-term behavior and performance of asphalt concrete mixes needs to be fully understood to ensure that premature failures resulting from ineffective blending or accelerated aging do not occur.

1.2 Problem Statements

While virgin material sources for pavement applications are becoming increasingly scarce, the volume of pavement material routinely reclaimed from in-service pavements is increasing. Consequently, there is growing interest in using significantly higher quantities of RAP and RAS in Caltrans asphalt mix designs. However, making this change has raised concerns regarding how these composite binders may influence the performance and durability of asphalt mixes under California traffic and environmental conditions. The following problem statements have been identified and require either additional research or refinement/calibration for California conditions:

- The effect of RAP and/or RAS on the performance grade of composite binders is unknown and needs to be addressed. Both general effects and the effects of specific RAP and RAS sources need to be investigated.
- The process of recovering asphalt binders from asphalt mixes involves relatively aggressive chemistry that may influence the blending of old and virgin binders. The potential effects of this need to be considered when testing the performance properties of recovered binders.
- The performance of asphalt mixes containing RAP and/or RAS is dependent on the properties of the constitutive components. These properties depend on the chemistry of the binders (which depends on crude oil source), changes during time in service after both short- and long-term aging, and diffusion of the old and new binders over time. Consequently, the current Superpave testing equipment and procedures may need to be adapted to accurately characterize the rheological properties of the composite binder with respect to high-, intermediate-, and low-temperature performance.
- The effects of mix production time and temperature on the degree of blending and on the properties of the composite binder need to be quantified.
- The effects of rejuvenating agents on the blending of aged and new binders and the long-term performance of mixes need to be evaluated.

1.3 Project Objectives

The objective of this project, funded by the National Center for Sustainable Transportation (NCST), was to investigate using higher percentages of reclaimed asphalt pavement (RAP) and reclaimed asphalt shingles (RAS) as a replacement for a percentage of the virgin binder in new asphalt mixes in California. This objective was achieved through the following tasks:

1. A review of the literature on research related to the topic, with special emphasis on the work of the Federal Highway Administration (FHWA) and on recent National Cooperative Highway Research Program (NCHRP) projects
2. Development of a work plan to evaluate the effect of virgin binder source and characteristics on properties of composite binders containing different percentages of RAP and/or RAS

3. Development of a robust and reliable testing procedure for evaluating the high-temperature properties of fine aggregate matrix (FAM) mixes using a solid torsion bar fixture in a dynamic shear rheometer (DSR). Low-temperature properties are being investigated in a separate study
4. Evaluation of the high-temperature rheological properties of composite FAM mixes with different virgin binder sources at different RAP and/or RAS percentages
5. Statistical analysis of the test results
6. Preparation of a summary report and preliminary recommendations for addressing the effect of virgin binder source on the performance of composite binders when incorporating RAP and/or RAS in new asphalt mixes

This report documents the work completed on all tasks.

It should be noted that this project was carried out as one part of a larger, comprehensive research initiative into the use of high quantities of RAP and RAS in new asphalt mixes in road and airfield pavements. Other participants include the California Department of Transportation, the California Department of Resources Recycling and Recovery, and the Federal Aviation Administration.

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 experiment plan and describes the materials and testing methodology used.
- Chapter 4 presents test results and associated discussion.
- Chapter 5 provides conclusions and preliminary recommendations.

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 technical memorandum, 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 viii.

2. Literature Review

2.1 Asphalt Binder

Asphalt binder is obtained from the distillation of crude oil and is a blend of complex hydrocarbons containing thousands of different molecules *(3)*. 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 *(3,4)*.

Asphaltenes have the highest polarity and molecular weight, followed by resins, aromatics, and saturates *(3)*. 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 *(4)*. Asphalt binder stiffness and strength properties are generally related to asphaltenes and resins, while viscous and plasticizing properties are generally related to the aromatics and saturates *(5)*. 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.

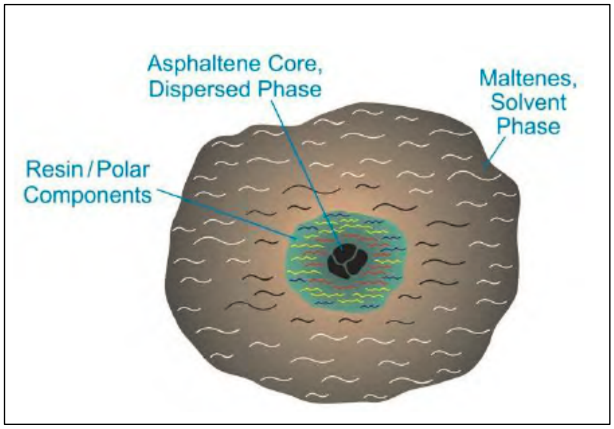


Figure 2.1: Asphalt binder colloidal structure.

2.2 Asphalt Binder Extraction

A number of studies have been conducted to evaluate different solvents and methods for the extraction and recovery of asphalt binder from mixes *(6,7-10)*. Petersen et al. *(11)* 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 *(9)*. A study by Stroup-Gardiner et al. *(12)* found that using normal propyl bromide (n-PB) as an alternative chemical solvent can reduce the amount of aging of the asphalt binder during extraction and recovery when compared to TCE. The study also found that the determined binder content was not influenced by solvent type. However, incompatibilities between various types of propyl bromide and polymer-modified binders were recognized.

2.3 Reclaimed Asphalt

RAP materials have been used in small quantities in new 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, as was common in many states including California until recently. Recent studies and field observations *(6,13-15)* 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.

2.4 Testing Blended Virgin/Reclaimed Asphalt Binders

2.4.1 Introduction

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 *(6,13,14,16-24)*. The extraction and recovery method has long been criticized for being labor intensive, for potentially altering 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 be completely representative of the actual properties of the binder in the mix *(11,14)*. Asphalt binder can also stiffen after extraction due to potential reactions between the binder compounds and the solvent *(25)*. 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.

RAP and RAS stockpiles are typically highly variable because they contain materials reclaimed from numerous locations. Consequently, obtaining representative binders for research-based laboratory testing by using chemical extraction and recovery is not possible. 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 some level of consistency for better understanding key aspects of the testing of composite binders *(26,27)*.

Two alternative methods to solvent extraction and recovery have been investigated for characterizing the properties of blended binders, namely testing asphalt mortar or testing only the fine aggregate matrix of a mix. Initial results cited in the literature for these alternative testing approaches indicate that they are appropriate and justify further investigation *(28-34)*.

2.4.2 Asphalt Mortar Testing

Asphalt mortar tests are conducted using two mortar samples: one containing virgin binder plus RAP, and one containing only virgin binder plus the 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 *(28-30)*. A number of studies have been conducted using this approach with dynamic shear rheometer (DSR) and bending beam rheometer (BBR) testing to assess the stiffness of the samples at high and low temperatures, respectively *(28-30)*. Ma et al. *(28*) 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 using the RAP. Swierz et al. *(28)* 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. *(7)* 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 critical 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.

Preliminary testing at the UCPRC *(35)* found that asphalt mortar samples prepared with asphalt binder and very fine aggregate (passing the #50 [300 µm] and retained on the #100 [150 µm] sieves) were sufficiently workable to conduct DSR testing provided that the binder replacement rate did not exceed 25 percent. Mortars with higher binder replacement rates were unworkable and could not be tested in a DSR. The study concluded that although the mortar test deserves further investigation, it may not be appropriate for testing samples with high binder replacement rates (i.e., >25 percent).

2.4.3 Fine Aggregate Matrix (FAM) Mix Testing

Testing FAM mixes as an alternative to testing asphalt mortar has also been investigated *(8-10)*. 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 cylindrical 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 the second containing virgin binder plus the aggregates obtained from processing RAP in an ignition oven. Any differences in the results can then be attributed to the RAP/RAS component of the FAM. Kanaan *(30)* evaluated the viscoelastic, strength, and fatigue cracking properties of FAM specimens with different amounts of RAS. The results showed that FAM testing detected differences in the properties evaluated among the various mixes, and specifically that the stiffness and strength of asphalt mixes increased with increasing RAS content. Under strain-control mode, the fatigue life of the FAM specimens decreased with increasing RAS content, while under stress-control mode, opposite trends were observed.

2.4.4 Quantifying Level of Diffusion and Blending

A number of studies have been undertaken recently to better understand the diffusion and blending of aged and virgin binders. Yar et al. *(27)* 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 temperature and times will need to be appropriately selected at asphalt plants to ensure sufficient blending between the virgin binder and aged RAP binder. Kriz et al. *(31)* completed a similar study with similar findings.

2.5 Literature Review Summary

Key learning 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. The compatibility of reclaimed and virgin asphalt binders from different sources and with different performance grades must be well understood to ensure optimal performance of asphalt mixes containing high quantities of reclaimed asphalt.

- 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 sufficiently aggressive to fully blend aged and virgin binders extracted from new mixes, thereby potentially providing misleading binder replacement values and nonrepresentative PG gradings of blended binders.
- Alternative methods to 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.

3. Experiment Design

This UCPRC study 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 RAP (i.e., ≥ 25 percent) and RAS. This chapter describes the experiment plan and the testing and evaluation methodologies used in this study.

3.1 Experiment Plan

The experiment plan included the following three main tasks:

- Determine the rheological properties of the virgin binders, recovered RAP binder, recovered RAS binder, and the blended binders at various binder replacement rates. Tests include:
  - + Performance grading
  - + Frequency and temperature sweep tests to develop master curves
- Determine the rheological properties of fine aggregate matrix (FAM) mixes containing different amounts of recovered RAP and RAS (by binder replacement rates) and various virgin binders. Tests include:
  - + Amplitude sweep strain test to determine the linear viscoelastic region
  - + Frequency and temperature sweep tests to develop master curves
- Compare the results of asphalt binder and FAM mix tests using different analysis techniques including statistical evaluation of significant factors

3.1.1 Material Sampling and Testing Factorial

Table 3.1 summarizes the sampling and testing factorial for the materials used in this study. Three binder grades were sampled from three different California refineries that use three different primary crude oil sources. The rejuvenating agent was obtained from one of the refineries.

Table 3.1: General Material Properties

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	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 base (sourced from Refinery-C) 12% by weight of total binder used in the mix

[1] Note that although PG 64-16 binder was requested from Refinery-B, the binder supplied met the requirements for PG 64-22

3.2 Asphalt Binder Testing

3.2.1 Performance Grading of Extracted Binder

In 2001, investigators in the NCHRP 9-12 project *(6)* 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 $G^*/\sin(\delta)$ 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 $G^*/\sin(\delta)$ 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 $G^* \times \sin(\delta)$ 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.

