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Investigation of the Effect of Reclaimed Asphalt Pavement and Reclaimed Asphalt Shingles on the Performance Properties of Asphalt Binders: Interim Report

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Partnered Pavement Research Center (PPRC) Contract Strategic Plan Element 4.46:
Investigation of the Effect of Reclaimed Asphalt Pavements and Reclaimed Asphalt Shingles on Performance Grade of Conventional Asphalt Binders

PREPARED FOR:

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Abstract:
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 binder replacement from a combination of RAP and reclaimed asphalt shingles (RAS). Although these changes can reduce the amount of virgin binder required in new mixes, concerns have been raised regarding the influence that the aged binder in RAP and RAS will have on the new binder properties.

Traditionally, solvent extraction and recovery have been used to characterize the rheological and performance properties of the asphalt binder in a mix. This approach has long been criticized for being labor intensive, for altering binder chemical and rheological properties, as being inappropriate for modified asphalt binders, and for creating hazardous chemical disposal issues. In the first phase of a UCPRC study described in this technical memorandum, alternative methods to solvent extraction and recovery were investigated for evaluating the performance properties of asphalt binders blended with RAP and RAS binders. These methods include testing asphalt mortars and fine aggregate matrix (FAM) mixes.

This technical memorandum summarizes a literature review on the topic and includes key observations from preliminary laboratory testing. Results from this testing indicate that testing asphalt mortar is probably limited to binder replacement rates not exceeding 25 percent. Preliminary results from FAM mix testing indicate that this method is repeatable and reproducible, and that representative results can be obtained from dynamic shear rheometer (DSR) tests on FAM mix specimens. Proposed further research includes the following:

- Investigate effective binder replacement rates, the compatibility of virgin binder and aged RAP and RAS binders, the effectiveness of rejuvenating agents, and the influences of production time and temperature on the degree of diffusion and blending of virgin and aged binders.
- Investigate relationships between the results of asphalt binder and FAM mix testing and identify possible reasons for differences between results focusing on the effect of solvent extraction on blended binder properties.
- Develop a method for preparing simulated RAP binders that are representative of typical RAP binders at high, intermediate, and low temperatures.
- Investigate the suitability of two-layer asphalt binder testing as a method for understanding the diffusion/blending mechanism between virgin and RAP and RAS binders.

Keywords:
Reclaimed asphalt pavement (RAP), reclaimed asphalt shingle (RAS), extraction and recovery, asphalt mortar, fine aggregate matrix (FAM), asphalt binder replacement

Proposals for implementation:
None

Related documents:
None

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DISCLAIMER STATEMENT

PROJECT OBJECTIVES

The objective of this project is to investigate the effect of reclaimed asphalt pavement (RAP) and reclaimed asphalt shingles (RAS) on the performance properties of asphalt binders. This objective will be achieved through the following tasks:

1. A review of the literature on research related to the topic, with special emphasis on different testing techniques for characterizing the influence of RAP and RAS on the properties of the composite asphalt binder.
2. Develop procedures to assess the effect of RAP and RAS binder properties on the properties of the composite binder. Procedures will include but not be limited to testing of recovered RAP and RAS binders, laboratory-prepared RAP binders, asphalt mortar, and fine aggregate matrix (FAM) mixes.
3. Develop an experimental testing plan to evaluate the effect of RAP and RAS type, source, quantity, and characteristics on the properties of the composite binder.
4. Evaluate the effects of short- and long-term aging on the rheological properties of composite binders with respect to performance in the field.
5. Prepare a report documenting the research undertaken in Tasks 1 through 4, and if appropriate, provide both recommendations for the use of higher RAP and RAS percentages in Caltrans mixes as well as training and workshop materials for Caltrans based on the results of the project.

This interim technical memorandum documents work completed to date on Tasks 1 through 3.

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- The UCPRC laboratory staff

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EXECUTIVE SUMMARY

This technical memorandum summarizes the main findings from the literature review and preliminary tests performed as a part of the PPRC SPE 4.46 project entitled "Evaluation of the Effect of Reclaimed Asphalt Pavements (RAP) and Reclaimed Asphalt Shingles (RAS) on the Performance Properties of Asphalt Binders." The main task of the first phase of this study was to evaluate techniques for characterizing the performance properties of composite binders in mixes with high RAP and/or RAS contents without having to extract and recover the binder with chemicals.

Caltrans currently allows up to 25 percent binder replacement from RAP. However, legislation recently passed that will eventually allow up to 40 percent binder replacement from a combination of RAP and RAS. Before this can be implemented, research is needed to address concerns regarding the degree of blending of virgin and RAP and RAS binders, and the effects of the aged RAP and RAS binders on long-term performance of the mix. Representative samples of the RAP binder are required for testing to address these concerns.

Solvent extraction and recovery is the most commonly used method for obtaining samples of blended binders from mixes containing RAP and/or RAS. However, this method has several disadvantages, including possible chemical reactions that could change the rheology of the recovered binder, incomplete extraction, unrepresentative extraction of asphalt rubber and polymer-modified binders, forced unrepresentative diffusion and blending between aged and virgin binders, and concerns with respect to the hazardous nature of the chemicals used. An alternative method of assessing binder performance properties was therefore investigated in this UCPRC study.

Preliminary laboratory tests were performed to investigate the properties of binders recovered from RAP and RAS samples, the properties of simulated RAP binder prepared in the laboratory, the properties of asphalt mortars, and the properties of fine aggregate matrix (FAM) mixes. Key observations from this preliminary testing 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) and bending beam rheometer (BBR).
- The guidelines recommended in NCHRP 9-12 for determining the performance grade (PG) of binders recovered from RAP samples was considered to be appropriate for the 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 pressure aging vessel (PAV) test scenarios were considered, but only the high critical temperature of the simulated binder was

similar to those of the recovered binders. The low critical temperatures were significantly different. It is unclear whether this could be attributed to the aging procedure or to the effect of the extraction chemicals.

- 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. Although the mortar test deserves further investigation, it may not be appropriate for testing samples with high binder replacement rates (i.e., ≥ 25 percent).
- 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 potentially appropriate for characterizing the performance properties of composite binder at binder replacement rates up to 40 percent and possibly higher. A method for preparing and testing FAM mix specimens was developed for future testing.
- Cylindrical specimens 0.5 in. (12.5 mm) in diameter cored from a Superpave gyratory-compacted FAM mix specimen could be tested using a torsion bar fixture on a DSR (also known as a dynamic mechanical analyzer, DMA). Testing procedures were developed as part of this preliminary testing phase to measure dynamic shear modulus at different temperatures and frequencies. Preliminary results indicated that repeatable, reproducible, representative results can be obtained.
- The testing of FAM mix specimens to characterize fatigue and damage behavior was explored. Preliminary test results indicated that this approach is potentially appropriate for accurately measuring the performance-related rheological properties of composite binders and of understanding the influence of RAP and RAS on these properties.

