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Preliminary Investigation into the Use of Reclaimed Asphalt Pavement in Gap-Graded Asphalt Rubber Mixes, and Use of Reclaimed Asphalt Rubber Pavement in Conventional Asphalt Concrete Mixes

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Reclaimed Rubberized Asphalt Pavement Studies

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Abstract:

This report describes a preliminary study that investigated the potential implications of using reclaimed rubberized asphalt pavement (R-RAP) materials as partial binder and aggregate replacement in new conventional dense-graded asphalt concrete mixes, and using reclaimed conventional asphalt pavement (RAP) materials as partial binder and aggregate replacement in new gap-graded asphalt rubber mixes. The use of rubberized hot mix asphalt (RHMA) in pavements in California has been increasing since the early 1990s. As these RHMA layers reach the end of their design lives they are being milled off and replaced with new hot mix asphalt (HMA) or new RHMA. The millings are being added to RAP stockpiles, which in turn are reused in new conventional HMA. There is no published information or experience documenting whether the use of R-RAP influences mix performance. Although Caltrans currently does not permit the use of any RAP in asphalt rubber mixes, there is increasing interest in allowing it as binder replacement in gap-graded mixes in order to reduce the amount of virgin binder required.

Laboratory test results indicate that adding R-RAP to dense-graded HMA could potentially yield some improvement in overall rutting performance, but it could also have a potentially overall negative effect on fatigue and low-temperature cracking performance. These findings are consistent with those from tests where conventional RAP was used. The degree of change in rutting and cracking resistance in the HMA mixes was dependent on the R-RAP source, with mixes containing millings only from RHMA layers performing slightly better than mixes containing both R-RAP and RAP. Based on these findings, there appears to be no reason or justification for separating R-RAP and RAP millings or maintaining separate stockpiles at asphalt plants.

Test results from the gap-graded RHMA mixes containing RAP indicated that rutting performance is likely to improve, but that adding RAP could have a potentially overall negative effect on fatigue and low-temperature cracking performance, which would negate the benefits of selecting RHMA-G as an overlay to retard the rate of reflection cracking.

Since only limited testing on asphalt rubber mixes containing RAP was undertaken in this study, further laboratory testing, followed by full-scale field testing in pilot projects or accelerated wheel load testing should be considered on a wider range of virgin binder, virgin aggregate, and RAP material sources to confirm the findings before any changes to current practice are considered.

Keywords:
Asphalt rubber, reclaimed asphalt pavement

Proposals for implementation:
None

Related documents:
None

Signatures:

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PROJECT OBJECTIVES

This project had two objectives:

1. Determine whether there are any potential implications in terms of binder replacement when using reclaimed rubberized asphalt pavement (R-RAP) materials in new conventional hot mix asphalt.
2. Determine whether there are any potential implications in terms of binder replacement when using reclaimed asphalt pavement (RAP) materials in new rubberized hot mix asphalt.

These objectives will be achieved through the following tasks:

1. Prepare a detailed workplan that includes major milestones, communication schedules, and deliverables.
2. Review relevant literature and collect samples.
3. Conduct laboratory tests to evaluate, characterize, and analyze the rheological and engineering properties of the RAP and blended RAP and virgin binders.
4. Conduct laboratory tests to evaluate the properties of new conventional hot mix asphalt that contains reclaimed rubberized asphalt pavement materials and new rubberized hot mix asphalt that contains reclaimed asphalt pavement materials.
5. Prepare progress reports and a final report that document the study.

This document covers all these tasks.

EXECUTIVE SUMMARY

This report describes a preliminary study that investigated the potential implications of using reclaimed rubberized asphalt pavement materials as partial binder and aggregate replacement in new conventional dense-graded asphalt concrete mixes, and using reclaimed conventional asphalt pavement materials as partial binder and aggregate replacement in new gap-graded asphalt rubber mixes.

The use of rubberized hot mix asphalt (RHMA) in pavements in California has been increasing since the early 1990s. As these RHMA layers reach the end of their design lives they are being milled off and replaced with new hot mix asphalt (HMA) or new RHMA. The millings are being added to reclaimed asphalt pavement (RAP) stockpiles, which in turn are reused in new conventional HMA. There is no published information or experience documenting whether the use of RAP containing rubber could influence mix performance. Although the California Department of Transportation (Caltrans) currently does not permit the use of any RAP in open-graded mixes or in rubberized gap-graded (RHMA-G) mixes, there is increasing interest in allowing some RAP as binder replacement in gap-graded mixes in order to reduce the amount of virgin binder required.

Key points from the literature review conducted as part of this study include the following:

- The asphalt binder in RAP can blend appreciably with virgin binder in new mixes. The level of blending between the aged and new binders depends on numerous factors including the chemical composition of the individual binders. To ensure the optimal performance of asphalt mixes containing high percentages of reclaimed asphalt, the compatibility of reclaimed and virgin asphalt binders from different sources and with different performance grades needs to be well understood.
- Appropriate methods for extracting aged binder from reclaimed asphalt materials are still being developed, with a focus on examining the effects of extraction solvents on the properties of recovered binders. The solvents in current use are aggressive enough to fully blend the binders extracted from new mixes containing aged and virgin binders, which is problematic because the forced blending can lead to potentially misleading binder replacement values and nonrepresentative performance gradings of the blended binders. Asphalt rubber binders cannot be chemically extracted because the rubber is separated from the base binder during the process. Alternative methods to the use of extraction and recovery are being explored to better characterize the performance properties of blended virgin and RAP binders. Further testing on mortar and fine aggregate matrix (FAM) mixes is warranted. Tests on mortar and fine aggregate matrix (FAM) mixes warrant further investigation.
- Adding RAP to a new asphalt mix can alter the volumetrics and performance of the mix. However, volumetric requirements can still be met with relatively high RAP contents (i.e., up to 25 percent). Compared to equivalent mixes without RAP, rutting performance was generally improved by the addition of RAP, but cracking performance was generally worse. Conflicting results with regard to laboratory testing performance were reported.

- Given that the use of RAP for binder replacement and not just for aggregate replacement is a relatively new practice, there is limited knowledge on the long-term field performance of mixes containing high RAP contents (i.e., above 25 percent binder replacement), specifically with regard to the rate of binder aging and its effect on stiffness and susceptibility to cracking. Conventional laboratory aging procedures have not been verified for high RAP mixes.
- No published literature on the use of reclaimed rubberized asphalt concrete in new asphalt mixes was located.
- Only limited published research on the use of RAP in rubberized asphalt concrete was located, and all of it referred to binders containing less than 10 percent rubber by weight of the binder and used in dense-graded mixes.
- Most of the research reported in the literature covered laboratory testing under controlled conditions. Only limited published work was found on long-term field assessments that compared mixes containing RAP with equivalent control mixes containing no RAP.

The following key observations were made during the development of mix designs used to prepare mixes for laboratory testing:

- Dense-graded HMA mixes:
  + No concerns were identified during the development of the conventional dense-graded mix with reclaimed rubberized asphalt pavement materials. Mixes with 15 and 25 percent RAP binder replacement were prepared, and they met all volumetric requirements listed in the Caltrans 2015 specifications.
- Gap-graded RHMA mixes:
  + Initial gap-graded mix design experimentation revealed that a maximum of only 10 percent RAP binder replacement could be achieved while still meeting the specified gradation requirements for gap-graded mixes; mixes with greater than 10 percent RAP binder replacement did not meet those requirements (the initial workplan proposed evaluating mixes with 15 and 25 percent RAP binder replacement). This was attributed to the processed RAP materials used in this study (and considered representative of RAP materials in California in general) having relatively high percentages of small and fine aggregate (74 percent passing the 4.75 mm [#4] sieve), much of which is not permitted in a gap-gradation. An attempt to use higher proportions of coarse RAP to compensate for the lower proportions of fine RAP resulted in a lower-than-target binder content, as coarse RAP fractions tend to have less asphalt binder coating than finer RAP fractions.
  + The accepted mix design met all Caltrans specification requirements except air-void content. Due to time and funding constraints, a decision was made to proceed with the preliminary tests despite not meeting the air void target given that general performance trends were unlikely to be significantly affected by this parameter.

The following key observations were made during the analysis of the results of binder testing (Phase 1a):

- Rubber modification appeared to reduce the aging susceptibility of asphalt binders in that less change was observed in their rheological properties than the rheology changes of the base binder after extended aging in a pressure aging vessel (PAV) for 40 hours at 100°C.

- The age-hardened asphalt rubber binder (R-RAP) was less temperature susceptible than the age-hardened conventional binder (RAP). At 64°C, the RAP and R-RAP binders had approximately the same stiffness; however, with an increase in temperature, the high performance-grade (PG) limit of the R-RAP binder was 15°C higher than that of the RAP binder. The viscosity of the R-RAP binder (at 135°C) was 10 times higher than that of the RAP binder.
- Blending simulated RAP binder with conventional binder increased the viscosity (at 135°C) and stiffness of the composite binder at both high and low in-service temperatures. It also reduced the relaxation potential of the binder at low temperature, which was indicated by a reduction in m-value. In addition, the average percent recovery and the recoverable creep compliance of conventional asphalt binder decreased when RAP binder was added.
- Adding R-RAP binder to conventional binder increased the viscosity (at 135°C) and stiffness at high temperatures, which implies that these mixes could be less workable and more difficult to compact, but could have better rutting performance. At low temperatures (i.e., -6°C) the added R-RAP binder caused small reductions in the creep stiffness and relaxation potential (m-value), which implies that the R-RAP would have a limited effect on low-temperature cracking. The average percent recovery of the composite binder increased (indicating improved rutting performance) and the recoverable creep compliance decreased (indicating diminished cracking performance) with increasing R-RAP content.
- Adding simulated RAP binder to asphalt rubber binder reduced its viscosity, but barely changed the high PG grade, indicating no adverse impact to workability or rutting performance. At the low test temperature, the creep stiffness of the asphalt rubber binder increased and the m-value decreased with increasing RAP content, which indicates an increased potential for thermal cracking. The effect of RAP content on average percent recovery and recoverable creep compliance of asphalt rubber binders was minimal.

The following key observations were made during the analysis of the results of fine aggregate matrix mix testing (Phase 1b):

- The stiffness of the mixes increased with increasing R-RAP or RAP content, as expected.
- The behavior of mixes prepared with laboratory-prepared R-RAP and RAP was inconsistent with that of the mixes prepared with field-sampled RAP and R-RAP materials, indicating that the laboratory aging procedures used in this study were not necessarily representative of field conditions. This contradicts findings reported in the literature.
- The trends in change of stiffness over the range of frequencies were similar for both types of mix; however, the gap-graded RHMA mixes appeared to be less sensitive to changes in frequency (i.e., less sensitive to changes in temperature) than the dense-graded HMA mixes.
- Adding 15 and 25 percent R-RAP sourced from two different road projects increased the mix stiffness by up to 3.8 and 9.2 times that of the control (at 0.001 Hz), respectively. This implies better rutting performance than the mixes containing no R-RAP. Mix behavior was dependent on R-RAP source, with the source known to be contaminated with conventional RAP millings having a greater effect on stiffness increase.
- Adding 10 percent RAP, sourced from a stockpile at an asphalt plant, to the gap-graded RHMA mix increased the stiffness by a maximum of almost two times that of the control (recorded at about 0.001 Hz, corresponding to a higher than median temperature).