3.2.2 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 per 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 unsuccessful, and therefore blended binder testing was only conducted on blended extracted RAP and virgin binders.

3.2.3 Frequency Sweep Tests

The RTFO-aged blended binders 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 3.1. The testing frequencies at any testing temperature were converted to the reduced frequency at the reference temperature using a time-temperature superposition principle (Equation 3.2) with the aid of an Arrhenius shift factor (Equation 3.3). 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 blended asphalt binders are shown in Figure and Figure 2, respectively.

$$log(|G^*(f_r)|) = \delta + \frac{\alpha}{1+e^{\beta+\gamma\times log(fr)}} \tag{3.1}$$

where: $\delta, \alpha, \beta, and\ \gamma$ are sigmoidal function parameters

f_r is the reduced frequency at reference temperature T_r.

$$log(f_r) = log\big(a_T(T)\big) + log(\,f) \tag{3.2}$$

where: f is the testing frequency at testing temperature *T*(ºC)

f_r is the reduced frequency at reference temperature T_r(°C)

$$log\big(a_T(T)\big) = \frac{1}{\ln(10)\times R}\left(\frac{1}{T} - \frac{1}{T_r}\right) \tag{3.3}$$

where: $a_T(T)$ is the shift factor value for temperature *T* (ºK)

E_a is activation energy term (Joules [J]/mol)

T_r is the reference temperature in degrees Kelvin

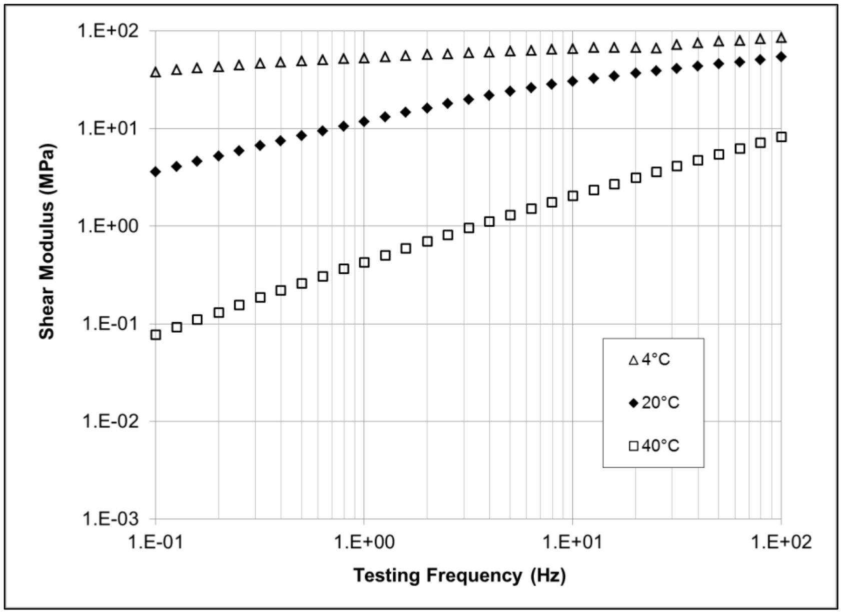


Figure 3.1: Example of measured shear modulus of a blended binder at 20°C.

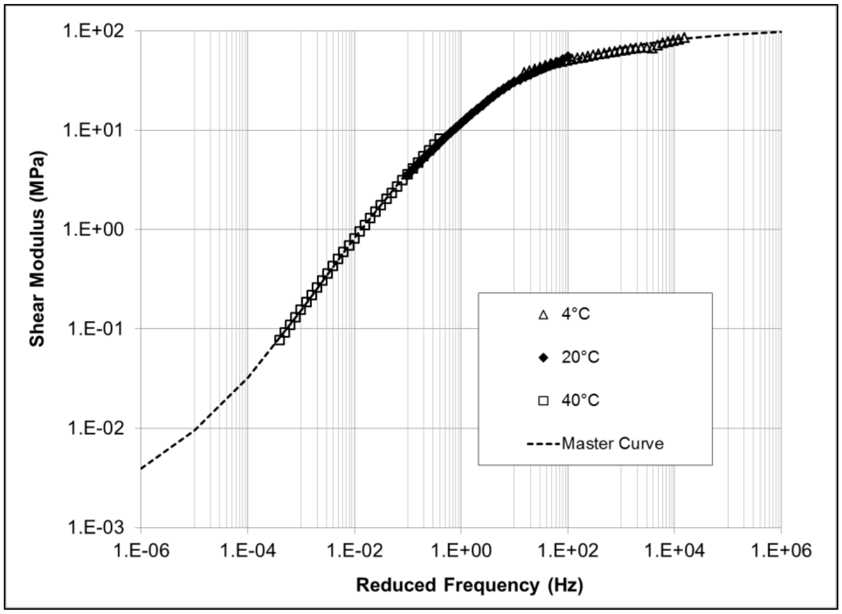


Figure 2.2: Example of a developed master curve for a blended asphalt binder at 20°C.

3.3 Fine Aggregate Matrix Testing

3.3.1 Preliminary Sample Preparation

Preliminary FAM sample preparation methods were based on those cited in the literature *(8-10)*. Mixes were prepared with material passing the #4 (4.75 mm), #8 (2.36 mm), and #16 (1.18 mm) sieves. The #4 and #8 mixes provided satisfactory quantities of FAM; the #16 mixes were difficult to sieve and very large samples needed to be prepared to obtain sufficient quantities of mix to prepare compacted specimens.

3.3.2 UCPRC FAM Sample Preparation Method

After a series of trial tests, the following procedure was developed and adopted for the preparation of FAM 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, #8, or #16). Where required, gently tamp down the mix to break up agglomerations. Mixes passing the #16 sieve are not recommended given that large volumes of material need to be prepared to obtain sufficient mix to prepare compacted samples.
5. 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).
6. Sieve the RAP material to obtain approximately 1.5 kg of the required gradation (i.e., #4, #8, or #16).
7. Determine the binder content and gradation of 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 5 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 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 specimen to long-term aging (i.e., PAV) if required for the testing phase.
14. Core 12.5 mm cylindrical FAM specimens from the 150 mm diameter specimen. Examples of a 150 mm compacted specimen and cored 12.5 mm specimens are shown in Figure .
15. Determine the air-void content of the FAM specimens by first determining the saturated surface-dry 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. The weigh station used for measuring FAM specimen air-void content is shown in Figure .
16. Dry the FAM specimens and store them in a sealed container (Figure) to prevent damage and excessive shelf-aging prior to testing.

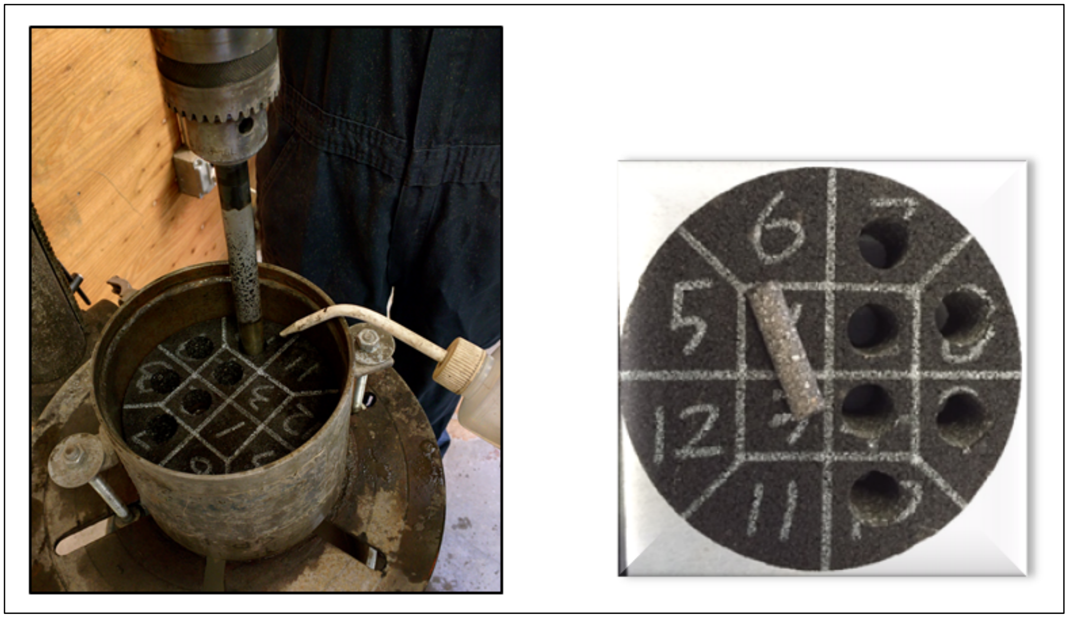
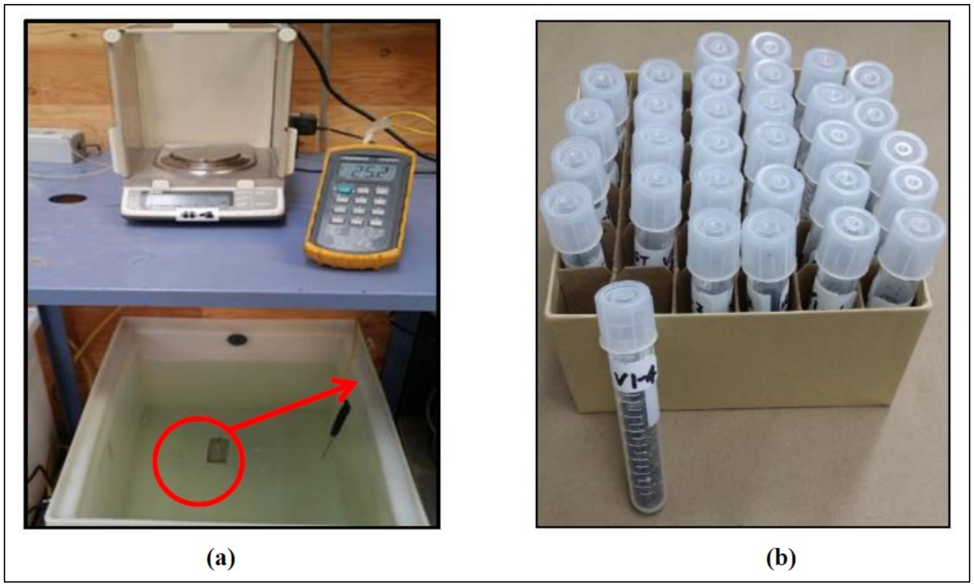


Figure 3.3: FAM specimens cored from a Superpave gyratory-compacted specimen.