Based on a review of relevant literature and the results of preliminary tests, fine aggregate matrix mix testing is considered to be a potentially appropriate alternative to testing of solvent-extracted binders for assessing the performance properties of composite virgin/RAP/RAS binders. The preparation and testing of simulated RAP binders is considered an appropriate method for understanding the effects of different binder replacement rates on the degree of diffusion and the blending of virgin and aged binders under controlled conditions. Laboratory testing should be continued to accomplish the following:

- Investigate effective binder replacement rates, the compatibility of virgin binder and aged RAP and RAS binders, the effectiveness of rejuvenating agents, and the influences of production time and temperature on the degree of diffusion and the blending of virgin and aged binders.
- Investigate relationships between the results of asphalt binder and FAM mix testing and identify possible reasons for differences between results focusing on the effect of solvent extraction on blended binder properties.
- Develop a method for preparing simulated RAP binders that are representative of typical RAP binders at high, intermediate, and low temperatures.
- Investigate the suitability of two-layer asphalt binder testing as a method for understanding the diffusion/blending mechanism between virgin and RAP and RAS binders.

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LIST OF ABBREVIATIONS

AASHTO	American Association of State Highway and Transportation Officials
AB	Assembly bill
BBR	Bending beam rheometer
Caltrans	California Department of Transportation
DMA	Dynamic mechanical analyzer
DSR	Dynamic shear rheometer
FAM	Fine aggregate mix
FTIR	Fourier transform infrared spectroscopy
G*	Dynamic shear modulus
HMA	Hot mix asphalt
NCHRP	National Cooperative Highway Research Program
n-PB	Normal propyl bromide
PAV	Pressure aging vessel
PG	Performance Grading
PPRC	Partnered Pavement Research Center
RAP	Recycled Asphalt Pavement
RAS	Recycled Asphalt Shingles
RTFO	Rolling thin-film oven
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 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 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 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
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 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

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 binder replacement from a combination of RAP and reclaimed asphalt shingles (RAS). Although these changes can reduce the amount of virgin binder required in new mixes, concerns have been raised regarding the influence that the aged binder in RAP and RAS will have on the new binder properties.

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 in Caltrans asphalt mix designs, but making this change has raised concerns regarding how composite binders may influence 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 the composite binder 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, 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 effect of mix production time and temperature on the degree of blending and on the properties of the composite binder needs to be quantified.
- The effects of rejuvenating agents on the blending of aged and new binders and the long-term performance of mixes needs to be evaluated.

1.3 Project Objectives

The objective of this project is to investigate the effect of RAP and RAS on the performance properties of asphalt binders. This objective will be achieved through the following tasks:

1. A review of the literature on research related to the topic, with special emphasis on different testing techniques for characterizing the influence of RAP and RAS on the properties of the composite asphalt binder.
2. Develop procedures to assess the effect of RAP and RAS binder properties on the properties of the composite binder. Procedures will include but not be limited to testing of recovered RAP and RAS binders, laboratory-prepared RAP binders, asphalt mortar, and fine aggregate matrix (FAM) mixes.
3. Develop an experimental testing plan to evaluate the effect of RAP and RAS type, source, quantity, and characteristics on the properties of the composite binder.
4. Evaluate the effects of short- and long-term aging on the rheological properties of composite binders with respect to performance in the field.
5. Prepare a report documenting the research undertaken in Tasks 1 through 4, and if appropriate, provide both recommendations for the use of higher RAP and RAS percentages in Caltrans mixes as well as training and workshop materials for Caltrans based on the results of the project.

This interim technical memorandum documents work completed to date on Tasks 1 through 3.

1.4 Report Layout

This interim technical memorandum summarizes the literature review and the results from preliminary laboratory testing, and is organized as follows:

- Chapter 2 summarizes the findings from preliminary asphalt binder testing, development of a procedure for preparing simulated RAP binder, and a procedure for testing the rheology of a two-layer asphalt binder specimen.
- Chapter 3 summarizes the findings from preliminary mortar testing.
- Chapter 4 summarizes the findings from preliminary fine aggregate matrix (FAM) mix testing.
- Chapter 5 describes proposed testing techniques and a tentative experimental plan for a second phase of the study.
- Chapter 6 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 xi.

2. LITERATURE REVIEW

Over time the binder in existing pavement oxidizes and age-hardens, significantly altering the properties of the original binder *(1)*. Despite this oxidation and aging, numerous studies *(2,3)* have shown that aged binder from reclaimed asphalt pavement (RAP) and reclaimed asphalt roofing shingles (RAS) can be used in new mixes, thereby reducing the amount of virgin binder that is used. These studies have shown that aged and virgin binders can blend appreciably, but that mixes containing the blended binders may perform differently than mixes only produced with virgin binders in terms of rutting, cracking, and raveling.

Because of the high quantities of asphalt binder used to produce roofing shingles (20 to 30 percent by weight of the shingle), there is increasing interest in the use of RAS as a source of asphalt binder for pavements. RAS is obtained either from shingles rejected during the production process (i.e., the binder has not been subjected to long-term aging) or from shingles that have been removed from roofs (known as tear-off shingles; the binder is usually highly aged). The asphalt binders used in RAS are air-blown during the production process, which results in rapid early aging of the binder *(4)*. As a result of this aging, the properties of RAS binders are usually very different from those of RAP binders, and therefore the use of RAS in new mixes is typically limited to between three and five percent by weight of the binder, corresponding to about 10 to 30 percent binder replacement *(5)*.

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 *(1-3,5-13)*. The extraction and recovery method has long been criticized for being labor intensive, for 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 *(3,14)*. Asphalt binder also becomes stiffer after extraction due to the potential reactions between binder compounds and the solvent *(15)*. 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 always 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 controlled consistency for better understanding key aspects of the testing of composite binders *(16,17)*. Testing asphalt mortar or only the fine aggregate matrix of a mix have been proposed as alternative methods to binder extraction for characterizing the properties of binders. Initial results cited in the literature for these alternative testing approaches indicate that they are appropriate and justify further investigation *(18-24)*.

Asphalt mortar testing is done on 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 burnt 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 *(18-20)*. 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 *(18-20)*. Ma et al. (*18*) 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 their study had a maximum of 25 percent binder replacement using the RAP. Swierz et al. *(18)* 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 their 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. *(20)* compared the performance grade properties of blended binder 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 the effect of the chemistry on additional hardening of the binders.

Testing fine aggregate matrix (FAM) mixes as an alternative to testing the asphalt mortar has also been investigated *(21-24)*. 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 mix must be representative of the binder content and gradation of the fine portion of a full-graded asphalt mix. Small FAM mix 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 and RAS component of the FAM mix. Kanaan *(24)* evaluated the viscoelastic, strength, and fatigue cracking properties of FAM mix specimens with different amounts 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 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, opposite trends were observed.

A number of studies have been undertaken recently to better understand the diffusion and blending of aged and virgin binders. Yar et al. *(17)* evaluated and quantified the effect of time and temperature on diffusion rate and the ultimate blending between 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. *(25)* completed a similar study with similar findings.