The following key preliminary observations were made during the analysis of the results of full-graded mix testing (Phase 2):

- The test methods used in this phase of the study were sufficiently sensitive to distinguish the behavior of the different mixes and to consistently distinguish the differences in performance of mixes containing no RAP (i.e., control mixes) and mixes containing R-RAP and RAP. However, all testing was undertaken on newly prepared laboratory specimens, and consequently do not necessarily reflect long-term performance of the mixes or the longer-term effects of the RAP and R-RAP binder on the rate of aging of the virgin binder.
- Adding RAP and R-RAP increased the stiffness of the mixes, which in most instances improved the rutting resistance of the mix, but diminished the fatigue cracking resistance at a given strain.
- Adding R-RAP to dense-graded HMA could potentially yield some improvement in overall rutting performance, but it could also have a potentially overall negative effect on fatigue and low-temperature cracking performance. These findings are consistent with those from tests where conventional RAP was used. However, the degree of change in rutting and cracking resistance was dependent on the R-RAP source, with mixes containing millings only from RHMA layers performing slightly better than mixes containing both R-RAP and RAP, but with test results for each source ranking consistently across the different tests.
- Adding RAP to gap-graded RHMA mixes appears to improve rutting performance but diminish cracking performance (when evaluated in a mechanistic analysis considering structure and load), thereby potentially negating the benefits of selecting RHMA-G as an overlay to retard the rate of reflection cracking. The potential effects of the higher-than-target mix design air-void content were considered during analysis of the results.

<u>Conclusions</u>

The results of tests conducted in this UCPRC study led to the following conclusions:

- Adding RAP milled from rubberized asphalt concrete pavement layers to new conventional dense-graded mixes will generally result in better rutting performance, but diminished cracking performance, at both high and low temperatures. Although mixes containing conventional RAP were not included as additional controls to compare performance of the R-RAP and RAP in dense-graded HMA mixes, the difference in behavior between the two different R-RAP sources (one contaminated with conventional RAP from the underlying layer) provides an indication that there could be a negligible difference between mixes prepared with R-RAP and mixes prepared with conventional RAP resulting from the earlier rubber modification (i.e., mixes containing R-RAP are likely to have marginally better performance than mixes containing conventional RAP). Based on these findings, there appears to be no reason or justification for separating R-RAP and RAP or maintaining separate R-RAP and RAP stockpiles at asphalt plants. Given that the mixes tested had the same gradation and binder content and similar volumetric properties, RAP should not be considered as a generic material with consistent properties.
- Adding RAP to gap-graded asphalt rubber mixes used in overlays will potentially have some improvement in overall rutting performance, but a potentially overall negative effect on fatigue cracking performance (based on a mechanistic analysis considering structure and load). More comprehensive testing should be carried out before any changes to current practice are considered.

- All testing in this study was undertaken on newly prepared laboratory specimens (with and without accelerated aging), and consequently do not necessarily reflect long-term field performance of the mixes or the longer-term effects of the RAP binder on the rate of aging of the virgin binder.

Recommendations

The following recommendations are made:

- Only limited testing on asphalt rubber mixes containing RAP was undertaken in this study. Therefore further laboratory testing and mechanistic analyses, followed by full-scale field testing in pilot projects or accelerated wheel load testing is recommended on a wider range of virgin binder, virgin aggregate, and RAP material sources to confirm the findings before any changes to current practice are considered. This future testing should also investigate the potential use of these mixes in intermediate layers in long-life pavement designs, where an optimal combination of rutting and cracking resistance might offer an appropriate alternative to conventional mixes in this type of structure.
- Additional investigation to assess the effect of replaced binder from RAP on the rate of aging of virgin binders and of potential consequential effects on cracking (low-temperature, top-down, and fatigue) is required as this parameter has not been adequately quantified.

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LIST OF ABBREVIATIONS

AASHTO	American Association of State Highway and Transportation Officials
APA	Asphalt pavement analyzer
APR	Average percent recovery
ASTM	American Society for Testing and Materials
BBR	Bending beam rheometer
Caltrans	California Department of Transportation
DMA	Dynamic mechanical analyzer
DP	Dust proportion
DSR	Dynamic shear rheometer
EPA	Environmental Protection Agency
FAM	Fine aggregate matrix
FHWA	Federal Highway Administration
G*	Dynamic shear modulus
GTR	Ground tire rubber
HMA	Hot mix asphalt
ITS	Indirect tensile strength
J_{NR}	Recoverable creep compliance
MSCR	Multiple stress creep recovery
MWAS	Manufacturer waste asphalt shingles
NCAT	National Center for Asphalt Technology
NCHRP	National Cooperative Highway Research Program
PAV	Pressure aging vessel
PG	Performance grade
RAP	Reclaimed asphalt pavement
RAS	Reclaimed asphalt shingle
R-RAP	Reclaimed asphalt rubber pavement
RHMA	Rubberized hot mix asphalt
RHMA-G	Gap-graded rubberized hot mix asphalt
RHMA-O	Open-graded rubberized hot mix asphalt
RPM	Revolutions per minute
RTFO	Rolling thin-film oven
SARA	Saturates, aromatics, resins, and asphaltenes
SHRP	Strategic Highway Research Program
TCE	Trichloroethylene
TOAS	Tear-off asphalt shingles
TWM	Total weight of mix
UCPRC	University of California Pavement Research Center
VFA	Voids filled with asphalt
VMA	Voids in mineral aggregate
δ	Phase angle

TEST METHODS CITED IN REPORT

AASHTO M 320	Standard Specification for Performance-Graded Asphalt Binder
AASHTO M 323	Standard Specification for Superpave Volumetric Mix Design
AASHTO R 30	Standard Practice for Mixture Conditioning of Hot-Mix Asphalt (HMA)
AASHTO R 35	Standard Practice for Superpave Volumetric Design for Asphalt Mixtures
AASHTO T 30	Standard Method of Test for Mechanical Analysis of Extracted Aggregate
AASHTO T 84	Standard Method of Test for Specific Gravity and Absorption of Fine Aggregate
AASHTO T 85	Standard Method of Test for Specific Gravity and Absorption of Coarse Aggregate
AASHTO T 164	Standard Method of Test for Quantitative Extraction of Asphalt Binder from Hot Mix Asphalt
AASHTO T 166	Standard Method of Test for Bulk Specific Gravity (Gmb) of Compacted Hot Mix Asphalt (HMA) Using Saturated Surface-Dry Specimens
AASHTO T 209	Standard Method of Test for Theoretical Maximum Specific Gravity (Gmm) and Density of Hot Mix Asphalt
AASHTO T 240	Standard Method of Test for Effect of Heat and Air on a Moving Film of Asphalt Binder (Rolling Thin-Film Oven Test)
AASHTO T 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
AASHTO T 316	Standard Method of Test for Viscosity Determination of Asphalt Binder Using Rotational Viscometer
AASHTO T 321	Standard Method of Test for Determining the Fatigue Life of Compacted Asphalt Mixtures Subjected to Repeated Flexural Bending
AASHTO TP 79	Standard Method of Test for Determining the Dynamic Modulus and Flow Number for Asphalt Mixtures Using the Asphalt Mixture Performance Tester (AMPT)
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 to the Study

The use of rubberized hot mix asphalt (RHMA) in pavements in California has been increasing since the early 1990s. As these RHMA layers reach the end of their design lives they are being milled off and replaced with new hot mix asphalt (HMA) or new RHMA. The millings are being added to reclaimed asphalt pavement (RAP) stockpiles, which in turn are reused in new conventional HMA. Currently, the amount of RAP used in new HMA in California varies between 15 and 25 percent, but this could increase to 40 percent or higher in the future. Although Caltrans currently does not permit the use of any RAP in open-graded mixes or in rubberized gap-graded (RHMA-G) mixes, there is increasing interest in allowing some RAP as binder replacement in gap-graded mixes in order to reduce the amount of virgin binder required.

1.2 Problem Statements

The following problem statements have been identified. The issues they raise require either additional research or the refinement/recalibration of existing knowledge to suit California conditions (a) to determine whether it is feasible and practical to use aged reclaimed rubberized asphalt pavement (R-RAP) as aggregate and binder replacement in new conventional hot mix asphalt pavements, and conventional RAP as aggregate and binder replacement in new gap-graded RHMA mixes, and (b) to identify the implications of using these materials this way.

- The differences between RAP and rubberized RAP (R-RAP) in terms of general properties, milled material properties, storage, management, and use in new mixes have not been evaluated.
- The use of higher quantities of RAP implies that higher amounts of older, oxidized (and thus stiffer) binder will be being mixed with the virgin binder in HMA. Although the implications of this on the properties and behavior of the composite binder (i.e., virgin binder blended with binder from RAP or R-RAP) and on mix performance are being studied by the University of California Pavement Research Center (UCPRC) and other research centers, that research has focused on non-rubberized RAP and no research is being undertaken specifically on the effects of R-RAP in the new mixes.
- There is no published research covering the use of RAP in RHMA-G mixes, but a number of issues have been identified concerning it. First, this use of RAP could theoretically reduce the amount of recycled tire rubber used in asphalt pavements, given that the rubberized binder content in the mix will be lower than that of mixes that do not contain any RAP. Second, the benefits of including rubber in the binder, specifically to limit the rate of fatigue cracking, retard the rate of reflective cracking, and increase the "toughness" of the binder to limit raveling, may be reduced.
- The degree of blending both between virgin binders and reclaimed asphalt rubber binders and between new asphalt rubber binders and binders from RAP, and the factors that influence this

blending are not fully understood. Consequently, accurate determination of the effective asphalt binder replacement from the reclaimed material is difficult.

- The short- and long-term effects of the RAP and R-RAP binders on the performance grade of the composite binder (i.e., virgin binder blended with binder from RAP or R-RAP) are unknown and need to be addressed.
- The performance of asphalt mixtures containing RAP or R-RAP is dependent on the properties of the constitutive components, which change during service after short- and long-term aging and as the new and aged binders diffuse over time. A simplified procedure using current Superpave equipment is needed to simulate field conditions in the laboratory and characterize the rheological properties of the blended binder with respect to rutting and cracking performance at high, intermediate, and low temperatures, without the need to chemically extract the binder from the mix.