(a)

(b)

Figure 3.4: Weigh station for air-void measurement (a) and FAM specimen storage (b).

After preparation of a number of trial mixes, it was observed that the #4 mixes had 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 #8 (2.36 mm) sieve.

3.3.3 Fine Aggregate Matrix Mix Test Setup

FAM specimens prepared according to the method described in Section 3.3.2 were tested using a solid torsion bar fixture in an Anton Paar MCR302 DSR. This testing configuration is known as a dynamic mechanical analyzer (DMA).

When performing tests on FAM 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 *(8-10,30)*, reference is made to the use of steel caps, glued to both ends of the FAM specimen, to secure the specimen into the testing frame. Initial testing at the UCPRC compared tests with and without the caps. This approach was 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 shows the fixed specimen in the DSR-DMA used in this project.

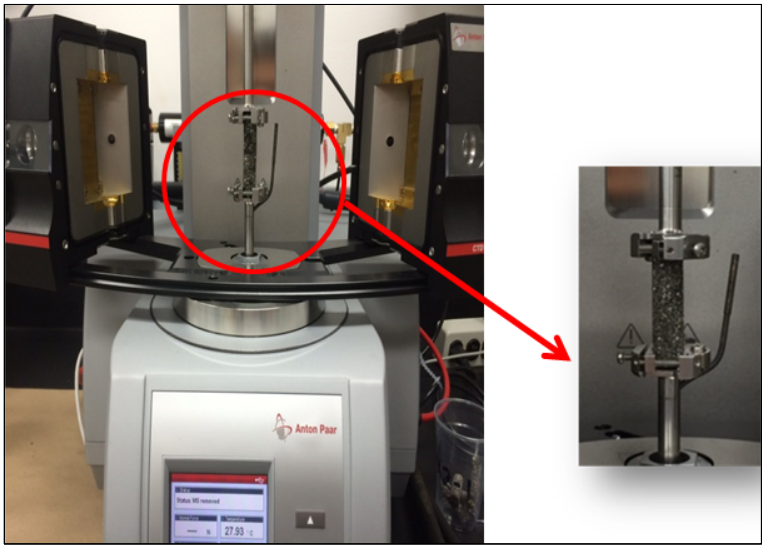


Figure 3.5: DSR-DMA torsion bar fixture used for FAM testing.

3.3.4 Amplitude Sweep Tests

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

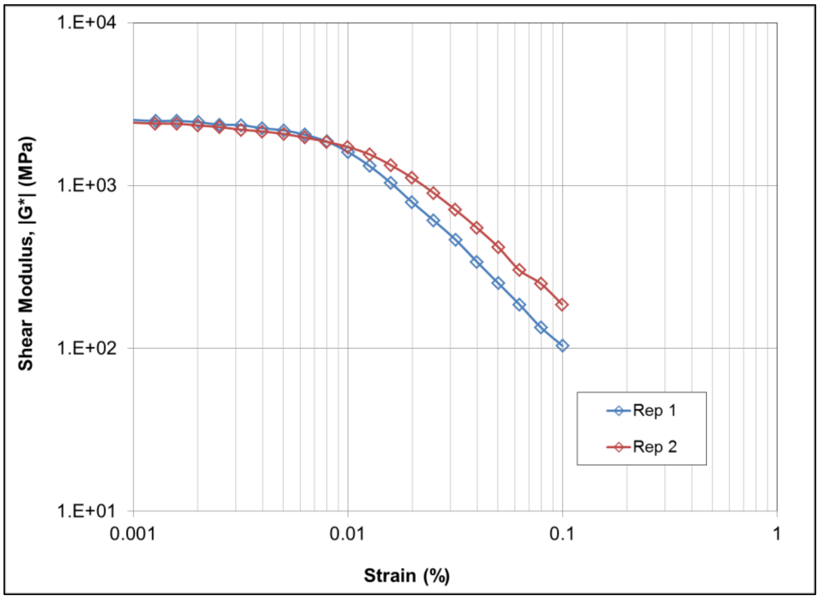


Figure 3.6: Example FAM specimen amplitude sweep test results.

3.3.5 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 specimen shear modulus master curves were constructed based on time-temperature superposition principles using the measured moduli over the range of temperatures and frequencies. The functions described in Section 3.2.3 were used to construct shear modulus master curves for the FAM specimens. Examples of shear modulus and developed master curves at the 20°C reference temperature for a FAM mix are shown in Figure and Figure , respectively.

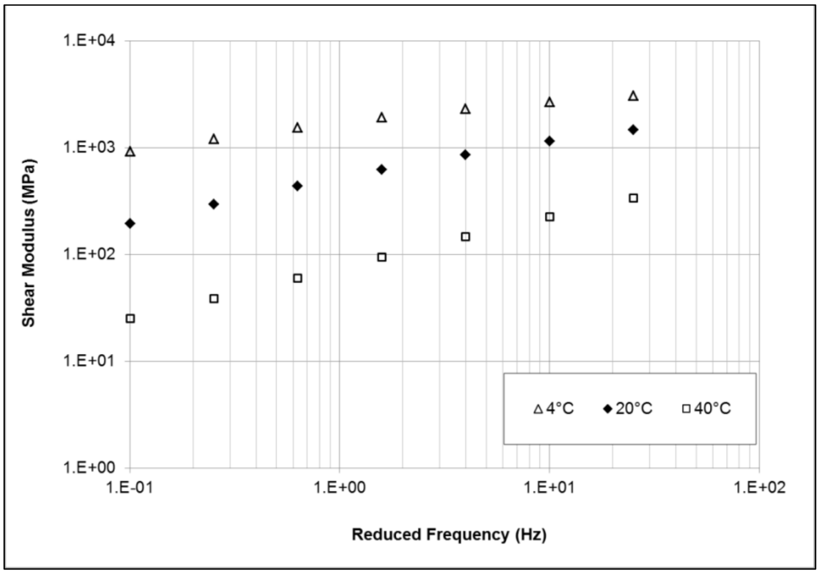


Figure 3.7: Example of measured shear modulus of a FAM specimen at 20°C.

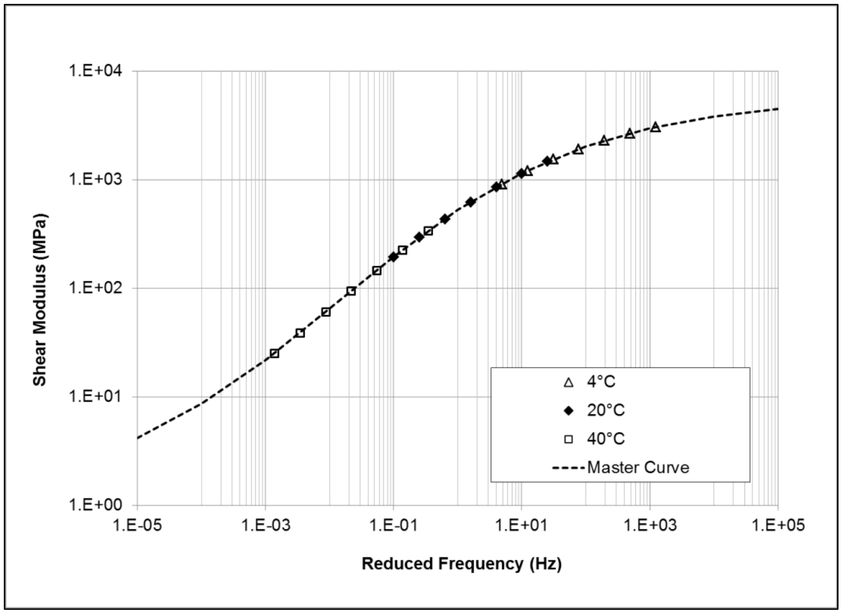


Figure 3.8: Example of shear modulus master curve of a FAM specimen at 20°C.

4. Test Results

4.1 Asphalt Binder Testing

4.1.1 RAP and RAS Binder Characterization

Representative samples of reclaimed asphalt pavement (RAP) and reclaimed asphalt shingle (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 3.2.1.

The performance grading criteria and values of the recovered RAP binders are listed in Table and suggest a mean grading equating to PG 88-6. 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 in any way. Further research is required to evaluate the influence of different chemical solvents on the extraction and recovery of binders from RAP materials, including those containing asphalt rubber and polymer-modified binders.

Table 4.1: High, Intermediate, and Low Critical Temperatures of RAP Binders

Critical Temperature	Parameter	Mean Temperature[1] (°C)	S (MPa)	m
High (Original, DSR)	G*/sinδ ≥ 1.00 kPa	92.8	N/A	N/A
High (RTFO-aged, DSR)	G*/sinδ ≥ 2.20 kPa	86.9		
Intermediate (RTFO-aged, DSR)	G* x sinδ ≤ 5,000 kPa	43.9		
Low @ 0°C (RTFO-aged, BBR)	Tested at 0°C	-6.3	310	0.262
Low @ 10°C	Tested at 10°C		127	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, as shown in Figure . This observation was consistent with other studies, which reported measured high PG limits of RAS binder in excess of 120°C and estimated limits to be as high as 240°C *(34,36)*.

4.1.2 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 *(31),* 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 3.1) 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

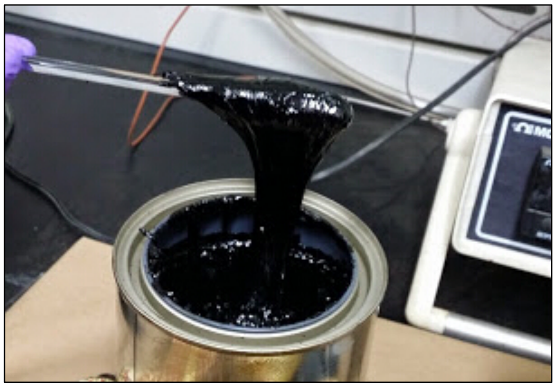


Figure 4.1: Recovered RAS binder after three hours of conditioning at 190°C.

The virgin and blended binders were short-term aged in an RTFO and then 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 master curve parameters for the evaluated binders are provided in Table .