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

- Appropriate methods for extracting aged binder from reclaimed asphalt pavement materials are still being developed. The effects of extraction solvents on the properties of recovered binders are being evaluated. 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 nonrepresentative PG gradings of blended binders.
- Alternative methods to extraction and recovery are being explored to better characterize the performance properties of RAP binders and RAP binders blended with virgin binders. Tests on mortar and fine aggregate mixes warrant further investigation.

- The two-layer asphalt binder testing approach appears to be an appropriate method of evaluating diffusion and blending between aged and virgin binders and will be explored in a later phase of this study, specifically with regard to the effects of the chemical compatibility of aged and virgin binders, the effects of production time and temperature on binder blending, and the effects of rejuvenating agents.

3. PRELIMINARY ASPHALT BINDER TESTING

3.1 Introduction

This part of the study focused on the characterization of extracted and recovered asphalt binder from RAP and RAS materials and review of accelerated aging processes for preparing simulated RAP binder.

3.2 Experiment Design

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.

3.2.1 Material Sampling

Samples of RAP material were collected from three different asphalt plants (two in northern California [Sacramento and Bay Area, referred to as RAP-A and RAP-B, respectively] and one in southern California, referred to as RAP-C). One tear-off RAS sample was obtained from a supplier in Oakland, California. Asphalt binder was sourced from one northern California refinery.

3.3 Evaluation of Properties of Extracted and Recovered RAP and RAS Binders

3.3.1 Test Method

A number of studies have been conducted to evaluate different solvents and methods for the extraction and recovery of asphalt binder from mixes *(1,25-28)*. Petersen et al. *(25)* evaluated different solvent types (trichloroethylene [TCE], toluene/ethanol, and *EnSolve*) and three combinations of extraction and recovery methods (centrifuge-Abson, centrifuge-Rotavapor, and SHRP 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 *(27)*. A study by Stroup-Gardiner et al. *(28)* 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.

In 2001, investigators in the NCHRP 9-12 project *(1)* 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 the performance grade of the virgin binder can be accurately selected from a blending chart. The following procedure, proposed in the NCHRP study guidelines, was used for determining the performance grading of the RAP binders used in the UCPRC study:

- Asphalt binder extraction and recovery
  1. Obtain a representative sample of RAP 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 RAP following the modified AASHTO TP 2 procedure (now AASHTO T 164). Toluene or n-propyl bromide may be used as the chemical solvent. Other solvents must be noted if used. Nitrogen blanketing is recommended to prevent undesired binder oxidation during extraction.
- Asphalt binder performance grading
  1. Determine the performance grading of the extracted RAP binder according to AASHTO MP 1 (now AASHTO M 320). Rotational viscometer, binder flash point, mass loss, and pressure aging vessel (PAV) are not required for RAP binder grading. PAV aging is not necessary given that the RAP binder has already been aged in the pavement.
  2. Perform a dynamic shear rheometer (DSR) test with 25 mm parallel plate geometry on the recovered RAP binder (following AASHTO T 315) to determine the critical high temperature of the binder (temperature at which G*/sin(δ) is 1.0 kPa).
  3. Age the extracted RAP binder in a rolling thin-film oven (following AASHTO T 240).
  4. Perform a DSR test with 25 mm parallel plate geometry on the rolling thin-film oven (RTFO)-aged recovered RAP 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 RAP binder based on the lowest values of temperatures obtained in Steps 2 and 4.
  6. Perform a DSR test with 8 mm parallel plate geometry on the RTFO-aged recovered RAP 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 (following AASHTO T 313) on the RTFO-aged recovered RAP 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 extracted RAP binder based on the highest (least negative) temperatures determined in Step 7.

3.3.2 Test Results

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 3.1.

Table 3.1: Extraction and Recovery Results for RAP and RAS Samples

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

RAS Binder

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 3.1. 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 *(29,30)*.

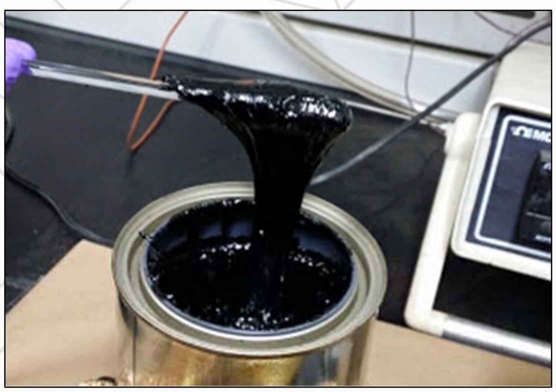

Figure 3.1: Recovered RAS binder after three hours of conditioning at 190ºC.

RAP Binders

The critical PG temperatures of the recovered RAP binders, determined according to AASHTO M 320, are provided in Table 3.2 and the PG values are listed in Table 3.3. 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 3.2: High, Intermediate, and Low Critical Temperatures of RAP Binders

Critical Temperature (°C)	Parameter	RAP-A (°C)		RAP-B (°C)		RAP-C (°C)	
High (Original, DSR)	G*/sinδ ≥ 1.00 kPa	92.8		88.0		95.2	
High (RTFO aged, DSR)	G*/sinδ ≥ 2.20 kPa	86.9		83.1		89.0	
Intermediate (RTFO aged, DSR)	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, BBR)	0	310	0.262	348	0.272	239	0.258
	6	NA	NA	163	0.328	NA	NA
	10	127	0.365	NA	NA	89.9	0.374
Critical Temperature (°C)	**Parameter**	**RAP-A (°C)**		**RAP-B (°C)**		**RAP-C (°C)**	
High (unaged)	-	92.8		89.0		95.2	
High (aged)	-	86.8		88.1		89.0	
Intermediate (aged)	-	43.8		41.2		41.2	
Low (aged)	-	-6.3		-7		-6.4	

Table 3.3: PG Grades of Extracted and Recovered RAP Binders

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

3.4 Evaluation of Properties of Simulated RAP Binders

3.4.1 Background

The testing proposed for the UCPRC studies require a large quantity of binder. Obtaining this quantity of binder using the AASHTO T 164 process was considered to be inappropriate and impractical 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 *(31,32)*. A number of recent studies have proposed approaches for preparing simulated RAP binder by aging virgin binders in a pressure aging vessel (PAV). Bowers et al. *(16)* recommended two PAV cycles based on the results of chemical analyses of the binders using Fourier transform infrared spectroscopy (FTIR). Another study by Yar et al. *(17)* also recommended two or more PAV cycles, given that each PAV cycle supposedly simulates seven to ten years of field aging.