1.3 Study Objective/Goal

This project has two objectives:

1. Determine whether there are any implications, in terms of binder replacement, of using reclaimed rubberized asphalt pavement materials in new conventional hot mix asphalt.
2. Determine whether there are any implications, in terms of binder replacement, of using conventional reclaimed asphalt pavement materials in new rubberized hot mix asphalt.

These objectives will be achieved through the following tasks:

1. Prepare a detailed workplan that includes major milestones, communication schedules, and deliverables.
2. Review relevant literature to compile information from past and current pavement recycling research in order to identify data gaps. Collect representative samples of reclaimed conventional and rubberized asphalt pavement for laboratory testing.
3. Conduct laboratory tests to evaluate, characterize, and analyze the rheological and engineering properties of the RAP binders and the blended RAP and virgin binders.
4. Conduct laboratory tests to evaluate the properties of new conventional hot mix asphalt that contains reclaimed rubberized asphalt pavement materials and new rubberized hot mix asphalt that contains reclaimed asphalt pavement materials.
5. Prepare progress reports and a final report that document the study.

This document covers all these tasks.

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 documents the experimental plan and describes the materials and testing methodologies followed.
- Chapter 4 details the mix design and specimen preparation process.
- Chapter 5 summarizes the results and analysis of asphalt binder rheology tests.
- Chapter 6 summarizes the results and analysis of fine aggregate matrix (FAM) mix tests.
- Chapter 7 summarizes the results and analysis of performance tests on full-graded mixes.
- Chapter 8 provides conclusions and preliminary recommendations.

1.5 Measurement Units

Although road agencies in California have 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 report, both English and metric units (provided in parentheses after the English units) are provided in the general discussion. Metric units are used in the reporting of test results. A conversion table is provided on page xv.

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2. LITERATURE REVIEW

2.1 Introduction

California is one of only a few U.S. states that uses asphalt rubber binders (i.e., defined as more than 15 percent recycled tire rubber by weight of the asphalt binder) in gap-graded and open-graded asphalt concrete mixes. The use of rubber asphalt mixes (RHMA) started in the early 1990s and this mix type currently constitutes up to 35 percent of all asphalt the concrete placed annually by the California Department of Transportation (Caltrans), significantly more than any other state. A number of states have recently been using smaller quantities of recycled tire rubber (typically less than 10 percent by weight of the binder) as a binder modifier in conventional dense-graded mixes. Given the limited use of asphalt rubber in the U.S., there is limited published research on the topic other than that conducted in California.

Many of the early-constructed asphalt rubber pavements have reached the end of their design lives and are being rehabilitated. In most instances, the old asphalt layers are being milled off and stored in stockpiles at asphalt plants. These layers are usually a combination of dense-graded conventional asphalt concrete, open-graded conventional asphalt concrete, and either gap-graded (RHMA-G) or open-graded (RHMA-O) asphalt rubber concrete. There is currently no requirement or perceived need to separate the conventional asphalt concrete millings from the rubberized asphalt millings. These reclaimed asphalt pavement (RAP) stockpiles are then crushed and screened, and the processed material is used as a substitute for virgin aggregate and virgin binder in new conventional dense-graded mixes. Caltrans currently allows up to 25 percent binder replacement in these conventional mixes, but does not allow the use of RAP in any RHMA-G, RHMA-O, or conventional open-graded friction course mixes.

No published research has been undertaken in California on the use of reclaimed asphalt rubber pavement (R-RAP) in new asphalt mixes, or on the use of RAP in new RHMA-G or RHMA-O mixes. Given the increasing amount of R-RAP that is being added to RAP piles and potentially being used in new mixes, and the growing interest in using some RAP as binder replacement in gap-graded mixes, further study on the topic is warranted.

2.2 Reclaimed Asphalt Materials

Reclaimed asphalt pavement is defined as "removed and/or reprocessed pavement materials containing asphalt binder and aggregates" *(1)*. As noted, it is mostly obtained by milling off aged or distressed pavement surface layers and is usually crushed and processed at an asphalt plant to produce well-graded aggregates, many still coated with asphalt binder. This processed material can then be incorporated into new mixes at varying percentages as a replacement for virgin aggregates and binders. RAP is by far the most recyclable material according to a survey conducted in the early 1990s by the Federal Highway Administration (FHWA) and the U.S. Environmental Protection Agency (EPA), which stated that of the more than 90 million tons of RAP produced every year in the United States, at least 80 percent of it could be recycled into new pavement construction projects *(1)*.

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

RAP materials have been used in small quantities in new highway mixes for many years. However, in the past this material has been considered only as a replacement for virgin aggregate (i.e., "black rock") and not as a part replacement for virgin asphalt binder. Consequently the potential binder replacement and properties of the aged RAP binder were not taken into account in new mix designs. This generally did not result in any problems as long as the percentage of RAP was kept below approximately 15 percent. Recent studies and field observations *(1,3-5)* 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.

2.3 Asphalt Binder Chemistry

Asphalt binder is obtained from the distillation of crude oil and is a blend of complex hydrocarbons containing thousands of different molecules *(6)*. 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 *(6,7)*.

Asphaltenes have the highest polarity and molecular weight, followed by resins, aromatics, and saturates *(6)*. 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 *(7)*. The stiffness and strength properties of asphalt binders are generally related to the asphaltenes and resins, while its viscous and plasticizing properties are generally related to the aromatics and saturates *(8)*. 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.

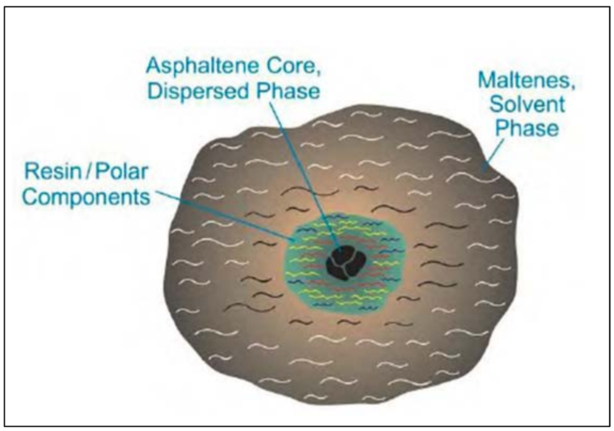

Figure 2.1: Asphalt binder colloidal structure *(7)*.

2.4 Asphalt Binder Extraction from Mixes Containing Reclaimed Asphalt

A number of studies have been conducted to evaluate different solvents and methods for the extraction and recovery of asphalt binder from mixes *(5,9-12)*. Petersen et al. *(13)* 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 *(11)*. A study by Stroup-Gardiner et al. *(14)* found that using normal propyl bromide rather than TCE as a chemical solvent could reduce the amount of aging of the asphalt binder during extraction and recovery. The study also found that the binder content determined was not influenced by solvent type. However, incompatibilities between various types of propyl bromide and polymer-modified binders were recognized.

Two studies *(15,16)* found that the solvent extraction process cannot be used to extract asphalt rubber binders from mixes for evaluation purposes because the process separates the rubber particles from the asphalt binder and consequently any tests on the binder would essentially represent the properties of the base binder only and not the modified binder.

2.5 Characterization of Blended Virgin and Reclaimed Asphalt Binders

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

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

No published research on whether the findings are applicable to mixes containing asphalt rubber binder and/or R-RAP was located.

2.5.1 Backcalculation of Blended Binder Properties

Conventional asphalt binder shear modulus can be predicted from the measured asphalt mix dynamic modulus using the Hirsch model *(17,18*). The Hirsch model represents the stiffness of an asphalt mix as a function of the asphalt binder shear modulus and the mix volumetric properties, including voids in mineral aggregates (VMA) and voids filled with asphalt (VFA). This approach has been used to evaluate the level of blending between aged and reclaimed binders and to predict the performance grade of blended binders. Hajj et al. *(9)* predicted asphalt binder modulus from mix modulus using the modified Huet-Sayegh model. Zofka et al. *(19)* used creep stiffness measurements at low temperatures, obtained from the inverse of creep compliance, with the Hirsch model to predict asphalt binder properties at low temperatures.

The Hirsch model can be used to predict the shear modulus, but it cannot be used to predict the phase angle. Both parameters are needed to understand the full viscoelastic behavior of asphalt binder. Phase angle is also a key parameter for determining the performance grade of asphalt binders. Typically it is difficult, if not impossible; to do routine tests on asphalt mixes at the high and low performance grade temperature limits of the asphalt binder. Therefore, the measured modulus of the asphalt mix has to be shifted, using time-temperature superposition, to predict the asphalt binder moduli at the desired performance grade temperatures. Recent work by Bennert and Dongre *(18)* used analytical approaches developed by Bonaquist *(17)* and Rowe *(20)* to estimate the shear modulus and phase angle of asphalt binders from the properties of asphalt mixes. Mixes with zero, 10, and 25 percent RAP were assessed and the results indicated that the measured shear modulus and phase angle of the recovered binders were comparable to the predicted values. It is unlikely that similar comparable results will be obtained with binders extracted from R-RAP given the concerns raised in Section 2.4.

2.5.2 Testing Extracted and Recovered Binders

To date, the majority of studies on the characterization and design of asphalt mixes containing RAP involve the extraction and recovery of asphalt binder from the mix using chemical solvents *(1,3-5,21-30)*. The extraction and recovery method has long been criticized for being labor intensive, for its potential to alter binder chemistry and rheology, and for creating hazardous chemical disposal issues. Studies have also demonstrated that some of the aged binder may still remain on the aggregate after extraction, and thus the measured properties from the extracted and recovered binder may not completely represent the actual properties of the binder in the mix *(3,13)*. After extraction, asphalt binder can also stiffen due to potential reactions between the binder compounds and the solvent *(31)*. Typically, the extraction process also blends aged and virgin binders into a homogenous composite binder that may not be truly representative of the actual composite binder in the mix after production.

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

2.5.3 Testing Simulated RAP Binders

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

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

2.5.4 Testing Asphalt Mortar

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

Hajj et al. *(9)* compared the performance grade properties of blended binder by using DSR and BBR testing of both recovered binder and asphalt mortar. The results were found to be dependent on the amount of RAP in the mix, and although the results of mixes with up to 50 percent RAP showed similar trends, the measured high, intermediate, and low performance grade (PG) temperatures of the mortar were lower than those measured on the extracted binder. The differences in results increased with increasing RAP content. The reasons for the differences were not forensically investigated, but were attributed in part to the influence of the extraction chemistry on full blending of the binders and possibly to the effect of the chemistry on additional hardening of the binders.

2.5.5 Testing Fine Aggregate Matrix Mixes

Testing fine aggregate matrix (FAM) mixes as an alternative to testing asphalt mortar has also been investigated *(10-12)*. 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 or prismatic bars can be tested with a solid torsion bar fixture in a DSR (known as a dynamic mechanical analyzer [DMA]). This testing approach is similar to that used for asphalt mortars in that two samples are tested, one containing virgin binder plus RAP, and 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 component of the FAM. Kanaan *(36)* evaluated the viscoelastic, strength, and fatigue cracking properties of FAM specimens with different quantities 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 the 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, an opposite trend was observed.