Table 4.2: Master Curve Parameters for Virgin and Blended Binders

Binder Replacement (%)	Mix Identification[1]	Master Curve Parameters				
		δ	α	B	γ	E_a (J/mol)
0	PG64A	-3	4.73	1.32	0.69	191,301
	PG64B	-3	4.61	1.34	0.70	194,798
	PG64C	-3	4.89	1.29	0.78	191,105
	PG58A	-3	4.53	1.08	0.76	181,467
	PG58B	-3	4.49	0.80	0.81	167,421
25 (RAP)	25%RAP_PG64A	-3	5.04	-1.39	-0.62	203,802
	25%RAP_PG64B	-3	5.02	-1.49	-0.58	211,663
	25%RAP_PG64C	-3	4.98	-1.75	-0.69	211,792
	25%RAP_PG58A	-3	5.08	-1.12	-0.60	195,467
	25%RAP_PG58B	-3	5.07	-1.03	-0.61	192,711
40 (RAP)	40%RAP_PG64A	-3	4.99	-1.83	-0.61	217,237
	40%RAP_PG64A+RA	-3	5.05	-1.14	-0.67	198,743
	40%RAP_PG58A	-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 shows the master curves of the five virgin binders evaluated. The moduli of the PG 58 asphalt binders were lower than the PG 64 binders, as expected. The three PG 64 binders had similar shear moduli, with one binder (Refinery-C) being slightly softer at low frequencies and stiffer at high frequencies. The PG 58-22 binder from Refinery-B was softer than the equivalent binder from Refinery-A.

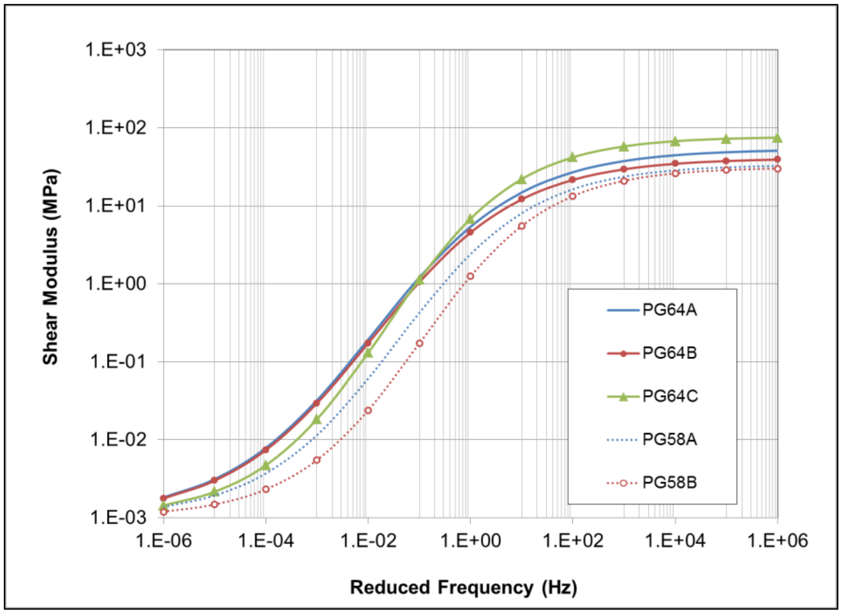


Figure 4.2: Shear moduli of virgin asphalt binders (20°C).

Figure shows the shear modulus master curves for blended binders with 25 percent RAP binder replacement. 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 shows the shear modulus master curves for blended binders containing 40 percent RAP binder replacement. 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.

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). 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.
- When using 40 percent RAP binder replacement, the stiffness of the blended binder increased by up to 13.5 times that of the virgin binder.
- When 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.

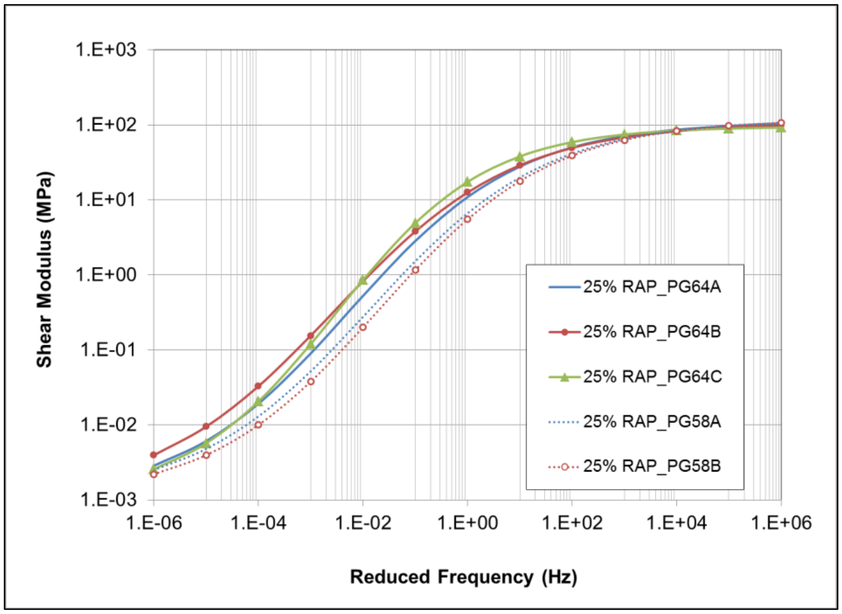


Figure 4.3: Shear moduli of binders with 25 percent RAP binder replacement (20°C).

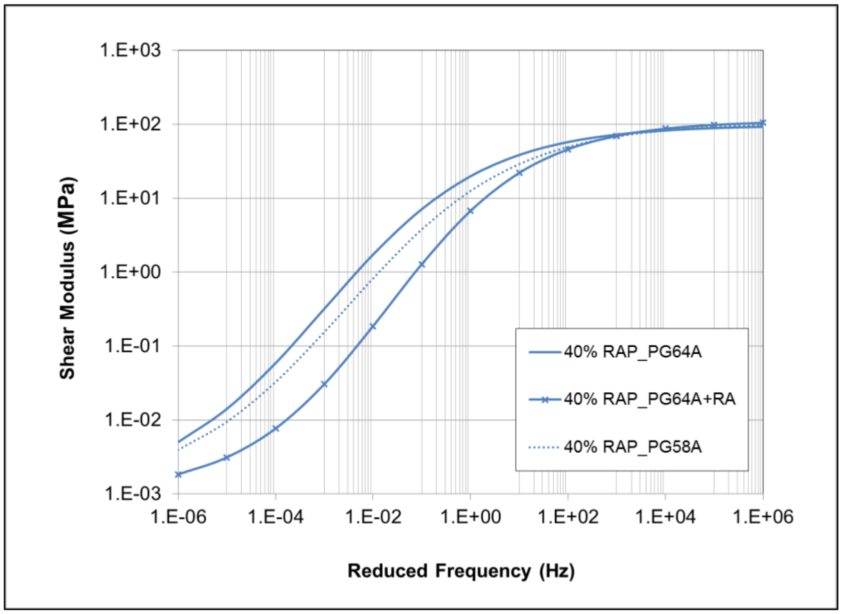
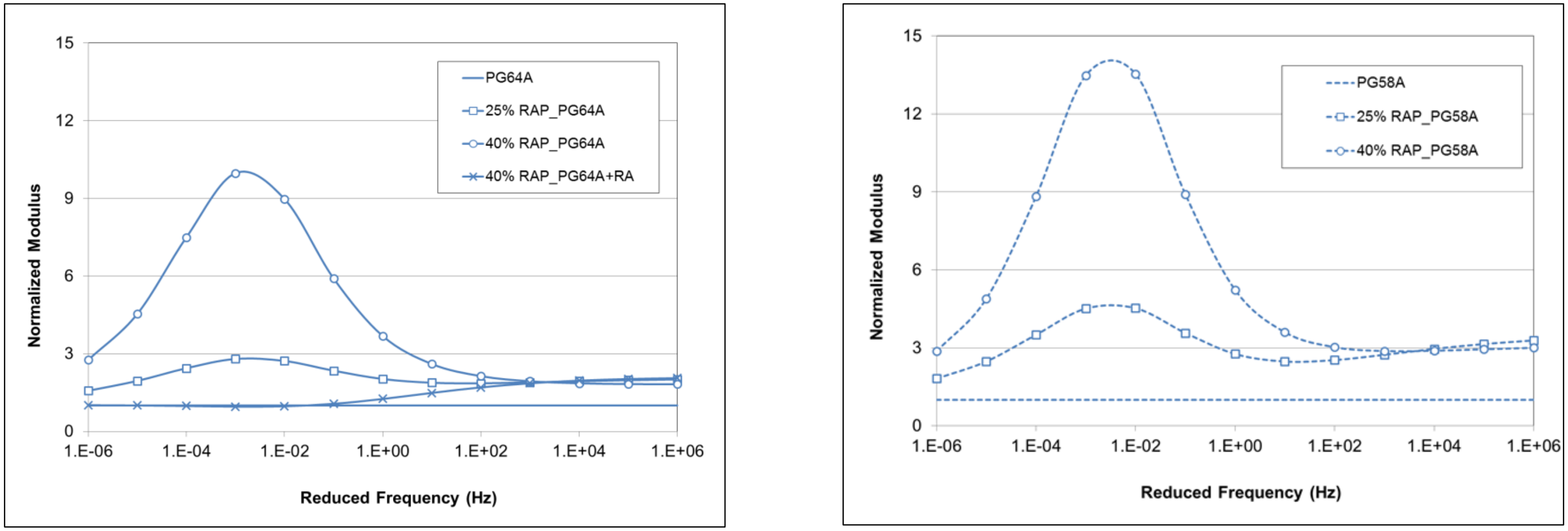
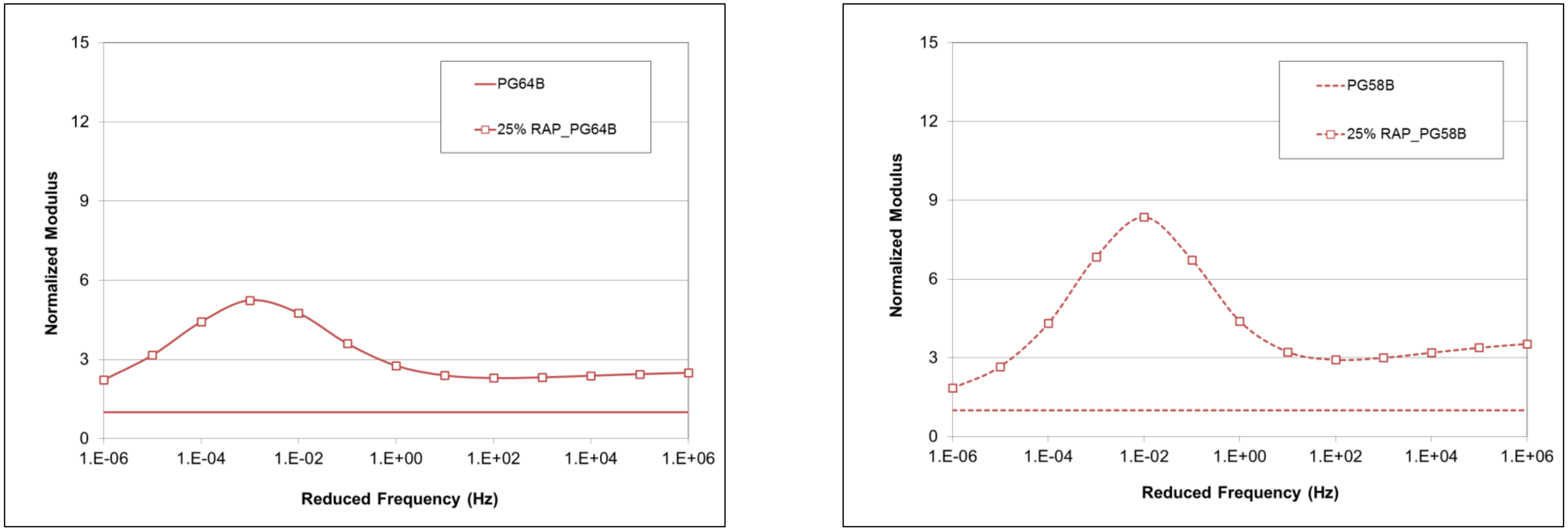