3.4.2 Test Results

A PG 64-16 asphalt binder was used in this part of the study. Samples of the binder were aged in a PAV for 40 and 60 hours at 100ºC and under 2.1 MPa of air pressure. The PG grades of these aged binders were then determined following the NCHRP 9-12 guideline for RAP binder grading. The results are listed in Table 3.4. A comparison of the PG grades of the PAV-aged binders with the PG grades of the extracted RAP binders (see Table 3.2) indicated that the critical high PG temperature of the 60-hour PAV-aged binder was comparable to the 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 later phase of this 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 3.4: Critical Temperatures for 40 and 60 Hour PAV-Aged Binder

Critical Temperature (°C)	Method	40 Hours (°C)	60 Hours (°C)
High	Unaged DSR/RTFO DSR	88.9/82.1	93.6/86.7
Intermediate	RTFO DSR	28.7	31.9
Low	RTFO BBR	-19.8	-17.24

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4. PRELIMINARY ASPHALT MORTAR TESTING

4.1 Introduction

Evaluating techniques that do not require chemical extraction for characterizing the performance properties of composite asphalt binders was the main task of this UCPRC study. Based on a preliminary literature review *(20)* and discussions with other practitioners, a decision was made to undertake asphalt mortar testing with a dynamic shear rheometer (DSR) as an appropriate approach for this testing. Two samples were tested in this process: one sample consisted of virgin binder plus RAP, and the other consisted of virgin binder plus the aggregates obtained from processing RAP in an ignition oven (i.e., the RAP binder was burnt off in an ignition oven). Provided that the aggregate gradations and total binder contents are exactly the same for both samples, any differences in the critical temperatures can be attributed to the RAP binder.

4.2 Experimental Design

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 tests on recovered binders from the three different sources indicated that the binder properties were similar (see Table 3.2). 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 compared to stiffer PG 64 or PG 70 binders.

4.2.1 Material Sampling

The RAP-A material sourced from a Sacramento asphalt plant (see Section 3.2) and asphalt binder sourced from the northern California refinery were used in this part of the testing.

4.3 Sample Preparation

The mortar sample preparation procedure developed by Hajj et al. and summarized in Figure 4.1 *(20)* was investigated prior to sample preparation in the UCPRC study. 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 binder replacement values and consequently the tests were not unduly influenced by high sample stiffnesses, which is typical of samples with high binder replacement values.

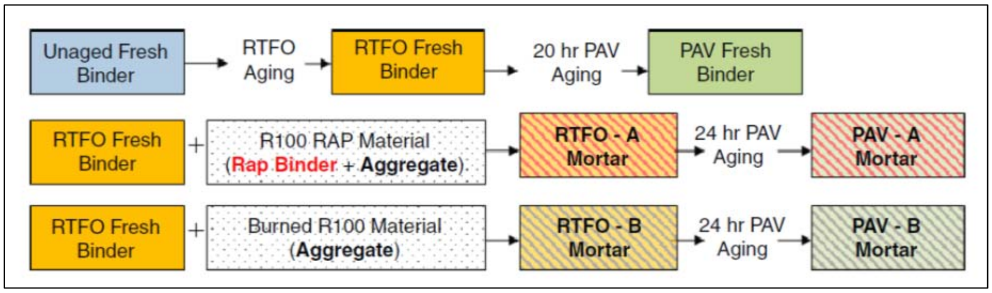

Figure 4.1: Sample preparation for asphalt mortar testing (After Hajj et al. *[20]*).

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 #50 (300 µm) sieve and retained on the #100 (150 µm) 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 30 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 the UCPRC study is focused on investigating the influence of higher binder replacement rates 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) could be investigated.

4.4 Preliminary Test Results

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 4.2. 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.

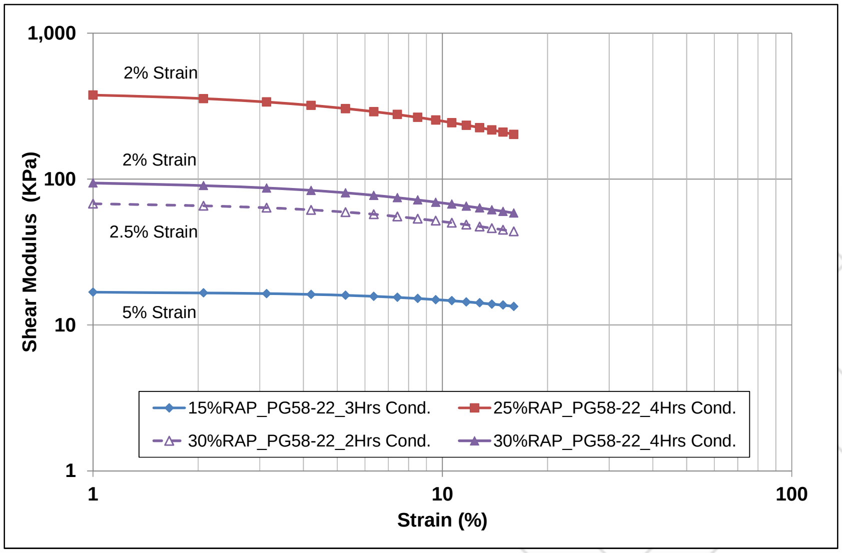

Figure 4.2: Results of amplitude sweep strain tests on asphalt mortar.

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5. PRELIMINARY FINE AGGREGATE MATRIX MIX TESTING

5.1 Introduction

Fine aggregate matrix (FAM) mixes are defined as a homogeneous blend of asphalt binder and fine aggregates with size passing either the #4 (4.75 mm), #8 (2.36 mm), or #16 (1.18 mm) 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 a full-graded asphalt mix. The performance properties are determined by testing small cylindrical bars 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 an appropriate alternative to asphalt mortar testing.

5.2 Experimental Design

The experimental plan for this part of the study included the following tasks:

- Develop a procedure for preparing FAM mix specimens for testing in a DSR-DMA to measure the following performance-related rheological properties:
  - + Amplitude sweep strain test to determine the linear viscoelastic region
  - + Frequency sweep test to develop master curves
  - + Appropriate tests to measure fatigue damage resistant properties
- Assess the sensitivity of the tests for measuring the effects of the following on the rheological properties of FAM mix specimens:
  - + RAP (at 25 and 40 percent binder replacement rates)
  - + RAS (at 15 percent binder replacement rate)
  - + Virgin binder PG grade (PG 64-16 and PG 58-22).

5.2.1 Material Sampling

Materials from the following sources were used:

- RAP-A sourced from a Sacramento asphalt plant
- RAS sourced from a supplier in Oakland
- PG 64-16 and PG 58-22 asphalt binders sourced from one refinery in northern California
- Aggregates (granite) sourced from a quarry in central California

5.3 FAM Mix Sample Preparation

5.3.1 Preliminary Sample Preparation Method

Preliminary sample preparation methods were based on those cited in the literature *(21-24)*. Mixes were prepared with material passing the #4, #8, and #16 sieves. The #4 and #8 mixes provided satisfactory quantities of FAM mix; 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.

5.3.2 UCPRC FAM Mix Sample Preparation Method

After a series of trial tests, the following procedure was developed and adopted for the preparation of FAM mix 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 following 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, the mix should be gently tamped to break down 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.
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 (following AASHTO T 209).
11. Short-term age the loose FAM mix for two hours at the mix compaction temperature following AASHTO R 35.
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 a 10 to 13 percent target air-void content.
13. Subject the specimen to long-term aging if required for the testing phase.
14. Core 12.5 mm cylindrical FAM mix specimens from the 150 mm diameter specimen. An example of a 150 mm compacted specimen and cored 12.5 mm specimens is shown in Figure 5.1.
15. Determine the air-void content of the FAM mix specimens by first determining the saturated surface-dry specific gravity (AASHTO T 166A) and then calculating the air-void content 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 undisturbed condition to prevent damage and excessive shelf-aging prior to testing in the DSR.