The UCPRC recently completed studies for Caltrans, the National Center for Sustainable Technology, and the Federal Aviation Administration on the development of FAM mix test procedures *(37-41)*. The studies found that FAM mix testing was an appropriate alternative to solvent extraction and recovery for determining the properties of binders in RAP and blended binders in new mixes.

2.6 Quantifying the Level of Diffusion and Blending Between Virgin and RAP Binders

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

McDaniel et al. *(5)* investigated whether RAP acts like a "black rock" or if there is some level of blending occurring between the age-hardened binder in RAP and virgin binder. Asphalt mixes were prepared with 10 and 30 percent RAP content using RAP materials collected from three different locations (Arizona, Connecticut, and Florida) and two grades of virgin binder. The mixes were fabricated to simulate actual asphalt plant conditions, zero binder blending, and full blending conditions. Statistical differences between the properties of the asphalt mixes fabricated at three blending conditions were only measured on the mix with 30 percent RAP. Based on these results, the investigators concluded that RAP should therefore not be considered as black rock and that significant blending does occur.

Bonaquist *(17)* evaluated the level of blending between reclaimed and virgin binder in mixes containing RAP and RAS. The shear modulus of the blended binder was predicted with the Hirsch model and then compared with the measured shear modulus of the recovered binder from the mixes. The results indicated that full blending occurred in an asphalt mix containing 35 percent RAP, but that only limited blending occurred between the virgin and RAS binder in a mix containing 5 percent RAS. The approach proposed by Bonaquist was used in other studies *(20,25,26,42)* to evaluate the level of blending between RAP and virgin binder in asphalt mixes containing RAP. Results from these studies indicated that complete blending occurred in most cases. Mogawer et al. *(43)* also evaluated the degree of blending between the aged and virgin binders by comparing the ratio of the measured mix dynamic modulus to the recovered binder modulus for the control and corresponding RAP mix. The study concluded that sufficient blending of the RAP and the virgin binders in the RAP mix were achieved.

Hung et al. *(44)* used extraction and recovery to investigate how aged RAP binder blended with virgin binder under normal mixing conditions. One source of RAP was mixed with virgin binder at different percentages. The results indicated that only a small percentage of the RAP blended with the virgin binder, with the remaining RAP binder forming a stiff coating around the RAP aggregate, thereby creating a "composite black rock." The investigators recommended further analysis to investigate a larger range of RAP sources and virgin binders under various mix conditions.

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

A recent UCPRC study investigated diffusion and aging mechanisms during blending between new and age-hardened asphalt binders in hot and warm mix asphalt during production and paving *(39)*. The study was undertaken to investigate assumptions that blending between age-hardened and new binders could potentially be improved with the aid of warm mix additives. Two-layer asphalt binder samples composed of one layer of virgin and one layer of simulated RAP binder were tested in a DSR after conditioning at hot mix and warm mix production, storage, placement, and compaction temperatures. Complete blending between aged and new binders was achieved at hot mix temperatures, but only partial blending was achieved at warm mix temperatures.

Zhou et al. *(2,46)* characterized tear-off asphalt shingles (TOAS) and manufacturer waste asphalt shingles (MWAS) from various sources and the blending of extracted binders with virgin binder and RAP binder using DSR and BBR tests. The results showed that the TOAS binder had distinguishably different properties than the MWAS binder, and the study concluded that RAS source needed to be considered in any mix design if use of RAS was planned. Changes in the high and low performance-related temperatures were generally linear up to 30 percent RAS content and nonlinear thereafter. Zhao et al. *(47)* and Zhou et al. *(48)* also quantified the rate at which reclaimed binder was mobilized to blend with virgin binder in mixes containing up to 80 percent RAP and up to 10 percent RAS. This was achieved by measuring the large molecular size percentage using gel permeation chromatography. The results showed that the asphalt binder mobilization rate decreased with increasing RAP content. The rate of binder mobilization was 100 percent for 10 to 20 percent RAP content, 73 percent for 30 percent RAP content, and 24 percent for 80 percent RAP content. In the mixes containing RAS, the maximum mobilization rate peaked at up to 5 percent RAS content and then decreased with increasing RAS content thereafter.

Falchetto et al. *(49)* compared backcalculated asphalt binder creep stiffnesses, determined from the properties of asphalt mixes containing RAP or RAS, to the measured creep stiffness values of the binder chemically extracted from those mixes. The measured creep stiffness values were higher than the backcalculated stiffness values. The difference was attributed to forced blending between the virgin and age-hardened RAP or RAS binders during the solvent extraction process.

2.7 Selection of Virgin Binder for RAP Mixes

Current practice (AASHTO M 323) specifies using one-grade softer virgin binder than is specified for the pavement location when 15 to 25 percent RAP is used in the mix. This is intended to compensate for the stiffening effect of the aged reclaimed binder. For higher amounts of RAP, the performance grade of the virgin binder must be determined from a blending chart, which requires testing of extracted and recovered reclaimed binder *(1,5)*.

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

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

Kriz et al. *(45)* found that the current AASHTO M 323 specification recommendation for using a one-grade softer asphalt binder in mixes with 15 to 25 percent RAP may not be justified, as test results demonstrated that a binder grade change was unnecessary for up to 25 percent RAP binder replacement for most of the blends investigated.

Sabouri et al *(50)* investigated how incorporation of RAP changes the binder grade. Testing was performed on both PG 64-28 and PG 58-28 binders and at zero, 20, and 40 percent RAP binder replacement. The results showed that mixes with the softer binder (PG 58-28) had better fatigue resistance properties. The study suggested the use of a soft binder while maintaining the optimum binder content or increasing the asphalt layer thickness when incorporating high quantities of RAP in mixes.

2.8 Properties of Asphalt Mixes Containing Reclaimed Asphalt

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

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

2.8.1 Effect of Reclaimed Asphalt on Mix Volumetric Properties

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

Swamy et al. *(51)* found negligible changes in volumetric properties when up to 10 percent RAP was used in a mix and that the effects of higher percentages of RAP (20 and 30 percent) on volumetric properties were inconsistent. Daniel and Lachance *(52)* observed increases in VMA and VFA values with increasing RAP up to 40 percent. The preheating of RAP materials was also found to influence volumetric properties. Studies in Minnesota *(53)* found that the volumetric properties of conventional mixes and mixes with 15, 25, and 30 percent RAP, mixes with 3 and 5 percent RAS, and mixes with combinations of RAP and RAS (10/5, 15/5, 25/5, 15/3, 25/3 percent) were similar and that all mixes satisfied the Minnesota Department of Transportation volumetric requirements.

Aurangzeb et al. *(54)* investigated the use of high percentages of RAP (30, 40, and 50 percent) in asphalt mixes to obtain desired volumetric and performance properties. The results showed that all of the mixes with RAP performed equally or better than the mixes prepared using virgin aggregate. Given that consistent and similar volumetric properties were achieved for all mixes, the researchers concluded that the performance properties of the tested mixes were a function of only their mechanical properties. Appropriate processing and fractioning of the RAP was recommended for high RAP mixes to ensure consistent quality.

Kvasnak et al. *(55)* investigated the best method of determining the bulk specific gravity of RAP aggregates, which is used for determining the VMA. Asphalt mixes with known aggregate properties were produced and aged, after which the aggregates were recovered for further analysis. The maximum theoretical specific gravity was determined for each mix and then used to estimate the bulk specific gravity of the aggregates. The study concluded that the bulk specific gravity of aggregates can be successfully estimated from the measured maximum theoretical specific gravity of the mix and then used to determine the VMA of the mix when a regional absorption value is known.

A joint study conducted by the National Center for Asphalt Technology (NCAT) and the University of Nevada-Reno *(56,57)* investigated three methods for characterizing RAP for binder content and aggregate properties, namely the ignition method, centrifuge extraction, and reflux extraction. Laboratory-produced RAP materials were prepared with aggregates from four different sources. Trichloroethylene was used as the solvent in both extraction methods. The properties of the virgin aggregates were compared to those of the recovered aggregates, with the results indicating that the asphalt binder content was best determined using the ignition oven method and that centrifuge extraction had the least effect on the gradation of the material recovered *(56)*. The combined bulk specific gravity of the aggregate recovered using the ignition method was the closest to the true values, except for the limestone aggregates *(57)*. The study found that solvent extraction was the most appropriate method for determining the gradation and specific gravity of the coarse and fine aggregates in mixes with RAP contents higher than 25 percent. However, the study concluded that any method used to recover RAP will cause some error in the determination of bulk specific gravity, especially if the degree of asphalt absorption is not known. Mixes containing up to 50 percent RAP had variances in VMA of up to ± 0.5 percent.

Mangiafico et al. *(58)* conducted a statistical analysis on how different variables influence the volumetric properties of mixes containing RAP. The selected variables included aggregate properties, gradation, filler properties, binder content, and binder properties. All mix design parameters were found to be statistically significant with respect to the complex modulus of a mix. When assessing fatigue resistance, the aggregate properties, aggregate gradation, and interaction of the binder content and binder properties were found to be the most significant.

Stroup-Gardiner and Wagner *(59)* investigated the used of RAP in Superpave designed mixes. Splitting the RAP stockpile into fine and course fractions increased the potential for maximizing RAP binder replacement to meet Superpave aggregate gradation requirements.

2.8.2 Effect of RAP and RAS on Mix Performance Properties

The Virginia Department of Transportation evaluated the effect of higher RAP percentages (20 to 30 percent) on performance properties and the relative cost for specific paving projects in 2007 *(60)*. The predicted performance of the control and high RAP mixes were found to be equal based on the results of rutting, fatigue, and moisture susceptibility testing. The addition of RAP did increase the high-temperature performance grade of the virgin binder by one or two grades and in some cases it increased the low-temperature grade by one (from -22°C to -16°C). No construction problems were observed with the high RAP mixes and adding RAP to the mix did not increase production or construction costs.

The constructability and accelerated field performance of RAP mixes were evaluated at the NCAT test track *(61,62)*. Mixes with 20 percent RAP content were more easily compacted than mixes with 45 percent RAP content. Mixes with 45 percent RAP and a softer binder (PG 58-28) required less compaction effort than the same mix with stiffer binder (PG 76-22 polymer-modified). A warm mix additive did not improve compaction. All the mixes evaluated showed acceptable rutting performance, but some low-severity longitudinal cracking, attributed to reflection cracks and/or construction defects was observed. Laboratory rut testing (asphalt pavement analyzer [APA]) on specimens sampled from the track showed that the use of RAP reduced the rutting potential. Specimens from the section with 45 percent RAP content and softer binder (PG 58-22) had a lower dynamic modulus than the mix with a stiffer binder, which could adversely affect mix durability at high-strain conditions. The mixes with 45 percent

RAP had shorter fatigue life than the mixes with 20 percent RAP and the control mixes with no RAP. However, in these tests fatigue life did not appear to be influenced by the stiffness of the virgin binder.