Figure 4.4: Shear moduli of binders with 40 percent RAP binder replacement (20°C).

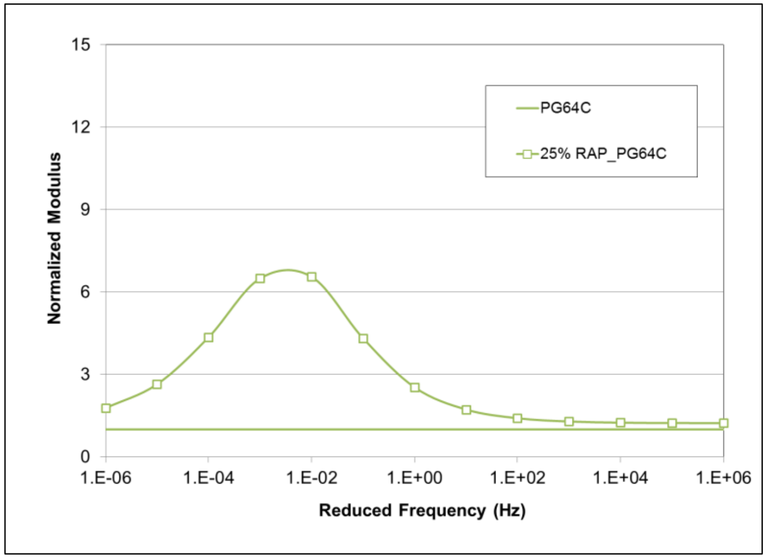


PG 64-16 (Refinery-A) PG 58-22 (Refinery-A)



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

Figure 4.5: Comparison of normalized shear moduli master curves for blended binders.



PG 64-16 (Refinery-C)

Figure 4.5: Comparison of normalized shear moduli master curves for blended binders *(continued)*.

4.2 Fine Aggregate Matrix Mix Testing

FAM mix specimens were prepared according to the procedure described in Section 3.3.2. 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 asphalt binder extraction test (AASHTO T 164). 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 . 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.

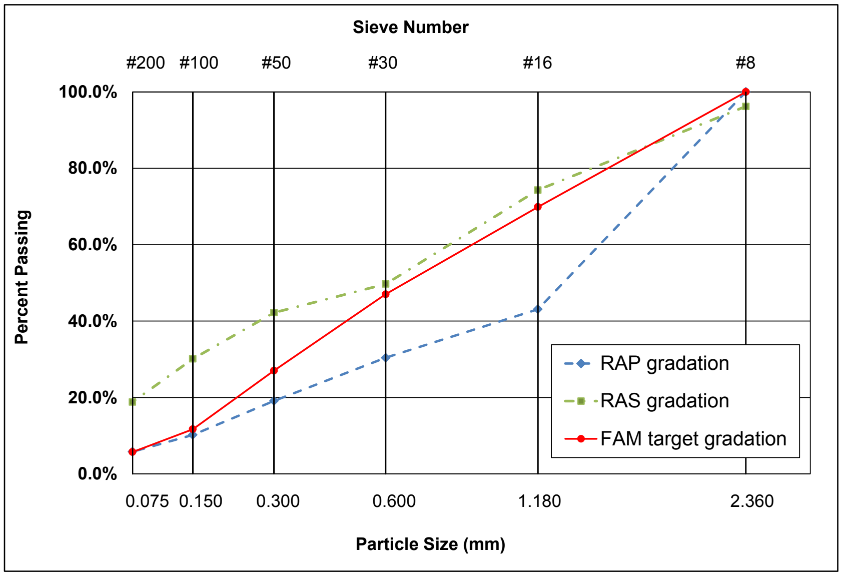


Figure 4.6: Gradation of FAM, RAP, and RAS materials.

4.2.1 FAM Specimen Air-Void Content

One of the main concerns with regard to the repeatability of test results using FAM specimens is the range of air-voids per mix type. Figure and Figure 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. Air-void contents were considered in all test result analyses.

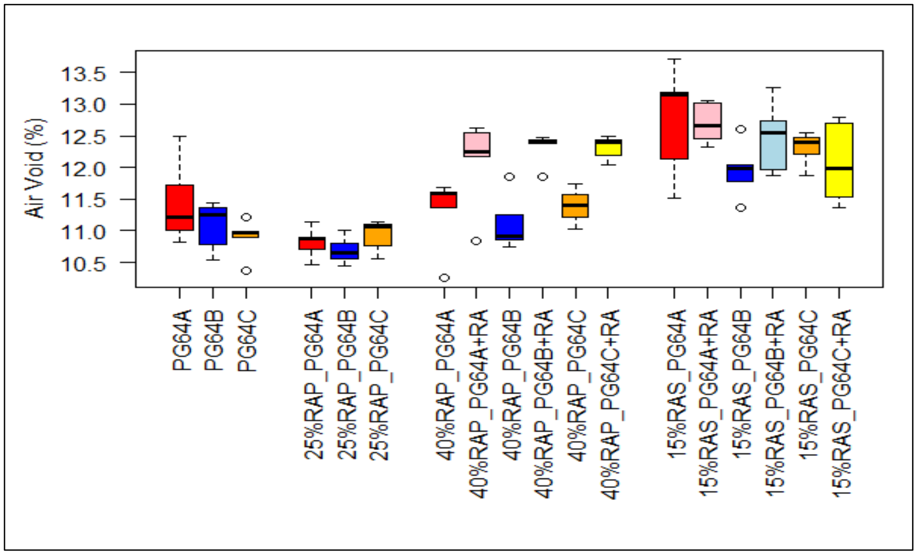


Figure 4.7: FAM specimen air-void contents for PG 64 mixes.

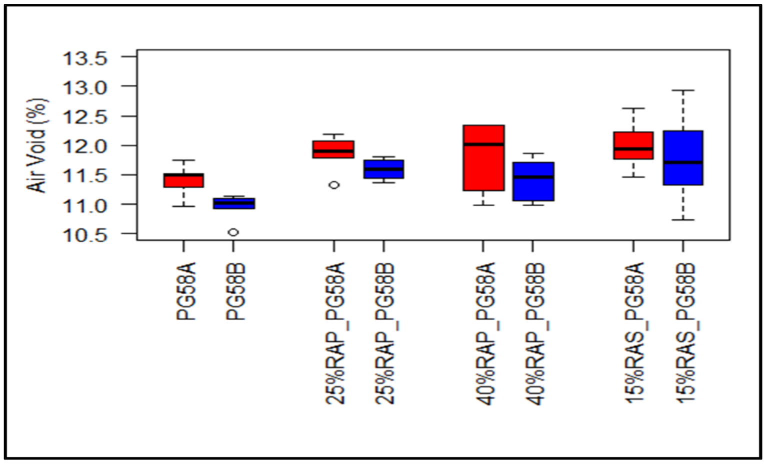


Figure 4.8: FAM specimen air-void contents for PG 58 mixes.

4.2.2 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 and Figure . The following observations were made:

- The LVE strain limits were influenced by virgin binder grade, binder source, and RAP/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.

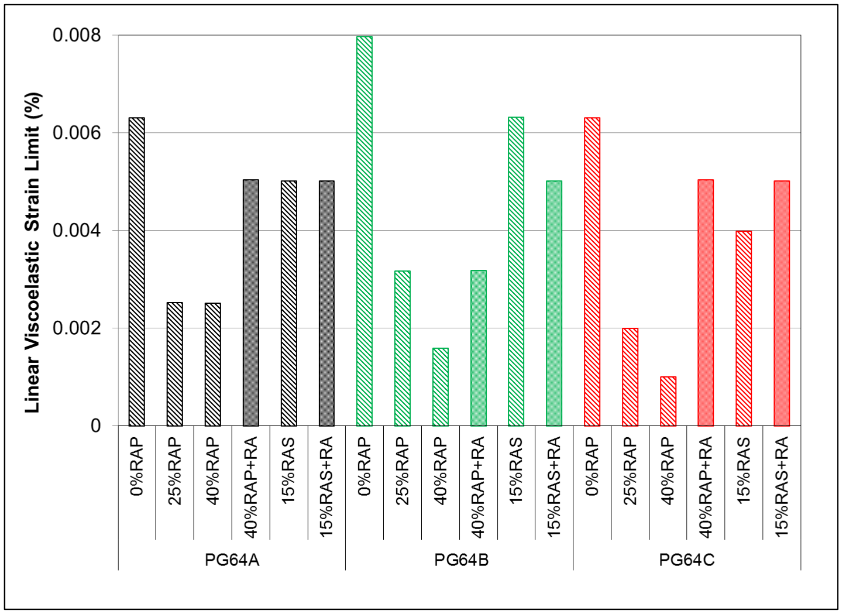


Figure 4.9: FAM specimen LVE range for mixes with PG 64 virgin binders.