Figure 5.1: FAM mix specimens cored from a Superpave gyratory-compacted specimen.

5.4 FAM Mix Testing Setup

FAM mix specimens were tested using a solid torsion bar fixture in an Anton Paar MCR302 DSR. The test geometry is known as a dynamic mechanical analyzer (DMA).

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 *(21-24)*, reference is made to the use of steel caps, glued to both ends of the FAM mix specimen, to secure the specimen into the testing frame. Initial testing at the UCPRC compared tests with and without the caps; however, the approach using caps was not pursued for the amplitude sweep strain test 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 the caps were only used for the frequency sweep test, which only applies small strains, and a custom clamp recommended by the DSR manufacturer was used for the amplitude sweep strain test. Figure 5.2 shows the fixed specimen in the DMA-DSR used in this project.

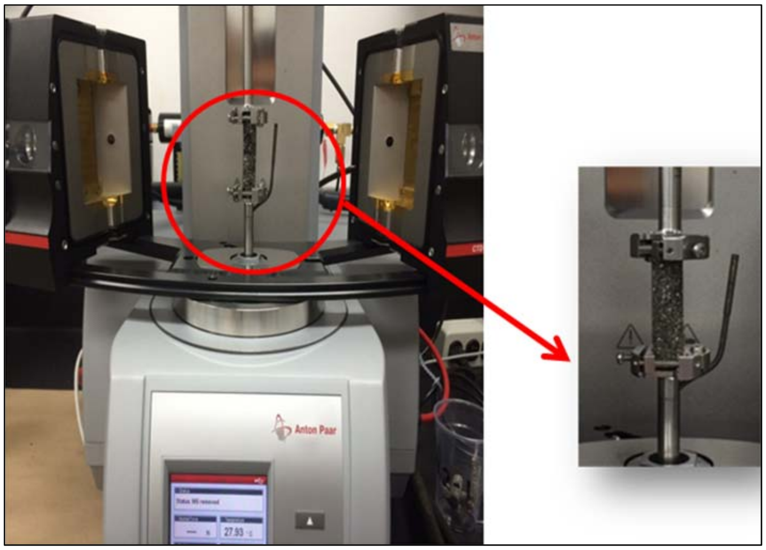

Figure 5.2: DSR-DMA torsion bar fixture used for FAM mix testing.

5.5 Preliminary FAM Mix Test Results

FAM mix specimens were prepared following the process described in Section 5.3.2 using virgin aggregates, RAP, RAS, and two grades of virgin binder (PG 64-16 and PG 58-22). Specimen details are summarized in Table 5.1. The aggregate gradation was the same for all FAM mix specimens regardless of binder grade and RAP and RAS content. Figure 5.3 shows the target FAM mix gradation as well as the gradation of RAP and RAS aggregates. The gradation and amount of virgin aggregate were adjusted in accordance with the known amount and gradation of the RAP and/or RAS in the mix so that the target FAM mix gradation was met. The FAM mix specimens containing RAS had a slightly coarser gradation than the other FAM mix specimens 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.

Table 5.1: FAM Mix Specimen Details

Specimen	Binder Replacement Rate (%)	RAP/RAS Content by Weight of Mix (%)	Virgin Binder Content by Weight of Mix (%)
0%RAP_PG64-16	0	0	8.6
25%RAP_PG64-16	25	30	6.4
40%RAP_PG64-16	40	48.1	5.2
15%RAS_PG64-16	15	5.4	7.3
0%RAP_PG58-22	0	0	8.6
25%RAP_PG58-22	25	30	6.4
40%RAP_PG58-22	40	48.1	5.2
15%RAS_PG58-22	15	5.4	7.3

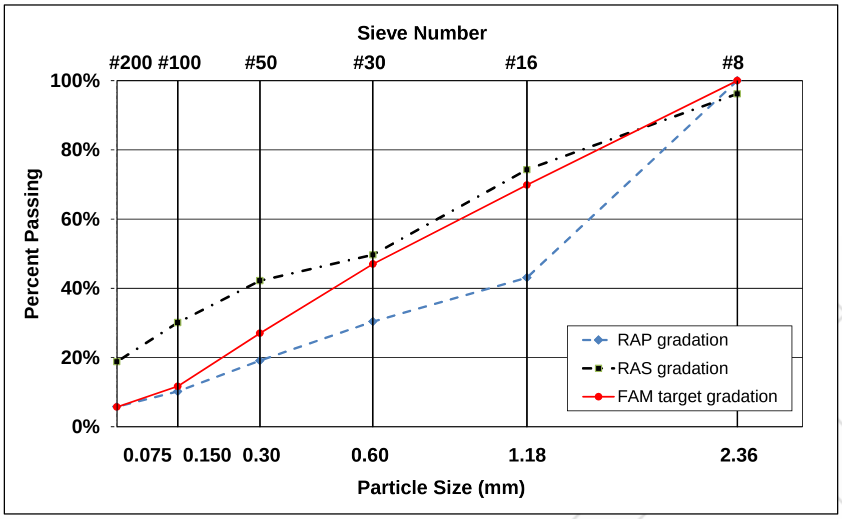

Figure 5.3: Gradation of FAM mix and RAP and RAS materials.

Initial testing of the FAM mix specimens in the DSR-DMA focused on the amplitude sweep strain test to determine the linear viscoelastic region, and frequency sweep tests for developing shear modulus (G*) master curves. Test methods to assess fatigue properties were investigated, but no testing was undertaken in this part of the study.

5.5.1 Amplitude Sweep Test Results

Amplitude sweep tests were performed on the FAM mix specimens by measuring the shear modulus at 4ºC and frequency of 10 Hz, when shear strain increased from 0.001 to 0.1 percent. The test results are shown in Figure 5.4. The results show that the shear stiffness of the material was independent of the rate of shear strain in the linear viscoelastic region. Figure 5.5 shows the strain limit for linear viscoelastic behavior determined for the FAM mix specimens. The linear viscoelastic strain limit decreased with increasing RAP content, but did not change appreciably when RAS was added.

5.5.2 Frequency Sweep Test Results

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. The 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). Shear modulus master curves were constructed based on time-temperature superposition principles using the measured moduli over the range of temperatures and frequencies.