Shah et al. *(63)* performed complex dynamic modulus and complex shear modulus tests on virgin binder and binder recovered from mixes with 15, 25, and 40 percent RAP. The results showed no statistical difference between the control binder and binder from the mixes with 15 and 25 percent RAP. Some differences were observed in the dynamic modulus of the control binder and the binder extracted from the mix with 40 percent RAP. Stiffening of the mix with increasing RAP content did not occur as expected.

Li et al *(53)* evaluated the stiffness and low-temperature fracture properties of asphalt mixes containing zero, 20, and 40 percent RAP from two sources and with two grades of base binder (PG 58-28 and PG 58-34). The results indicated that the mix stiffness (dynamic modulus) increased with increasing RAP content. Using a softer virgin binder reduced the stiffness of the control and RAP mixes. The fracture energy of the mixes at low temperatures decreased with increasing RAP content. The source of the RAP did not influence performance at low temperatures, but was found to be significant in influencing stiffness at higher temperatures.

Mogawer et al. *(43)* evaluated how the stiffness and performance of plant-produced RAP are affected by plant type and production parameters. Tests included dynamic modulus, moisture susceptibility, Hamburg wheel-track, cracking, and workability. The results indicated that mixes with up to 30 percent RAP showed moisture damage susceptibility and rutting and low-temperature cracking performance that were similar to the control mixes. Workability was found to be a potential construction issue because mix workability decreased with an increase in RAP content. The results also showed that selection of the virgin binder grade for mixes with high RAP content should be based on the desired performance, given that notable differences were observed in performance between similar mixes with different virgin binder PG grades. In another study, Mogawer et al. *(21)* investigated the performance characteristics of plant-produced mixes with up to 40 percent RAP. The results showed improved rutting and moisture damage resistance with increasing RAP content, but reduced cracking resistance, compared to the control with no RAP.

Anderson et al. *(64)* compared the long-term field performance of mixes with no RAP and mixes containing up to 25 percent RAP. Based on the available performance data, the study found that pavement sections with RAP had better rutting resistance than the control sections, but exhibited a lower ride quality and more cracking.

Kim et al. *(65)* investigated the effects of using polymer-modified binder in mixes with zero, 15, 25, and 35 percent RAP on laboratory rutting (asphalt pavement analyzer) and cracking (indirect tensile strength) tests. No significant differences were noticed in the results between the different mixes.

Tarbox and Daniel *(66,67)* investigated the effect of long-term aging on asphalt mixes containing RAP. Mixes with zero, 20, 30, and 40 percent RAP were compacted and then aged in an oven for two, four, or eight days at 185°F (85°C) before testing. A comparison of dynamic modulus test results showed that the susceptibility of mixes to aging-related stiffness increases reduced with increasing RAP content. Similar results were obtained in a similar study completed by Singh et al. *(68)*.

2.9 Use of Reclaimed Rubberized Asphalt Concrete in New Asphalt Mixes

No published literature on the use of reclaimed rubberized asphalt concrete in new asphalt mixes was located.

2.10 Use of Reclaimed Asphalt in New Rubberized Asphalt Concrete

Limited published research on the use of RAP in new rubberized asphalt concrete mixes was located.

Xiao studied the effect of fine rubber particles (100 percent passing the #40 [0.425 mm] sieve) and RAP over a number of years *(69-74)*. Early studies *(69)* investigated the fatigue-cracking properties of rubberized asphalt concrete with and without the addition of RAP. The mixing and compaction temperatures, determined according to AASHTO TP 4 (now AASHTO T 312), increased with increasing rubber content and RAP content. The effects of rubber and RAP binder on the fatigue performance of blended binder was analyzed using DSR results ($G^* \times \sin\delta$ at 25°C). Fatigue performance improved with increasing amounts of rubber and dropped with increasing amounts of RAP. Tests on mixes indicated that the fatigue life of the rubberized mixes with up to 30 percent RAP was significantly lower than the fatigue life of rubberized mixes containing no RAP.

Xiao et al. extended the study *(70-73)* to further investigate the effects of rubber and RAP on other mix performance properties. Mixes included different amounts of the same fine crumb rubber (zero, 5, 10, and 15 percent by weight of base binder) obtained from two different sources (ambient-ground and cryogenically-ground) and different percentages of RAP (zero, 15, 25, and 30 percent by weight of the total mix) obtained from two different sources. A PG 64-16 binder was used for RAP contents of 15 and 25 percent, and a PG52-28 binder was used for RAP contents of 30 percent. Asphalt rubber binders were prepared using a wet process by blending the base binders with the different percentages and sources of crumb rubber at a temperature of 375°F (177°C) for 30 minutes at a shear rate of 700 rpm. Mixes were prepared according to South Carolina Department of Transportation Superpave specifications. All mixes had a dense-gradation and the gradation was not changed to accommodate the rubber. However, the optimum binder contents of the mixes were influenced by the amount of crumb rubber and RAP added, with binder content increasing with increasing amounts of rubber and decreasing with increasing amounts of RAP. The addition of rubber and RAP also had opposite effects on the VMA parameter, with VMA increasing with increasing rubber content and decreasing with increasing RAP content. The mixes containing both rubber and RAP were more workable than the mixes with only RAP.

Indirect tensile strength (ITS) test results from dry and wet tests indicated that strengths decreased with increased rubber content, but increased with increasing RAP contents up to 25 percent *(70-73)*. Rubber and RAP contents of 10 and 25 percent, respectively, provided optimal strengths. The dry and wet strengths of the mix with PG 52-28 binder and 30 percent RAP content were lower than the strengths recorded on the control mixes. Results from tests to assess rutting performance (using an asphalt pavement analyzer) *(73)* and fatigue performance *(74)* showed similar trends to the ITS tests.

Vahidi et al. *(76)* investigated the effects of adding ground tire-rubber (GTR, 100 percent passing #40 sieve) modified binders (rates of 10 and 15 percent by weight of binder) to asphalt mixes containing no RAP and 40 percent RAP. Rubber was added to the PG 58-28 base binder in a wet process at 5,000 rpm at 374°F (190°C) before being mixed with the aggregate. Additional mixes were made by first adding a wax-based warm mix additive to the rubber particles, mixing these treated particles with the aggregates in a dry process, and then adding the asphalt binder. A dense aggregate gradation was used and was not altered to accommodate the rubber. An optimum binder content of 6 percent was determined. Test results indicated that stiffness increased with increasing rubber and RAP content, with the stiffening effect of the rubber greater than that of the RAP. Rutting resistance (Hamburg Wheel-track Test) improved with increasing rubber and RAP content. Mixes with GTR and no RAP had better low-temperature cracking resistance in the thermal stress-restrained specimen test than the mixes with 40 percent RAP; however, the addition of rubber did improve the cracking performance of the mix with RAP.

Ambaiowei and Tighe *(77)* investigated the low-temperature performance of rubberized asphalt concrete mixes with zero, 15 and 20 percent RAP. A total of seven mixes were collected from the 2011 Ontario rubber demonstration projects, including three dense-graded control mixes with 15 and 20 percent RAP; one dense-graded rubberized mix made with terminal-blend rubber modified binder (10 percent rubber by weight of binder) and 20 percent RAP; and three gap-graded rubberized mixes made with field-blended wet-process asphalt rubber binder (20 percent rubber by weight of binder) and 20 percent RAP. Stiffness, rutting performance, and thermal cracking performance were evaluated. Test results showed that the mixes containing both rubber and RAP performed better than the mixes containing only RAP. The gap-graded mixes were stiffer and performed better in the low-temperature cracking tests, while the dense-graded mix performed better in rutting tests. Both types of rubberized asphalt mix containing RAP had lower fracture stress and fracture temperature than the control mixes with conventional binder and the same quantity of RAP, suggesting that rubberized asphalt mixes in general would have better resistance to thermal cracking.

2.11 Literature Review Summary

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

- The asphalt binder in RAP and RAS can blend appreciably with virgin binder in new mixes. The level of blending between the aged and new binders depends on the chemical composition of the individual binders. To ensure the optimal performance of asphalt mixes containing high quantities of reclaimed asphalt, the compatibility of reclaimed and virgin asphalt binders from different sources and with different performance grades needs to be well understood.
- Appropriate methods for extracting aged binder from reclaimed asphalt materials are still being developed, with a focus on the effects that extraction solvents have on the properties of the recovered binders. The solvents in current use are considered to be aggressive enough to fully blend the binders extracted from new mixes containing aged and virgin binders, which is problematic because the forced blending can lead to potentially misleading binder replacement values and nonrepresentative performance gradings of the blended binders. Asphalt rubber binders cannot be chemically extracted because the rubber is separated from the base binder during the process.
- Alternative methods to the use of extraction and recovery are being explored to better characterize the performance properties of blended virgin and RAP and/or RAS binders. Tests on mortar and FAM mixes warrant further investigation.
- Adding RAP to a new asphalt mix can alter the volumetrics and performance of the mix. However, volumetric requirements can still be met with relatively high RAP contents (i.e., up to 25 percent). Compared to equivalent mixes without RAP, rutting performance was generally improved by the addition of RAP, but cracking performance was generally worse. Conflicting results with regard to laboratory test performance were reported.
- Given that the use of RAP for binder replacement and not just for aggregate replacement is a relatively new practice, there is limited knowledge on the long-term field performance of mixes containing high RAP contents (i.e., above 25 percent binder replacement), specifically with regard to the rate of binder aging and its effect on stiffness and susceptibility to cracking. Conventional laboratory aging procedures have not been verified for high RAP mixes.
- No published literature on the use of reclaimed rubberized asphalt concrete in new asphalt mixes was located.
- Only limited published research on the use of RAP in rubberized asphalt concrete was located, and all of it referred to dense-graded mixes.

- Most of the research reported in the literature covered laboratory testing under controlled conditions. Only limited published work was found on long-term field assessments that compared mixes containing RAP with equivalent control mixes containing no RAP.

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3. EXPERIMENT PLAN

The experiment plan followed in this UCPRC study was based on a workplan *(78)* that was developed at the start of the project and approved by CalRecycle.

3.1 Materials

The materials used in this study were limited to the following:

- Asphalt binder (one grade from one source [PG 64-16 from a northern California refinery])
- Virgin aggregate (one source [crushed alluvial from a northern California asphalt plant])
- Conventional reclaimed asphalt pavement (RAP) (one source [from a northern California asphalt plant stockpile])
- Reclaimed rubberized asphalt pavement (R-RAP) (two sources [These are referred to as Source-A and Source-B from milling projects on two different Caltrans highways. The Source-B R-RAP was known to be contaminated with some conventional RAP from the underlying dense-graded layer during the milling operation.])
- Recycled tire rubber (one source [from a northern California manufacturer])
- Extender oil (one source [from a northern California asphalt rubber producer])

Only one source of conventional reclaimed asphalt pavement was used since earlier testing on multiple different California RAP samples from different locations indicated that there was very little difference in the properties of the RAP from the different sources *(37)*.