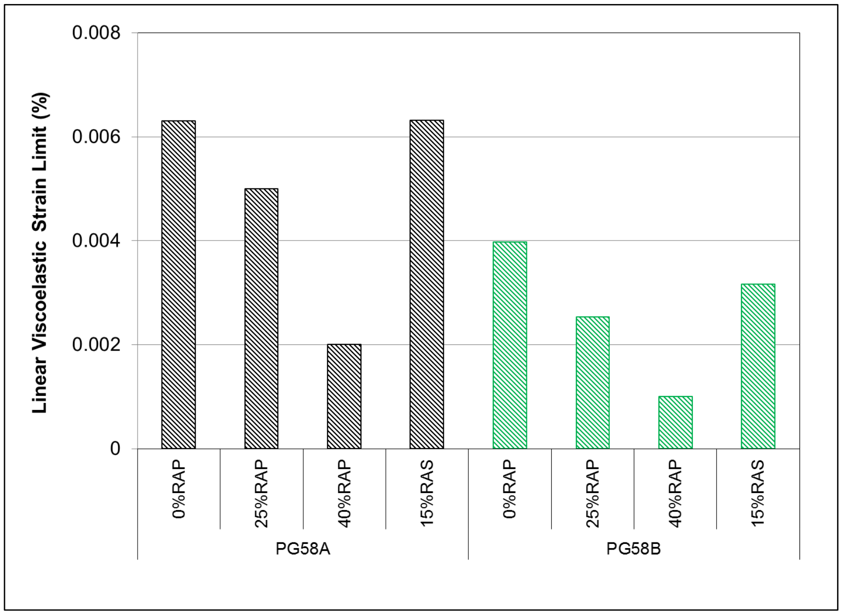


Figure 4.10: FAM specimen LVE range for mixes with PG 58 virgin binders.

- The LVE strain limit decreased with increasing RAP content, as expected. Replacing 25 and 40 percent of the virgin binder with aged binder from the RAP resulted in about 20 to 70 percent and 70 to 90 percent reduction in the LVE strain limit, respectively.
- 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.

4.2.3 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 3.1) and activation energy term in the Arrhenius shift factor (Equation 3.3) for the FAM mixes are provided in Table .

Table 4.3: Master Curve Parameters for FAM Mixes

Binder Replacement (%)	Mix ID[1]	Master Curve Parameters				
		δ	α	β	γ	E_a (J/mol)
0	PG64A	0	3.76	-0.96	-0.52	164,414
	PG64B	0	3.87	-0.93	-0.43	174,701
	PG64C	0	3.63	-1.41	-0.62	172,503
	PG58A	0	3.71	-0.79	-0.52	162,828
	PG58B	0	3.74	-0.53	-0.51	158,722
25 (RAP)	25%RAP_PG64A	0	4.17	-1.06	-0.39	176,435
	25%RAP_PG64B	0	3.99	-1.19	-0.38	179,082
	25%RAP_PG64C	0	4.10	-1.22	-0.45	179,341
	25%RAP_PG58A	0	3.96	-1.07	-0.42	170,216
	25%RAP_PG58B	0	3.99	-1.19	-0.38	165,906
40 (RAP)	40%RAP_PG64A	0	4.21	-1.06	-0.34	180,414
	40%RAP_PG64A+RA	0	3.84	-1.03	-0.46	166,743
	40%RAP_PG64B	0	4.08	-1.14	-0.36	177,121
	40%RAP_PG64B+RA	0	4.14	-0.86	-0.40	170,255
	40%RAP_PG64C	0	4.60	-0.94	-0.35	173,209
	40%RAP_PG64C+RA	0	3.95	-1.17	-0.49	167,399
	40%RAP_PG58A	0	4.10	-1.15	-0.38	171,885
	40%RAP_PG58B	0	4.29	-0.85	-0.36	169,832
15 (RAS)	15%RAS_PG64A	0	3.74	-0.93	-0.45	170,253
	15%RAS_PG64A+RA	0	3.80	-0.70	-0.48	162,233
	15%RAS_PG64B	0	3.65	-0.88	-0.42	171,575
	15%RAS_PG64B+RA	0	3.47	-0.87	-0.49	169,124
	15%RAS_PG64C	0	3.77	-1.18	-0.53	166,295
	15%RAS_PG64C+RA	0	3.98	-0.74	-0.54	160,332
	15%RAS_PG58A	0	3.79	-0.88	-0.42	170,828
	15%RAS_PG58B	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 through Figure , and differentiated by binder source are shown in Figure through Figure . 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. 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 being 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 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 4.2.2 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 and Figure).
- The shear moduli of the FAM mixes with rejuvenating agent were lower 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.

4.2.4 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 $G^*_{0.001\ \mathrm{Hz}}$, $G^*_{1\ \mathrm{Hz}}$, and $G^*_{1{,}000\ \mathrm{Hz}}$ 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 $G^*_{0.001\ \mathrm{Hz}}$ 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).

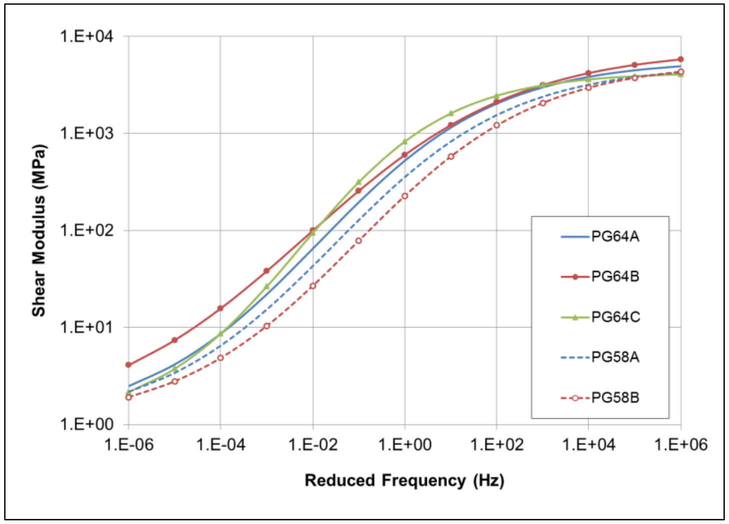


Figure 4.11: Master curves of control FAM mixes.

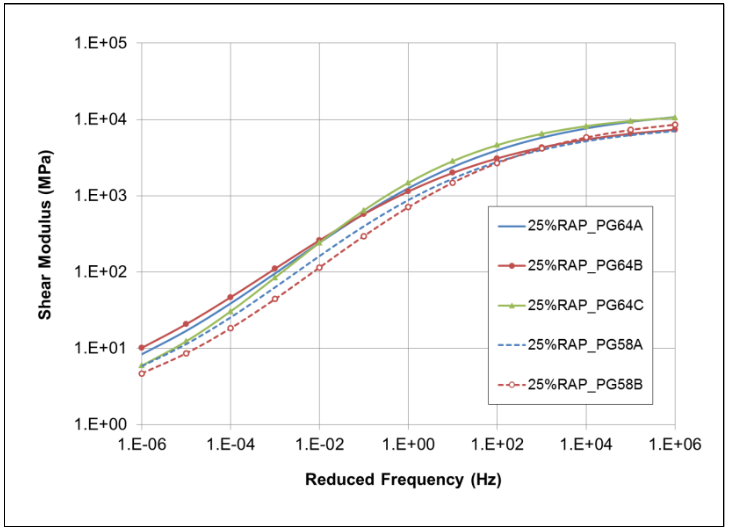


Figure 4.12: Master curves of FAM mixes with 25 percent RAP binder replacement.

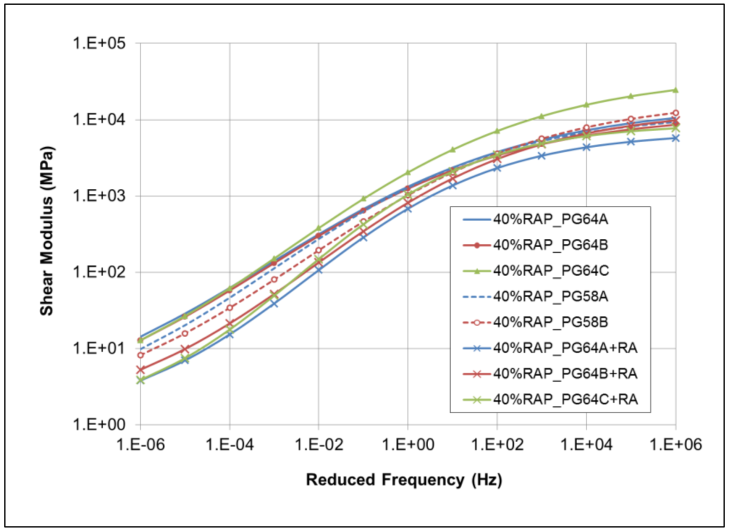


Figure 4.13: Master curves of FAM mixes with 40 percent RAP binder replacement.

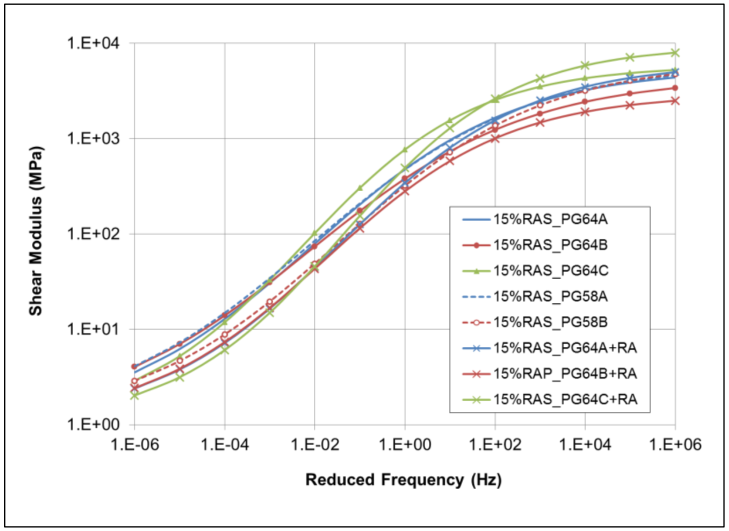


Figure 4.14: Master curves of FAM mixes with 15 percent RAS binder replacement.