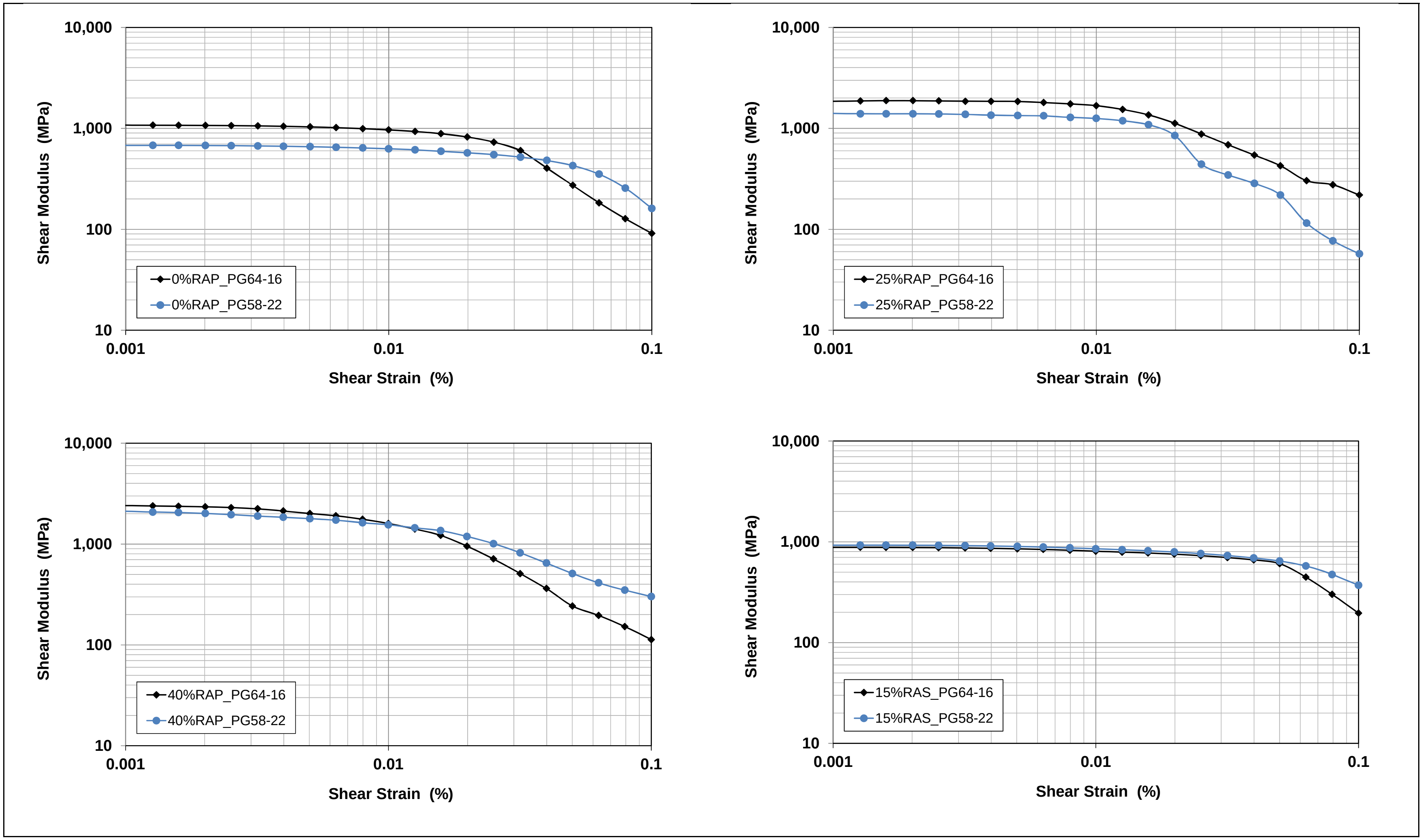

Figure 5.4: FAM mix specimen amplitude sweep test results.

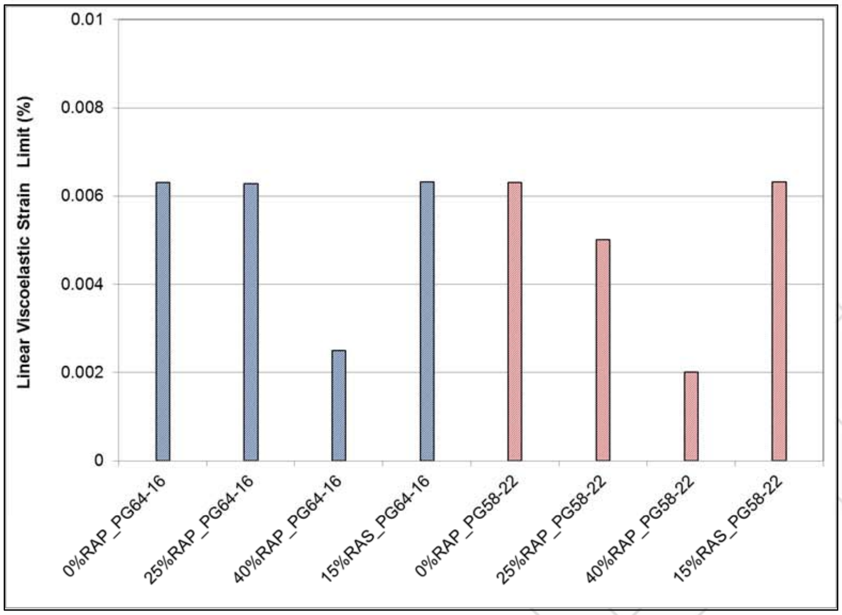

Figure 5.5: FAM mix specimen linear viscoelastic strain limit.

A sigmoidal function (Equation 5.1) with Arrhenius equation shift factor (Equation 5.2) was used to develop the shear modulus master curve. The Arrhenius shift factor is used to convert testing frequencies at any temperature to the corresponding reduced frequencies at the defined reference temperature using Equation 5.3. A reference temperature of 20°C was used in this study. 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. Figure 5.6 shows an example of the measured shear modulus values and the constructed master curve at 20ºC. The master curve parameters for the specimens are provided in Table 5.2. The repeatability of the test was found to be satisfactory.

$$log(|G^*(f_r)|) = \delta + \frac{\alpha}{1+e^{\beta+\gamma\times log(f_r)}} \quad \textbf{(5.1)}$$

Where: $\delta, \alpha, \beta, and\ \gamma$ are sigmoidal function parameters
f_r is the reduced frequency at reference temperature T_r.

$$\log(a_T(T)) = \frac{E_a}{Ln(10)\times R}\left(\frac{1}{T} - \frac{1}{T_r}\right) \quad \textbf{(5.2)}$$

Where: $a_T(T)$ is the shift factor value for temperature T (ºK)
E_a is activation energy term (Joule [J]/mol)
R is the universal gas constant (Joule [J]/(mol·K)
T_r is the reference temperature in degrees Kelvin

$$log(f_r) = log\big(a_T(T)\big) + log(\,f) \quad \textbf{(5.3)}$$

Where: f is the testing frequency at testing temperature T(ºC)
f_r is the reduced frequency at reference temperature T_r (ºC)