3.1.1 Processing of RAP and R-RAP Materials

The RAP material had already been processed (crushed and sized) by the producer and did not require further processing. RAP passing the 2.36 mm (#8) sieve was sampled from a portion of the material for preparation of FAM mixes. All RAP materials were dried in an oven at 50°C (104°F) to constant weight prior to mixing. R-RAP millings were dried in an oven at 50°C (104°F) to constant weight and then sieved to remove all material larger than 13 mm (~ 0.5 in.). R-RAP passing the 2.36 mm (#8) sieve was sampled from a portion of this sieved material for preparation of FAM mixes.

Representative quantities of RAP and R-RAP were sampled and sent to a contracting laboratory for extraction and recovery of the asphalt binder to determine the binder content and the gradations of the recovered aggregates. Binders were extracted using trichloroethylene (AASHTO T 164) and recovered using the Abson method (ASTM D1856). The extracted binders were not used for preparation of any mixes, given that extraction and recovery of binders from R-RAP will only extract the base binder, with most of the rubber particles remaining with the recovered aggregates. Table 3.1 shows the gradation and binder content of the RAP and R-RAP materials. The proportion of fine and coarse R-RAP fractions was 90:10 for R-RAP Source-A and 91:9 for Source-B. These proportions were used for designing the full-graded mixes containing R-RAP materials.

Table 3.1: Gradations and Binder Contents of RAP and R-RAP Materials

Sieve Size		RAP		R-RAP (Source-A)		R-RAP (Source-B)	
Metric	U.S.	% Passing 9.5 mm	% Passing 2.36 mm	% Retained on 2.36 mm	% Passing 2.36 mm	% Retained on 2.36 mm	% Passing 2.36 mm
25.4	1.0	100	100	100	100	100	100
19.0	3/4	100	100	100	100	100	100
12.5	1/2	100	100	100	100	100	100
9.5	3/8	96.4	100	93	100	92	100
4.75	#4	74.1	100	49	100	47	100
2.36	#8	55.7	100	22	99	19	99
1.20	#16	43.0	80	16	69	14	71
0.60	#30	32.7	55.8	11	50	12	53
0.30	#50	21.6	32.5	8	37	9	39
0.150	#100	12.7	17.4	7	25	6	23
0.075	#200	7.7	10.6	5	16	4	17
Binder content[1]		4.5	6.6	5.9	9.0	5.3	11.5
[1] percent total weight of mix (TWM)							

3.1.2 Preparation of Laboratory-Produced Asphalt Rubber Binder

Asphalt rubber binder was prepared in the laboratory according to Caltrans specifications. Rubber content was set at 18 percent (25 ± 2 percent high natural rubber and 75 ± 2 percent recycled tire rubber [ambient grinding]). The gradation of the rubber used is summarized in Table 3.2. Extender oil was added at a rate of 4 percent by weight of the base binder.

Table 3.2: Crumb Rubber Gradation

Sieve Size		% Passing		
Metric	U.S.	Tire Rubber	Natural Rubber	Combined
2.36	#8	100	100	100
2.00	#10	100	100	100
1.20	#16	56	99	67
0.60	#30	20	40	25
0.30	#50	5	17	8
0.15	#100	0	4	1
0.075	#200	0	0	0

Binders were prepared as follows:

1. Add 4 percent asphalt modifier (by weight of the base binder) to asphalt binder at about 160°C (320°F) during heating, and gently stir the binder with a glass rod until the mixture is uniform.
2. Raise the temperature of the base binder to 195°C (383°F).
3. Add 18 percent crumb rubber (by weight of the total binder).
4. Blend the crumb rubber, asphalt modifier, and asphalt binder in a mixer at 2,000 revolutions per minute (RPM) for 30 minutes at a temperature between 190°C and 196°C (374°F to 385°F). Lower the mixer speed to 1,000 RPM and mix for a further 30 minutes while maintaining the mixing temperature between 190°C and 196°C.

This mixing process was considered to be appropriately representative of plant production for the purposes of this research, based on earlier work done at the UCPRC *(16)*. Binders were produced in batches, stored in 500 mL containers, and then reheated prior to testing.

3.1.3 Preparation of Artificially Aged Binders

Artificially aged binders were prepared in the laboratory based on accepted practice published in the literature *(32,33)* and verified in earlier studies at the UCPRC *(38)*. Conventional asphalt and laboratory-prepared asphalt rubber binders were aged in a pressure aging vessel (PAV) for 40 hours at 2.1 MPa (300 psi) pressure and 100°C (212°F) to simulate age-hardened binder in RAP and R-RAP. It should be noted that although these artificially aged binders are useful for understanding the rheological properties of blended new and aged binders, it is accepted that they do not truly represent the properties of actual aged RAP and R-RAP binders.

3.1.4 Preparation of Blended Binders

Conventional binder was blended with artificially aged binder at the predetermined ratios by hand stirring with a glass rod in a glass beaker at 163°C (325°F).

3.2 Testing Plan

Table 3.3 summarizes the sampling and testing factorial for the materials used in this study. This factorial equates to a total of seven different full-graded mixes and ten different FAM mixes tested in the different phases.

Table 3.3: Experimental Design Factors and Factorial Levels

Factor	Factorial Level	Details
Asphalt binder	2	Virgin PG 64-16 and laboratory-prepared asphalt rubber binder
Crumb rubber	1	
Extender oil	1	
Aggregate source	1	Crushed alluvial from a northern California asphalt plant
RAP source	1	RAP stockpile at a northern California asphalt plant
R-RAP source	2	Milling projects on two different northern California highways
Simulated RAP binder	1	Laboratory-prepared (used only for FAM mixes)
Simulated R-RAP binder	1	Laboratory-prepared (used only for FAM mixes)
RAP content[1]	2	RHMA-G (0 and 10% RAP) RHMA-G FAM (0 and10% RAP)
R-RAP content[1]	3	HMA (0, 15, 25% R-RAP from both sources) HMA FAM (0, 15, and 25% R-RAP from both sources)
Simulated RAP binder content[1]	2	RHMA-G FAM (15 and 25% simulated RAP binder)
Simulated R-RAP binder content[1]	1	HMA FAM (15 and 25% simulated R-RAP binder)
[1] by binder replacement		

Testing on this UCPRC project was conducted in three phases, namely tests on asphalt binders (Phase 1a), tests on fine aggregate matrix (FAM) mixes (Phase 1b), and tests on full-graded mixes (Phase 2). The testing plan is summarized in Figure 3.1. Details on the materials used and the test methodologies followed in each phase are summarized below.

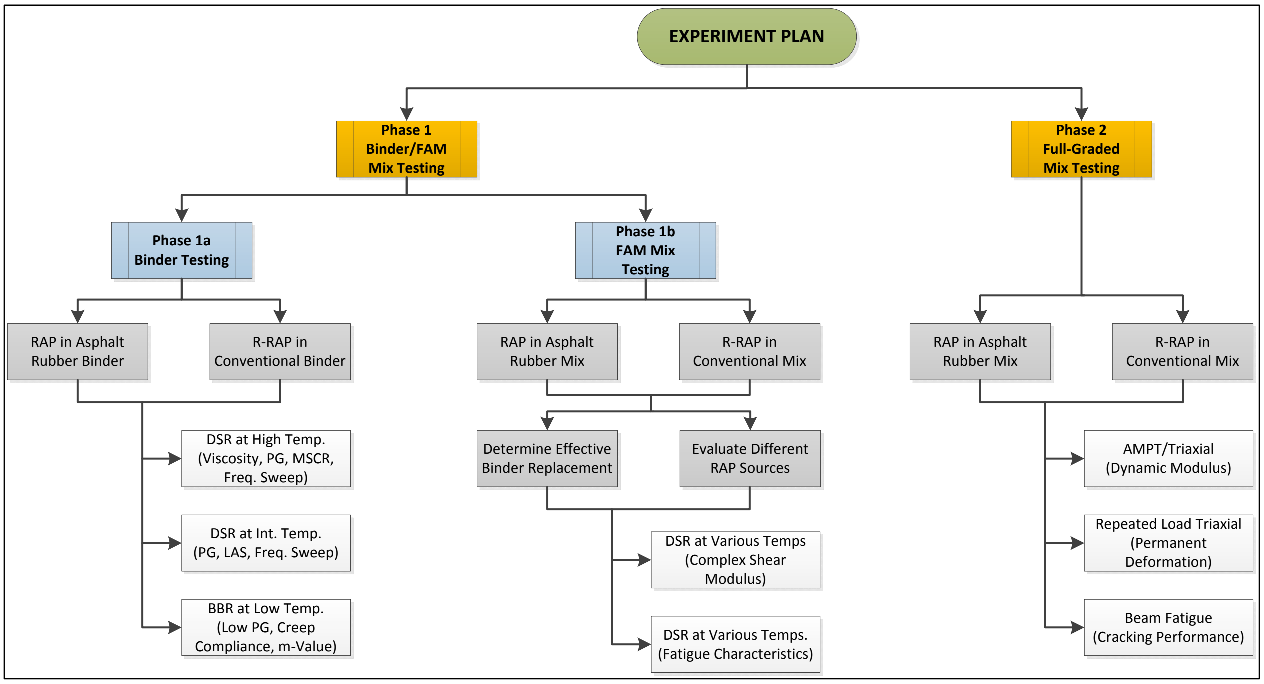

Figure 3.1: Experiment plan.

3.3 Phase 1: Asphalt Binder and Fine Aggregate Matrix Mix Testing

3.3.1 Asphalt Binder Testing (Phase 1a)

The conventional PG 64-16 binder used for control purposes, for preparation of asphalt rubber binder, and for preparation of mixes to assess the effects of R-RAP on conventional mix performance was tested according to standard AASHTO testing procedures (AASHTO M 320). Laboratory-produced asphalt rubber binders were tested according to a new procedure developed at the UCPRC specifically for these binders *(79,80)*. This procedure uses concentric cylinder geometry instead of parallel plate geometry.

Aged rubberized asphalt binder cannot be satisfactorily extracted from R-RAP and then tested using conventional procedures because the chemicals and mechanical processes used during the extraction separate the rubber from the asphalt. Consequently, the properties of this extracted binder will be closer to the original base binder and not the rubberized binder. Artificially aged binders were therefore used as an alternative to extracted binders in this phase of the study. Standard and UCPRC-developed tests using a dynamic shear rheometer (DSR) and bending beam rheometer (BBR) were conducted on the aged binders to determine their rheological properties.