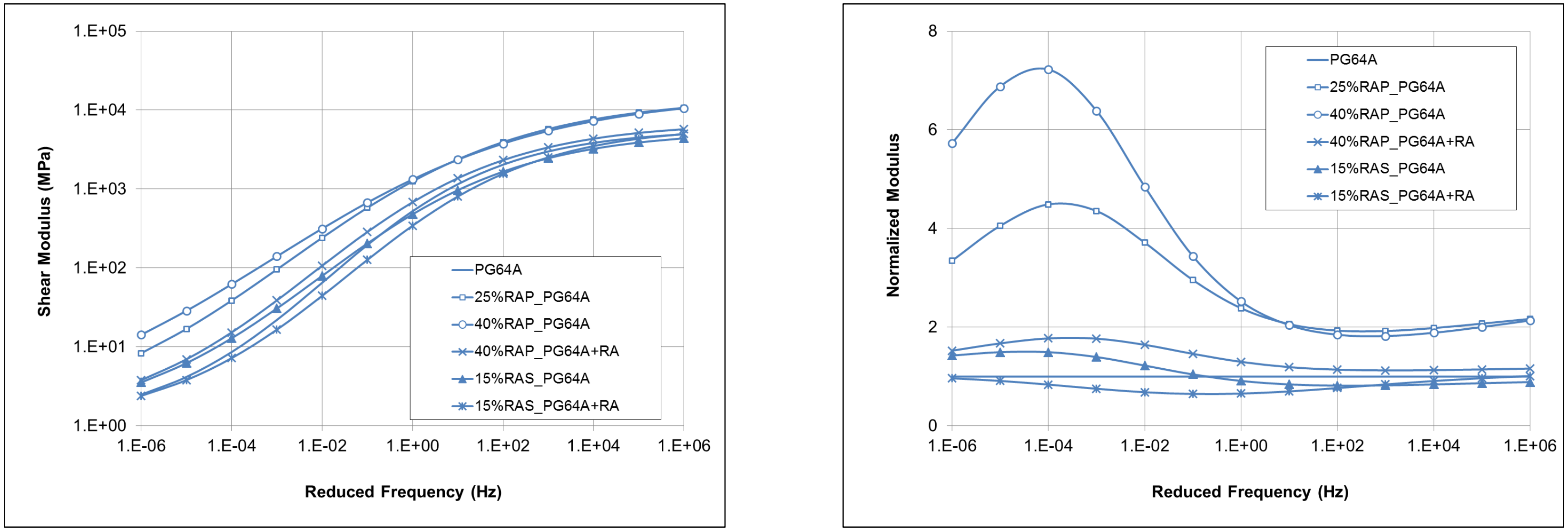


Figure 4.15: PG 64-16-A: Shear and normalized modulus master curves of FAM mixes.

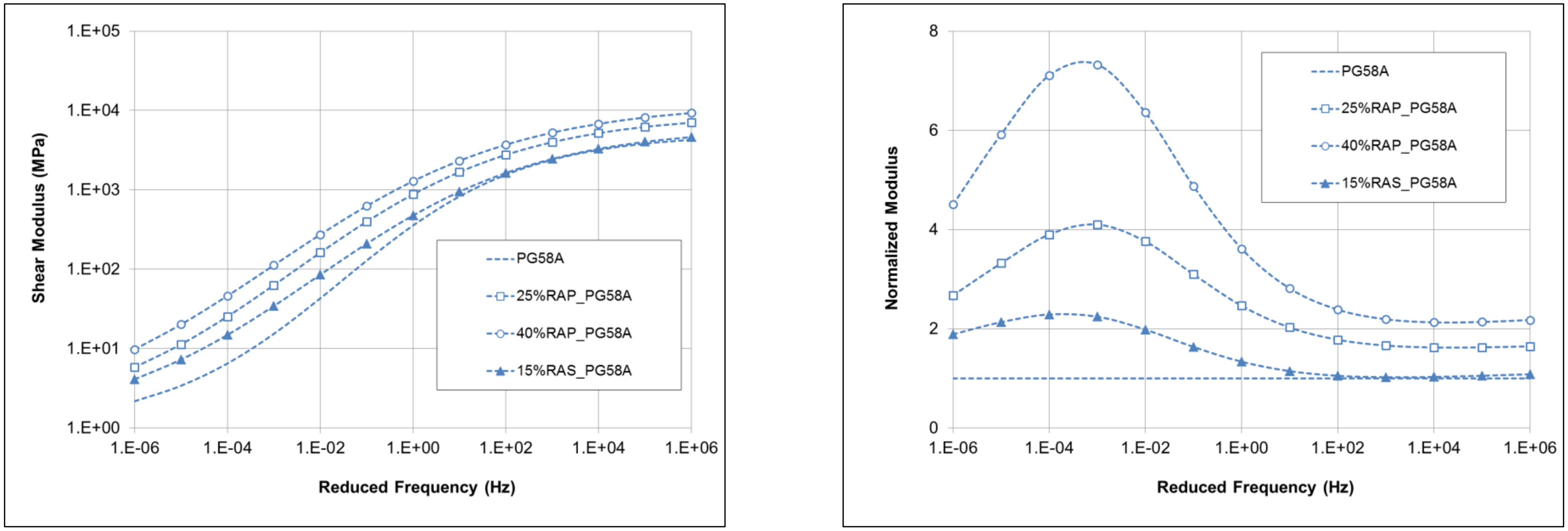


Figure 4.16: PG 58-22-A: Shear and normalized modulus master curves of FAM mixes.

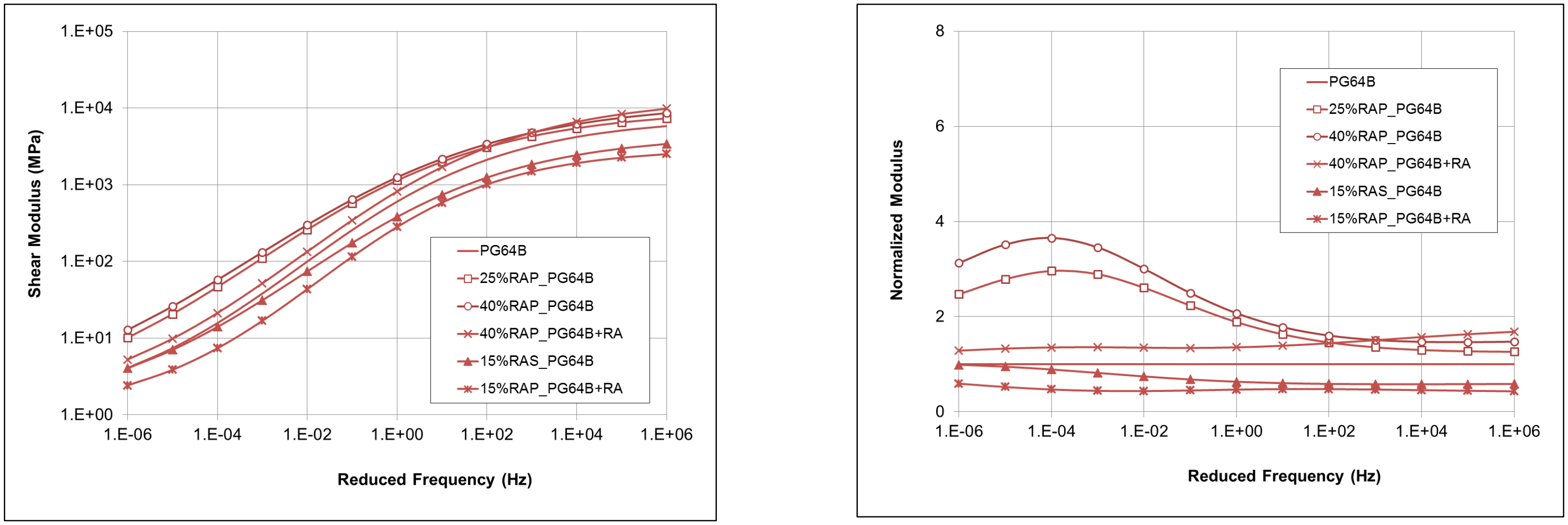


Figure 4.17: PG 64-16-B: Shear and normalized modulus master curves of FAM mixes.

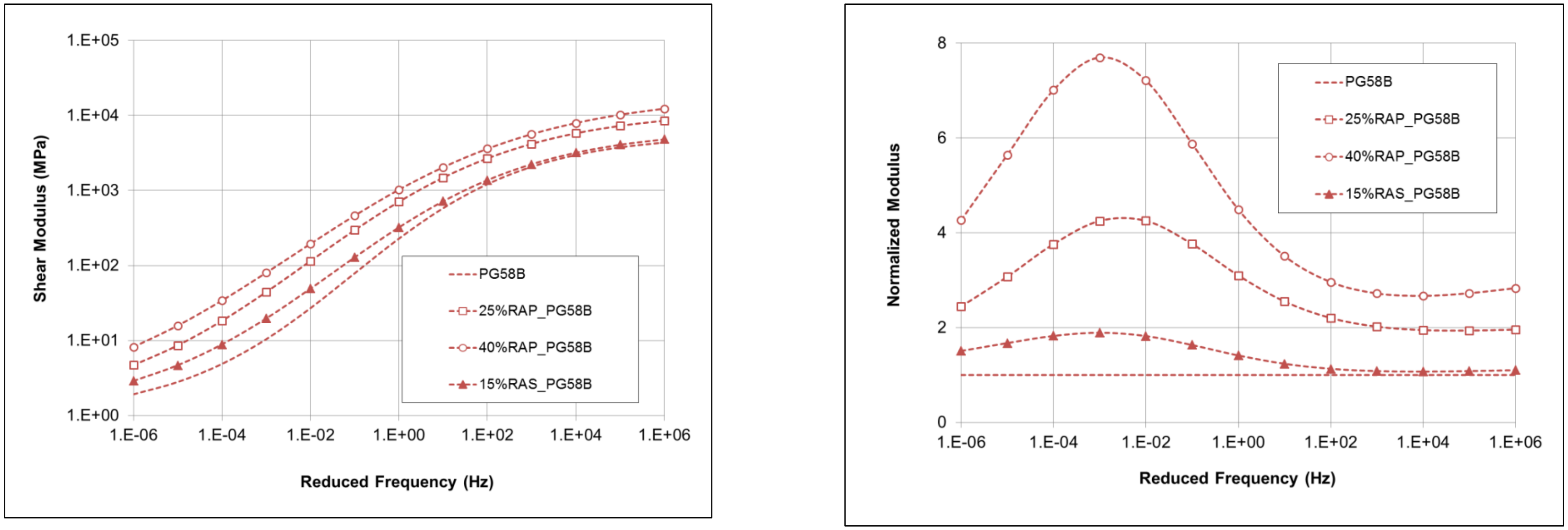


Figure 4.18: PG 58-22-B: Shear and normalized modulus master curves of FAM mixes.