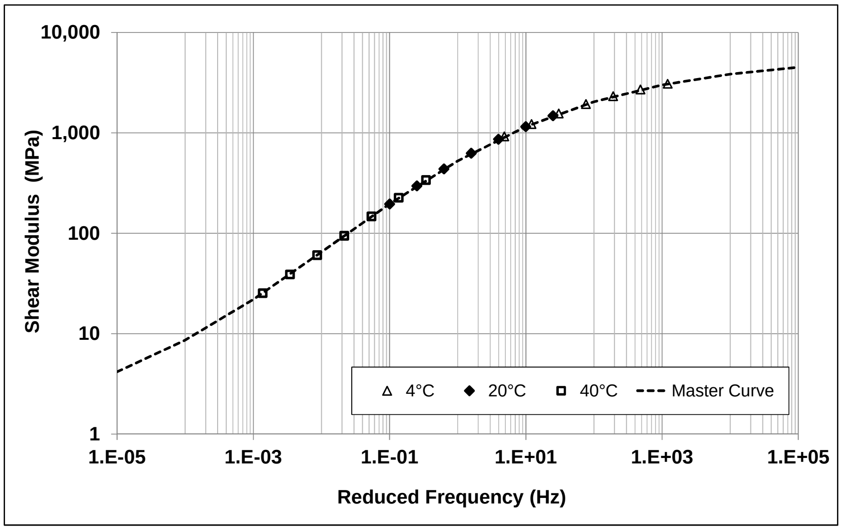

Figure 5.6: Typical FAM mix specimen shear modulus master curve at 20°C.

Table 5.2: FAM Mix Specimen Master Curve Parameters

Specimen ID	Master Curve Parameters				
	δ	***α***	***β***	***γ***	**E_a (Jol/mol)**
0%RAP_PG64-16	0	3.76	-0.96	-0.52	164,409
25%RAP_PG64-16	0	4.17	-1.06	-0.39	176,430
40%RAP_PG64-16	0	4.21	-1.06	-0.34	180,415
15%RAS_PG64-16	0	3.74	-0.93	-0.45	170,251
0%RAP_PG58-22	0	3.71	-0.79	-0.52	162,827
25% RAP_PG58-22	0	3.96	-1.07	-0.42	170,216
40%RAP_PG58-22	0	4.1	-1.15	-0.38	171,881
15%RAS_PG58-22	0	3.79	-0.88	-0.42	170,824

Figure 5.7 shows the modulus of the FAM mix specimens at a reference temperature of 20°C. The following observations were made:

- Preliminary results indicate that tests on FAM mix specimens can realistically differentiate between mixes with different binder grades and varying amounts of RAP and/or RAS.
- FAM mixes with soft virgin binder (PG 58-22) had lower stiffnesses than the corresponding mixes with stiffer virgin binder (PG 64-16), as expected.
- Stiffnesses increased with increasing RAP content in mixes with the same grade of virgin binder, as expected, given that the age-hardened RAP binder will increase the stiffness of the composite binder.
- Mix stiffnesses increased when RAS was incorporated into the mix; this was attributed to the air-blown induced additional stiffness of the age-hardened RAS binder.
- The effect of RAS on stiffness increase was more noticeable at lower frequencies, with the PG 64-16 mix with 40 percent RAP binder replacement having the highest stiffness.
- The influence of binder grade was comparatively low in the mixes with 40 percent RAP binder replacement. RAP binder replacements of 25 and 40 percent had a greater influence on binder

stiffness than RAS binder replacements of 15 percent, indicating that both replacement quantity and replacement binder properties will influence the stiffness of a mix.

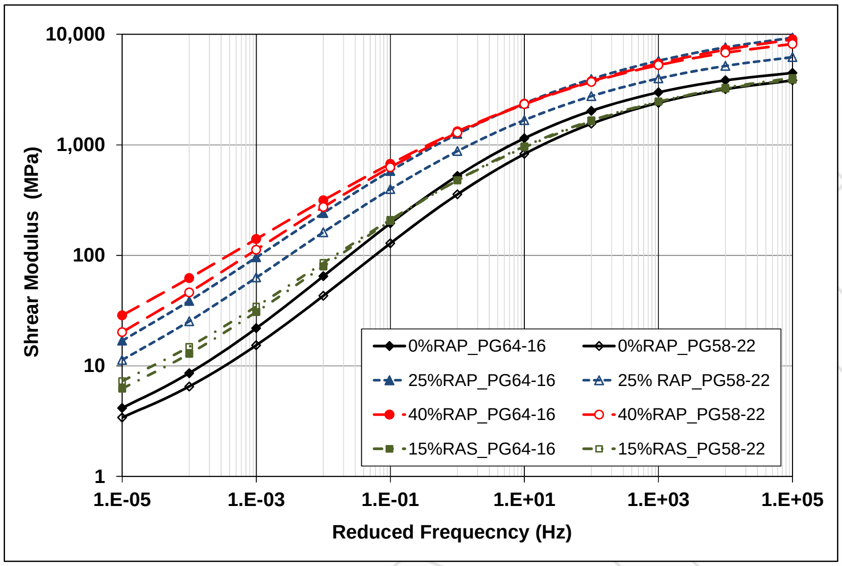

Figure 5.7: FAM mix specimen shear modulus master curve at 20°C.

5.6 Preliminary Conclusions

Based on the preliminary results discussed above, testing of FAM mix specimens was found to be a potentially effective method of measuring the performance-related rheological properties of composite binders and of understanding the influence of RAP and RAS on these properties.

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6. EXPERIMENTAL PLAN FOR PHASE 2 LABORATORY TESTING

6.1 Introduction

Based on the findings from the preliminary laboratory tests discussed in the previous chapters, an experimental plan was developed for Phase 2 testing to address the following refined questions with regard to meeting the objective of the study, namely to investigate the effect of RAP and RAS on the performance properties of asphalt binders:

- What is the best method to accurately determine the performance grade of the composite binder in mixes containing RAP and RAS?
- What are the effective binder replacement rates in asphalt mixes containing different amounts of RAP and/or RAS?
- What is the influence of production time and temperature on the degree of diffusion and blending between fresh and aged RAP and RAS binders?
- To what extent do rejuvenating agents improve the blending and compatibility of RAP and RAS binder and virgin binder?
- What are the effects of virgin binder type and source on the performance-related properties of mixes containing different amounts of RAP and/or RAS?
- What are the effects of RAP and RAS source and chemistry on the performance-related properties of mixes containing different amounts of RAP and/or RAS?
- What are the relationships between the performance properties measured in fine aggregate mix specimens and those measured in full-graded asphalt mix specimens?
- What are the effects of short- and long-term aging on the rheological properties of composite binders with respect to rutting and cracking performance in the field?

6.2 Provisional Experimental Plan

The provisional experimental plan consists of five tasks, described below. Table 6.1 summarizes the factors and factorial level in the plan.

6.2.1 Task 1: Laboratory Aging Protocol

In this task, a laboratory aging protocol will be developed that ages virgin binders to the extent that they have high-, intermediate-, and low-temperature properties similar to the binder recovered from RAP samples. This will facilitate the production of simulated RAP binders in the laboratory.