3.3.2 Fine Aggregate Matrix Mix Testing (Phase 1b)

FAM testing eliminates the need for chemical extraction. FAM mixes consist of binder and fine aggregate (typically passing the 4.75 mm [#4], 2.36 mm [#8], or 1.18 mm [#16] sieve). Aggregates can be virgin aggregate, RAP, R-RAP, or a combination of the two. Cores (12.5 mm × 50 mm) and beams (10 mm × 10 mm × 50 mm) cut from larger gyratory-compacted specimens are tested in a dynamic mechanical analyzer (DMA) mounted in a DSR to determine the rheological properties of the FAM mix. Tests include amplitude sweep and frequency sweep to determine the linear viscoelastic range and complex shear modulus, respectively. Test procedures used in this study followed those developed at the UCPRC in an earlier study *(38)*.

Although the FAM mix testing process was considered suitable for assessing the blending between virgin and aged asphalt rubber binders and between virgin asphalt rubber binder and aged conventional binders, some variables needed to be understood before detailed testing could be undertaken. The following incremental steps were undertaken to understand these variables:

1. Asphalt rubber binder was prepared in the laboratory.
2. Portions of conventional base binder and asphalt rubber binder were artificially aged in a pressure aging vessel to produce simulated RAP and R-RAP binders.
3. The rheological properties of the simulated RAP and R-RAP binders were compared to those of the corresponding unaged binders.
4. The simulated RAP and R-RAP binders were then blended with virgin asphalt rubber binder, virgin conventional binder, and unaged rubberized binder, and then the rheological properties of the blends were determined.
5. Once the properties of these blended binders were understood, FAM mixes were prepared with virgin aggregates, virgin binders, and RAP and R-RAP materials at different binder replacement rates and then compacted in a gyratory compactor. The rheological properties of small cores or beams removed from these specimens were determined and compared against the properties of the blended binders only.
6. If appropriate results were obtained in Step #5, fine aggregate mixes were prepared from blends of virgin materials and the different actual RAP and R-RAP sources and then tested.
7. The results were statistically analyzed to identify any key issues influencing the blending of aged asphalt rubber binders with virgin conventional binders, and aged conventional binders with virgin asphalt rubber binder.

3.3.3 Phase 1 Testing Factorials

Phase 1a: Blending between Virgin Conventional Binders and Aged Asphalt Rubber Binders

The testing factorial for assessing blending between virgin conventional binder and aged asphalt rubber binders included the following:

- Step #1:
  - PG 64-16 virgin binder, one source
  - Asphalt rubber binder using same PG 64-16 base binder with 18 percent rubber and 4 percent extender oil meeting the Caltrans specification.
- Step #2:
  - Binders developed in Step #1
  - Laboratory long-term aging of asphalt rubber binder to produce simulated R-RAP binder
- Step #3:
  - DSR testing at high and intermediate temperatures, and BBR testing at low temperatures
- Step #4:
  - Blends of 85:15, 75:25 and 60:40 virgin binder to artificially aged binder (three blended binders)
  - Tests as listed in Step #3.
- Step #5:
  - Simulated R-RAP binder, one binder content, typical FAM gradation based on previous research
  - Preparation of fine aggregate mix specimens
  - DSR tests on FAM cores or beams
- Step #6:
  - Blends of 85:15 and 75:25 virgin material to simulated R-RAP material prepared in Step #5
  - Preparation of fine aggregate mix specimens
  - DSR tests on cores
- Step #7
  - Blends of 85:15 and 75:25 virgin material to sourced R-RAP material (two R-RAP sources)
  - Preparation of fine aggregate mix specimens
  - DSR tests on cores

Phase 1b: Blending between Virgin Asphalt Rubber Binders and Aged Conventional Binders

The testing factorial for assessing blending between aged conventional binders and new rubberized binders included the following:

- Step #1:
  - PG 64-16 virgin binder, one source
  - Asphalt rubber binder using same PG 64-16 base binder with 18 percent rubber and 4 percent extender oil meeting Caltrans specification
- Step #2:
  - Binders developed in Step #1
  - Aging condition of conventional binder determined based on literature review
- Step #3:

  DSR testing at high and intermediate temperatures, and BBR testing at low temperatures
- Step #4:
  - Blends of 85:15, 75:25, 60:40 asphalt rubber binder to aged conventional binder (three blended binders)
  - Tests as listed in Step #3.

- Step #5:one binder content, typical gradation based on previous research
  + Preparation of fine aggregate mix specimens
  + DSR tests on cores
- Step #6:
  + Blends of 85:15 and 75:25 virgin material to simulated RAP material prepared in Step #5
  + Preparation of fine aggregate mix specimens
  + DSR tests on cores
- Step #7
  + Blends of 90:10 and 85:15 virgin material to sourced RAP material (one RAP source)
  + Preparation of fine aggregate mix specimens
  + DSR tests on cores

3.4 Phase 2: Full-Graded Mix Testing

This task included a range of tests on compacted full-graded specimens to assess typical performance-related properties of the various mixes, and as a cross check to the test results of FAM mixes. Compacted specimens were prepared according to Superpave mix design methods. The full testing factorial included the following:

- Materials
  + RAP sources, laboratory-prepared (artificial): one conventional and one rubberized
  + RAP sources, field: one conventional and one rubberized (selected based on Task #3 findings)
  + Binder sources: one conventional and one rubberized (produced in the laboratory)
  + Proportions of rubberized RAP in conventional mixes: 100:0, 85:15, and 75:25
  + Proportions of RAP in RHMA-G mixes: 100:0, 90:10, and 85:15
- Tests
  + Dynamic modulus (specimens prepared in a gyratory compactor)
  + Flexural modulus (specimens prepared using a rolling wheel compactor)
  + Repeated load triaxial/flow number (specimens prepared in a gyratory compactor)
  + Beam fatigue (specimens prepared using a rolling wheel compactor)

No moisture sensitivity tests (i.e., Hamburg Wheel-Track and/or tensile strength retained) were undertaken in this UCPRC test program given that past testing with this aggregate has indicated that it is not moisture sensitive and no reference was found in the literature review stating that adding RAP to a mix altered or increased the moisture sensitivity of that mix.

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4. MIX DESIGNS AND SPECIMEN FABRICATION

4.1 Dense-Graded Asphalt Concrete Design

4.1.1 Dense-Graded HMA Control Mix

A Caltrans Superpave mix design for dense-graded HMA with a nominal maximum aggregate size of 19 mm (0.75 in.), provided by the asphalt plant from which the aggregates were sourced, was verified and used in this UCPRC study. The mix was designed for traffic of 3 million to 30 million equivalent single axle loads. Table 4.1 shows the gradation, bulk specific gravity, and absorption of the aggregate structure used in the mix. The Caltrans specification's target limits for aggregate gradation are also provided.

Table 4.1: Aggregate Properties of Dense-Graded HMA Mix

Sieve Size		% Passing	Target Limits
Metric	U.S.		
25.4	1.0	100	100
19.0	3/4	98	90 – 98
12.5	1/2	84	70 – 90
9.5	3/8	72	–
4.75	#4	47	42 – 58
2.36	#8	30	29 – 43
1.20	#16	21	–
0.60	#30	15	10 – 23
0.30	#50	10	–
0.150	#100	7	–
0.075	#200	4	2 – 7
Bulk specific gravity		2.448	
Absorption		1.85	

Dense-graded HMA mixes were prepared at 5.0 and 5.5 percent binder content by total weight of the mix. Asphalt binder (PG 64-16) was heated to 150°C (302°F) and aggregates were heated to 165ºC (329ºF) before mixing. The aggregates and binder were thoroughly blended using a Lancaster mixer for long enough (three to five minutes) to provide a uniform mix with aggregates fully coated with asphalt binder. Loose mixes were then short-term aged for two hours at the compaction temperature of 140°C (285°F) according to AASHTO R 30. The short-term aged mixes were compacted at the design number of gyrations (N_{design} = 85) under 600 kPa (87 psi) pressure and with a 1.16° internal gyration angle. The mixing and compaction temperatures were selected based on recommendations provided by the asphalt binder supplier. The optimum binder content of the mix was verified to be 5.5 percent by total weight of the mix. Table 4.2 lists the measured volumetric properties of the compacted dense-graded mixes along with the Caltrans specification requirements.

Table 4.2: Volumetric Properties of Dense-Graded HMA Control Mix

Volumetric Property	Caltrans Specification Limits	Binder Content (%)			
		5.0	Pass?	5.5	Pass?
Air-void content (%)	4.0	2.7 2.6 Average: 2.7	No	4.2 4.5 Average: 4.4	Yes
Voids in mineral aggregate (%)	>13	13.5 13.4 Average: 13.4	Yes	13.9 14.1 Average: 14.0	Yes
Voids filled with asphalt (%)	65 – 75	79.1 80.9 Average: 80	No	69.9 68.5 Average: 69.2	Yes
Dust proportion (%)	0.6 – 1.2	0.9 0.9 Average: 0.9	Yes	1.0 1.0 Average: 1.0	Yes

4.1.2 Dense-Graded HMA Mixes Containing Rubberized Reclaimed Asphalt Pavement

Mixes containing 15 and 25 percent reclaimed asphalt rubber pavement (R-RAP) (by binder replacement) from both R-RAP sources were prepared using the total optimum binder content and aggregate gradation determined for the control mix, but some of the virgin aggregate was replaced with R-RAP aggregate to meet the target virgin binder replacement. Quantities of R-RAP required to meet the binder replacement target were calculated using the R-RAP binder content determined from extraction or ignition oven tests.

The predetermined gradation of R-RAP material was preheated to 110°C (230°F) for one hour before it was mixed with virgin materials in order to raise its temperature closer to the mixing temperature but without aging the asphalt binder in the RAP further. After this preheating, the R-RAP material was mixed with the virgin binder and virgin aggregates, short-term aged, and then compacted as described for the control mix. Initial compaction trials revealed that five- and ten-minute squaring times (i.e., holding the specimen in the compaction mold at constant height) were required for the mixes with 15 and 25 percent R-RAP, respectively, to prevent expansion of the specimen due to the presence of the rubber particles in the R-RAP. The volumetric properties of the compacted mixes with R-RAP are shown in Table 4.3. All mixes passed the volumetric requirements.

4.2 Gap-Graded Rubberized Asphalt Concrete Design

4.2.1 Gap-Graded RHMA Control Mix

A Caltrans Superpave mix design for gap-graded rubberized asphalt concrete (RHMA-G) with a nominal maximum aggregate size of 12.5 mm (0.5 in.), provided by the asphalt plant from which the aggregates were sourced, was verified and used in this UCPRC study. The mix was also designed for traffic of 3 million to 30 million equivalent single axle loads. Table 4.4 shows the gradation, bulk specific gravity, and absorption of aggregate structure used in the mix. Caltrans specification target limits for aggregate gradation are also provided.