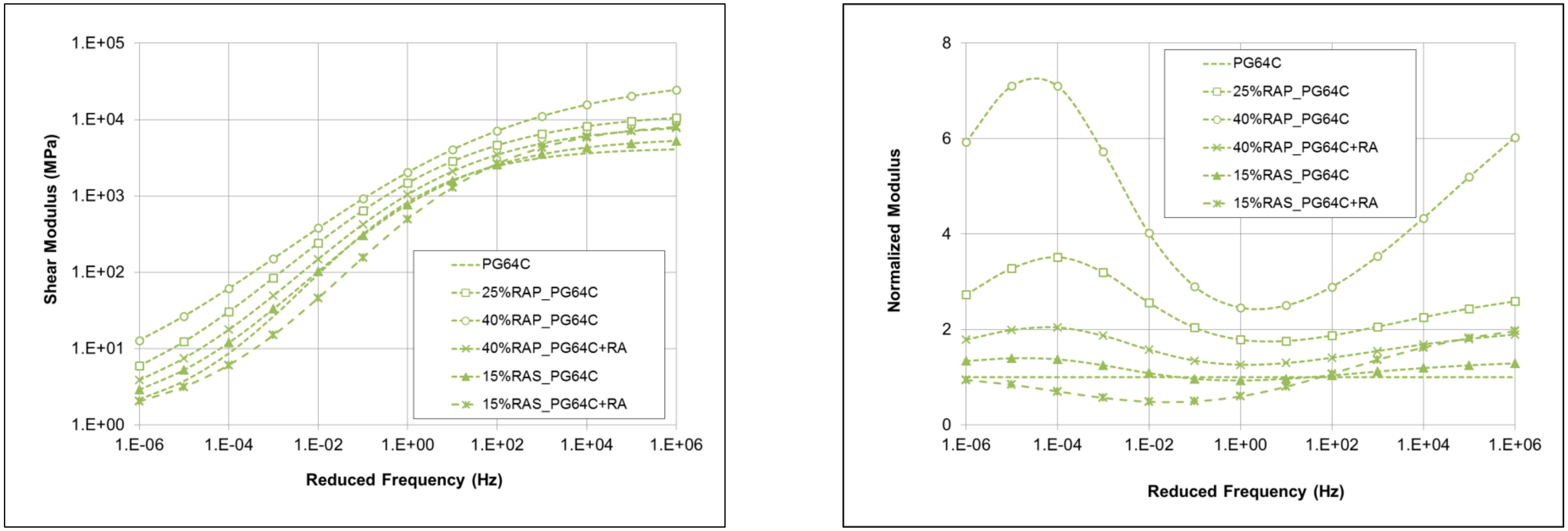


Figure 4.19: PG 64-16-C: Shear and normalized modulus master curves of FAM mixes.

The ANOVA results are listed in Table . 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 FAM mixes at the selected frequencies.

Table 4.4: ANOVA Results

Variable	Type	$G^*_{0.001\ \text{Hz}}$		$G^*_{1\ \text{Hz}}$		$G^*_{1{,}000\ \text{Hz}}$	
		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 Effect	No RA With RA	91.360	1.68e-12	69.448	9.58e-11	15.319	0.000298

4.2.5 Comparing Asphalt Binder and FAM Test Results

Figure through Figure show the relationship between the shear moduli of 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.

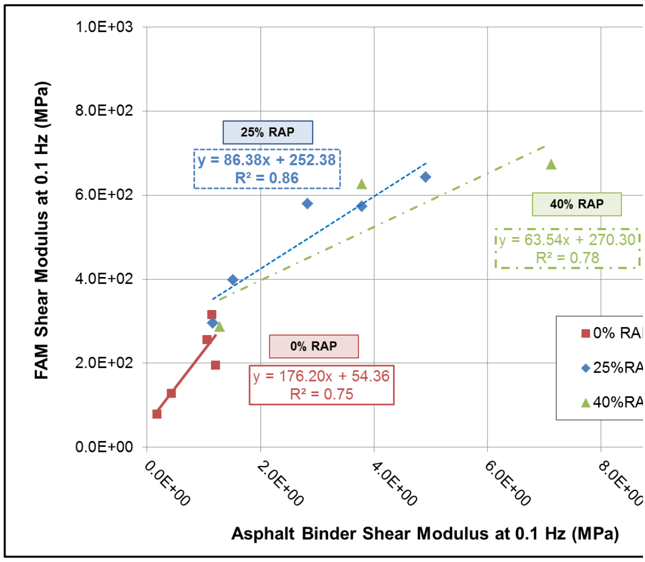


Figure 4.20: Comparison of asphalt binder and FAM mix shear modulus (0.1 Hz at 20°C).

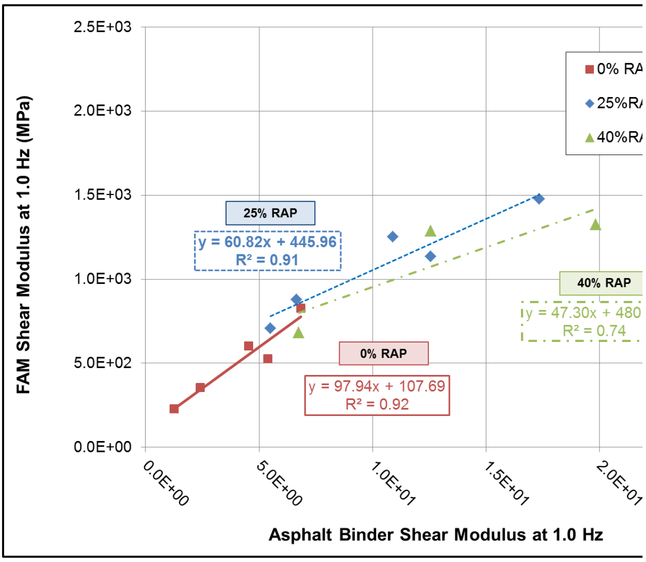


Figure 4.21: Comparison of asphalt binder and FAM mix shear modulus (1.0 Hz at 20°C).

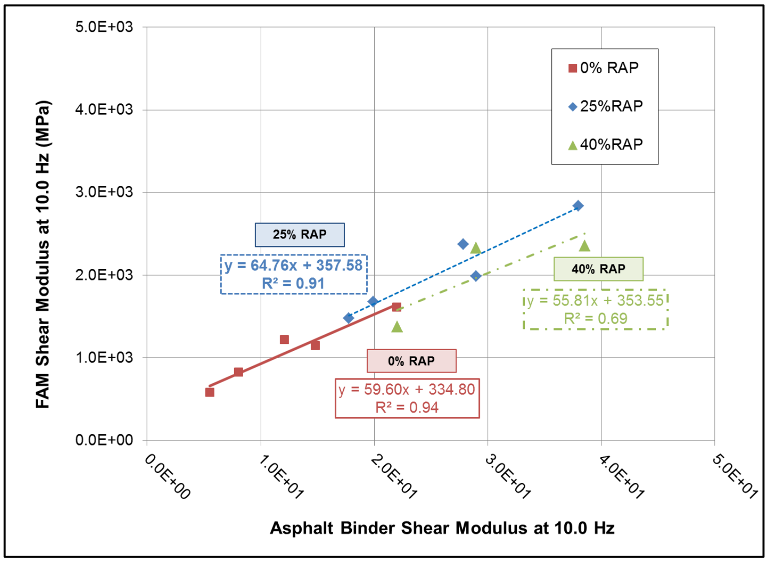


Figure 4.22: Comparison of asphalt binder and FAM mix shear modulus (10 Hz at 20°C).

5. Conclusions and Interim Recommendations

This report summarizes the main findings from a project funded by the National Center for Sustainable Transportation (NCST) to investigate the use of higher percentages of reclaimed asphalt pavement (RAP) and reclaimed asphalt shingles (RAS) as a replacement for a percentage of the virgin binder in new asphalt mixes in California. The research focused on testing procedures that do not first require chemical extraction and recovery of the age-hardened asphalt binders from the RAP and RAS.

Five different asphalt binders covering two performance grades (PG 64-16 and PG 58-22) and sourced from three California refineries were evaluated in this study. The influence of two different percentages of RAP (25 and 40 percent by binder replacement) and one percentage of RAS (15 percent by binder replacement) were evaluated through partial factorial asphalt binder testing and full factorial fine aggregate matrix (FAM) mix testing. The effect of a petroleum-based rejuvenating agent added to selected mixes (with 40 percent RAP and 15 percent RAS binder replacement) was also investigated. Testing was limited to the intermediate temperature properties of the mixes (i.e., 4°C to 40°C). Key observations and findings from this project 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 samples for testing in a dynamic shear rheometer (DSR) or in a bending beam rheometer (BBR).
- Testing procedures were developed as part of this preliminary testing phase to measure dynamic shear modulus at different temperatures and frequencies, and a method for preparing and testing FAM specimens was developed. Cylindrical specimens 0.5 in. (12.5 mm) in diameter cored from a Superpave gyratory-compacted FAM specimen were tested using a torsion bar fixture in a DSR. Preliminary testing of FAM mixes prepared with materials passing the #4, #8, or #16 (4.75 mm, 2.36 mm, or 1.18 mm) sieves indicated that this approach is repeatable and reproducible, and produces representative results for characterizing the performance related properties of composite binder at binder replacement rates up to 40 percent and possibly higher. Use of materials passing the #8 sieve (2.36 mm) is recommended.
- 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 indicated that asphalt binder grade and source, RAP and RAS content, and rejuvenating agent all had a significant influence on FAM mix stiffness, as expected.
- 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 asphalt binder and the stiffnesses of FAM mixes at testing frequencies ranging from 0.1 Hz to 10 Hz. 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. This warrants further investigation.

Based on the findings from this study, FAM mix testing is considered to be a potential appropriate procedure 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 warrants further investigation.

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