6.2.2 Task 2: Effective Asphalt Binder Replacement

Additional comprehensive FAM mix and mortar testing will be undertaken to determine effective asphalt binder replacement rates. The following steps are proposed for this task:

1. Determine the performance grade of the binder recovered from a range of RAP and RAS samples.

2. Prepare simulated RAP binders that have similar performance properties to the binders recovered from the RAP and RAS samples.
3. Prepare composite binders with different proportions of RAP and/or RAS. A minimum of two different binder replacement rates (25 percent and 40 percent) will be investigated and compared to a control virgin binder with no RAP. Tests with additional binder replacement rates will be considered based on the initial test results.
4. Determine the performance properties of the composite binders.
5. Prepare and test FAM mix specimens with the composite binders.
6. Compare the results from tests on the composite binder and the FAM mix specimens to determine and quantify effective binder replacement.

Two-layer binder testing will be investigated as a means of quantifying the degree of diffusion and blending between virgin and RAP and RAS binders.

6.2.3 Task 3: Effect of Production Temperature on Binder Properties

This task will investigate the effect of production temperatures on the degree of diffusion and blending of virgin and RAP and RAS binders. FAM mixes with various contents of RAP and RAS will be prepared and conditioned at aggregate temperatures representative of hot mix and warm mix production temperatures (e.g., 150°C hot mix, 135°C for warm mix by water injection, and 120°C for warm mix by additive). FAM mix specimens will be prepared from the conditioned mixes. The performance properties of the FAM mix specimens with and without additional aging (e.g., three, five, and ten days at 85ºC) will be measured and the results compared.

6.2.4 Task 4: Effect of Rejuvenating Agent

In this task, the performance properties of FAM mix specimens prepared with combined RAP and RAS binder replacement rates of 25 and 40 percent and different dosages of different rejuvenating agents will be measured and compared. The FAM mix specimens will be subjected to different levels of long-term aging prior to testing. The results will be analyzed to assess the sensitivity of FAM mix testing for evaluating the influence of rejuvenating agents on performance properties when they are added at different rates.

6.2.5 Task 5: Relationship between FAM and Full-Grading Mix Properties

Based on the results of Tasks 2 through 4, selected mixes will be prepared to compare the performance properties of FAM mix specimens and specimens prepared using the complete aggregate grading. Tests on the standard mix design specimens will include the following:

- Dynamic modulus to assess overall mix stiffness characteristics
- Repeated load tri-axial to assess resistance to permanent deformation
- Flexural beam fatigue to assess resistance to fatigue cracking

Table 6.1: Factors and Factorial Levels Considered in the Provisional Testing Plan

Factor	Factorial Level	Notes
Asphalt binder	2	Soft (PG 58-22) and regular (PG 64-16)
Aggregate	1	Local California source
RAP	3	Sourced throughout California. One source will be used after completion of preliminary tests.
RAP content	3	0, 25, and 40% binder replacement rate
RAS	1	Tear-off from local California source
RAS content	1	5% by total weight of mix
Rejuvenating agent	2	Petroleum-based and plant-based
Rejuvenating agent dose	3	Selected based on manufacturers' recommendations and including zero percent
Short-term aging condition	3	HMA and WMA production temperatures (150°C, 135°C, and 120ºC)
Long-term aging condition	3	Field aging conditions (3, 5, and 10 days at 85ºC)

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7. CONCLUSIONS AND INTERIM RECOMMENDATIONS

7.1 Project Summary

This technical memorandum summarizes the main findings from the literature review and preliminary tests performed as a part of the PPRC SPE 4.46 project entitled "Evaluation of the Effect of Reclaimed Asphalt Pavements (RAP) and Reclaimed Asphalt Shingles (RAS) on the Performance Properties of Asphalt Binders." The main task of this part of the study was to evaluate techniques for characterizing the performance properties of composite binders in mixes with high RAP and/or RAS contents without having to extract and recover the binder with chemicals.

Caltrans currently allows up to 25 percent binder replacement from RAP in new asphalt mixes. However, legislation has recently been passed that will eventually allow up to 40 percent binder replacement from a combination of RAP and RAS. Concerns have been raised with respect to the degree of blending of virgin and RAP and RAS binders, and the effect of the aged binder on long-term performance of the mix. Representative samples of the RAP binder are required for testing to address these concerns.

Solvent extraction and recovery is the most commonly used method for obtaining samples of blended binders from mixes containing RAP and/or RAS. However, this method has several disadvantages including possible chemical reactions that could change the rheology of the recovered binder, incomplete extraction, unrepresentative extraction of asphalt rubber and polymer-modified binders, forced unrepresentative diffusion and blending between aged and virgin binders, and concerns with respect to the hazardous nature of the chemicals used. An alternative method of assessing binder performance properties was therefore investigated in the UCPRC study.

Preliminary laboratory tests were performed to investigate the properties of binders recovered from RAP and RAS samples, the properties of simulated RAP binder prepared in the laboratory, the properties of asphalt mortars, and the properties of fine aggregate matrix (FAM) mixes. Key observations from this preliminary testing 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) and bending beam rheometer (BBR).
- The guidelines recommended in NCHRP 9-12 for determining the performance grade (PG) of binders recovered from RAP samples was considered to be appropriate for the 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 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.

- 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. Although the mortar test deserves further investigation, it may not be appropriate for testing samples with high binder replacement rates (i.e., ≥ 25 percent).
- 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 potentially appropriate for characterizing the performance properties of composite binder at binder replacement rates up to 40 percent and possibly higher. A method for preparing and testing FAM mix specimens was developed for future testing.
- Cylindrical specimens 0.5 in. (12.5 mm) in diameter cored from a Superpave gyratory-compacted FAM mix specimen could be tested using a torsion bar fixture on a DSR (also known as a dynamic mechanical analyzer, DMA). Testing procedures were developed as part of this preliminary testing phase to measure dynamic shear modulus at different temperatures and frequencies. Preliminary results indicated that repeatable, reproducible, and representative results can be obtained.
- The testing of FAM mix specimens to characterize fatigue and damage behavior was explored. Preliminary test results indicated that this approach is potentially appropriate for accurately measuring the performance-related rheological properties of composite binders and of understanding the influence of RAP and RAS on these properties.

7.2 Conclusions and Recommendations

Based on a review of relevant literature and the results of preliminary tests, fine aggregate matrix (FAM) mix testing is considered to be an appropriate alternative to solvent-extracted binders for assessing the performance properties of composite virgin/RAP/RAS binders. The preparation and testing of simulated RAP binders is considered an appropriate method for understanding the effects of different binder replacement rates on the degree of diffusion and the blending of virgin and aged binders under controlled conditions. Laboratory testing should be continued to accomplish the following:

- Investigate effective binder replacement rates, compatibility of virgin binder and aged RAP and RAS binders, the effectiveness of rejuvenating agents, and the influences of production time and temperature on the degree of diffusion and blending of virgin and aged binders.
- Investigate relationships between the results of asphalt binder and FAM mix testing and identify possible reasons for differences between results focusing on the effect of solvent extraction on blended binder properties.
- Develop a method for preparing simulated RAP binders that are representative of typical RAP binders at high, intermediate, and low temperatures.

- Investigate the suitability of two-layer asphalt binder testing as a method for understanding the diffusion/blending mechanism between virgin and RAP and RAS binders.

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