Table 4.3: Volumetric Properties of Dense-Graded HMA Mix with R-RAP

Mix	Mix Volumetric Properties				Pass?
	Air-Voids (%)	Voids in Mineral Aggregate (%)	Voids Filled With Asphalt (%)	Dust Proportion	
Caltrans specification limits	4	>13	65 – 75	0.6 – 1.2	–
R-RAP-A @ 15% (HMA_15RRAP_A)	3.7 3.4 Average: 3.6	14.0 13.8 Average: 13.9	73.6 75.1 Average: 74.4	0.9 0.9 Average: 0.9	Yes
R-RAP-A @ 25% (HMA_25RRAP_A)	3.2 3.3 Average: 3.3	13.6 13.7 Average: 13.7	76.5 76.1 Average: 76.3	0.9 0.9 Average: 0.9	Yes
R-RAP-B @ 15% (HMA_15RRAP_B)	3.2 3.3 Average: 3.4	13.6 13.7 Average: 13.7	76.5 75.3 Average: 75.9	0.9 0.9 Average: 0.9	Yes
R-RAP-B @ 25% (HMA_25RRAP_B)	3.9 4.2 Average: 4.1	13.5 13.8 Average: 13.6	71.2 69.8 Average: 70.5	1.0 1.0 Average: 1.0	Yes

Table 4.4: Aggregate Properties of Gap-Graded RHMA Mix

Sieve Size		% Passing	Target Limits
Metric	U.S.		
25.4	1.0	100	100
19.0	3/4	100	100
12.5	1/2	97	90 – 98
9.5	3/8	87	83 – 87
4.75	#4	42	28 – 42
2.36	#8	19	14 – 22
1.20	#16	12	–
0.60	#30	9	–
0.30	#50	6	–
0.150	#100	4	–
0.075	#200	3	0 – 6
Bulk specific gravity		2.669	
Absorption		1.54	

RHMA-G mixes were prepared by mixing virgin aggregates and laboratory-prepared asphalt rubber binder at 7.5, 8.0, and 8.5 percent binder by total weight of the mix. Aggregates and binder were heated to 170°C (338°F) before mixing. Producing a uniform mix with fully coated aggregates required a longer mixing time (five to seven minutes) than the conventional mix due to the higher viscosity of the asphalt rubber binder. The loose mix was then short-term aged for two hours at the compaction temperature of 164°C (327°F). Mixes were compacted to 150 gyrations at 825 kPa (120 psi) pressure and a 1.16° internal gyration angle. Specimens were held under pressure in the compaction mold for 30 minutes to prevent expansion of the specimen due to the rubber. The mixing and compaction temperatures and specimen hold time were selected based on recommendations from a previous UCPRC study *(81)* and Caltrans specifications, which state that RHMA-G mixes must be compacted to 4 percent air-void content with between 50 and 150 gyrations. Table 4.5 shows the measured volumetric properties of the RHMA-G mixes along with the Caltrans specified volumetric requirements. The optimum binder content of the RHMA-G mix was verified to be 8.5 percent by total weight of the mix.

Table 4.5: Volumetric Properties of Gap-Graded RHMA Control Mix

Volumetric Property	Specification Limits	Binder Content (%)					
		7.5	Pass?	8.0	Pass?	8.5	Pass?
No. of gyrations	50 – 150	150	Yes	150	Yes	150	Yes
Air-void content (%)	4.0	6.1 5.4 Avg.: 5.8	No	5.4 5.3 Avg.: 5.4	No	3.9 4.3 Avg.: 4.1	Yes
VMA (%)	18 – 23	20.5 19.4 Avg.: 19.9	Yes	20.8 20.8 Avg.: 20.8	Yes	20.5 20.8 Avg.: 20.7	Yes
VFA (%)	Report only	70.4 72.0 Avg.: 71.2	NA	74.2 74.3 Avg.: 74.2	NA	81.1 79.5 Avg.: 80.3	NA
Dust Proportion (%)	Report only	0.5 0.5 Avg.: 0.5	NA	0.4 0.4 Avg.: 0.4	NA	0.4 0.4 Avg.: 0.4	NA
Avg. = Average, NA = Not applicable							

4.2.2 Gap-Graded RHMA Mixes Containing Reclaimed Asphalt Pavement

The initial workplan proposed evaluating mixes containing 15 and 25 percent RAP (by binder replacement). However, initial mix design experimentation revealed that a maximum of only 10 percent RAP (by binder replacement) could be added, after which the specified gradation requirements for gap-graded mixes could not be met. This was attributed to the processed RAP materials used in this study (and considered representative of RAP materials in California in general) having relatively high percentages of small and fine aggregate (74 percent passing the 4.75 mm [#4] sieve), much of which is not permitted in a gap-gradation. An attempt to use higher proportions of coarse RAP to compensate for the lower proportions of fine RAP resulted in a lower than target binder content, as coarse RAP fractions tend to have limited asphalt binder coating.

Mixes were prepared using the total optimum binder content and aggregate gradation determined for the control mix, but replacing a portion of the virgin aggregate with RAP aggregate to meet the reduced target virgin binder replacement of 10 percent.

The predetermined gradation of RAP material was preheated to 110°C (230°F) for one hour before it was mixed with the virgin materials, and then mixed with the virgin binder and virgin aggregates, short-term aged, and then compacted as described for the control mix. The volumetric properties of the compacted mixes with RAP are shown in Table 4.6. All properties except air-void content met the design requirements. Due to time and funding constraints, a decision was made to proceed with the preliminary mix tests using this mix design, despite it not meeting the air void target given that general performance trends were unlikely to be significantly affected by this parameter.

Table 4.6: Volumetric Properties of Gap-Graded RHMA Mix with RAP

Mix	Mix Volumetric Properties				Pass?
	Air-Voids (%)	**Voids in Mineral Aggregate (%)**	**Voids Filled with Asphalt (%)**	**Dust Proportion**	
Caltrans specification limits	4	18 – 23	Report only	Report only	
RAP-A @ 10% (RHMA_G_10RAP)	6.6 6.9 Average: 6.8	20.7 21.0 Average: 20.9	68.3 67.3 Average: 67.8	0.46 0.46 Average: 0.46	No

4.3 Fine Aggregate Matrix Mix Design

Previous UCPRC studies *(37,38,40,41)* recommended and used materials passing the 2.36 mm (#8) sieve to prepare FAM mixes. However, initial trials in this current study found that insufficient material of this size could be separated from the mix to design and prepare a representative FAM mix, given the limited quantity of this fraction permitted in gap-graded mixes. There was also concern that the presence of large rubber particles (i.e., maximum size of 2 mm) similar in size to the maximum aggregate size in the mix (i.e., 2.36 mm) could potentially impact the variability of test results.

Based on these limitations, the restriction on maximum permissible aggregate size was relaxed to those passing the 4.75 mm (#4) sieve. Although the larger size was expected to introduce more variability into the test results, successful FAM mix testing with this maximum aggregate size has been reported in the literature *(36)*.

The binder content and aggregate gradations determined for the dense- and gap-graded mixes were used as the basis for the FAM mix design. Only the fine fraction of the R-RAP and RAP materials (passing 2.36 mm [#8]) was used in the preparation of FAM mixes (see Table 3.1). The FAM mix design process included the following steps:

1. Prepare full-graded control HMA and RHMA-G mixes according to AASHTO R 35. The dense-graded mix was prepared at the predetermined optimum binder content of 5.5 percent. Initial trials revealed that fine particles (i.e., passing 4.75 mm) could not be effectively separated from an RHMA-G mix since they agglomerate due to the increased adhesiveness of the asphalt rubber binder. Consequently, a surrogate mix was prepared using the base binder plus the extender oil, but without the addition of any rubber particles. The optimum base binder content was recalculated to be 7.0 percent as follows (Equation 4.1):

$$(\text{Optimum asphalt rubber binder content}) \times (100 - \text{rubber content}) \qquad (4.1)$$

2. Short-term age the loose asphalt mixes for two hours at the predetermined compaction temperatures following AASHTO R 30.

3. Sieve the loose asphalt mixes to obtain representative samples (approximately 1.5 kg) of material passing the selected sieve (i.e., 4.75 mm in this study). Where required, gently tamp the mixes to break up weak agglomerations.
4. Determine the binder contents of the mixes. In this study, the binder contents of the FAM mixes were determined using the ignition oven test (AASHTO T 308) as it was considered to provide a more accurate indication of the total binder content than solvent extraction. For the RHMA-G FAM mix, the required amount of asphalt rubber binder was determined using Equation 4.2.

   (Base binder content of surrogate mix) / (100 - rubber content) (4.2)

   The binder contents of the HMA and RHMA FAM mixes were determined to be 8.3 percent and 11.6 percent by total weight of mix, respectively.
5. Prepare representative samples of fine R-RAP and RAP materials with the required gradation (passing 4.75 mm [#4] in this UCPRC study) and at the respective optimum binder contents.
6. Determine the binder content and gradation of the R-RAP and RAP aggregates by ignition oven or by extraction and recovery. (The extraction method was used in this UCPRC study as it was considered to provide a better estimation of the amount of available binder in the RAP materials that will mobilize and effectively blend with the virgin binder. The ignition method is, however, still considered to be a satisfactory method if solvent extraction is not available.)
7. Determine virgin binder, virgin aggregate, R-RAP, and RAP quantities for selected binder replacement values based on the binder content and aggregate gradations determined in Step 4 and Step 6.

4.4 Specimen Preparation

4.4.1 Fine Aggregate Matrix Mixes

FAM mix specimens were fabricated as follows:

1. Prepare dense- and gap-graded mixes as described in Sections 4.1 and 4.2 with different percentages of R-RAP and RAP based on the required binder replacement rate.
2. Determine the theoretical maximum specific gravity of the FAM mixes (AASHTO T 269).
3. Short-term age the loose mixes by conditioning for four hours at 135°C (275 F) as specified in AASHTO R 30.
4. Heat the loose mixes to the required compaction temperature and then compact them in a gyratory compactor (as described for full-graded mixes) to fabricate specimens 150 mm in diameter and 50 mm high with between 10 and 13 percent target air-void contents.
5. Extrude the specimens from the molds.
6. Core 12.5 mm specimens from the dense-graded gyratory specimens. Cut 10 mm × 10 mm specimens from the gap-graded gyratory specimens (note that mixes containing asphalt rubber binder cannot be cored due to rubber build-up on the core bit). Examples of the FAM mix specimens are shown in Figure 4.1 and Figure 4.2.
7. Determine the air-void content of the cored/sawn specimens by first determining the saturated surface-dry specific gravity (AASHTO T 166A) and then calculate the air-void contents with these values and the previously measured theoretical maximum specific gravity (Step 2).

8. Dry the FAM specimens and store them in a sealed container to prevent damage and excessive shelf-aging prior to testing.

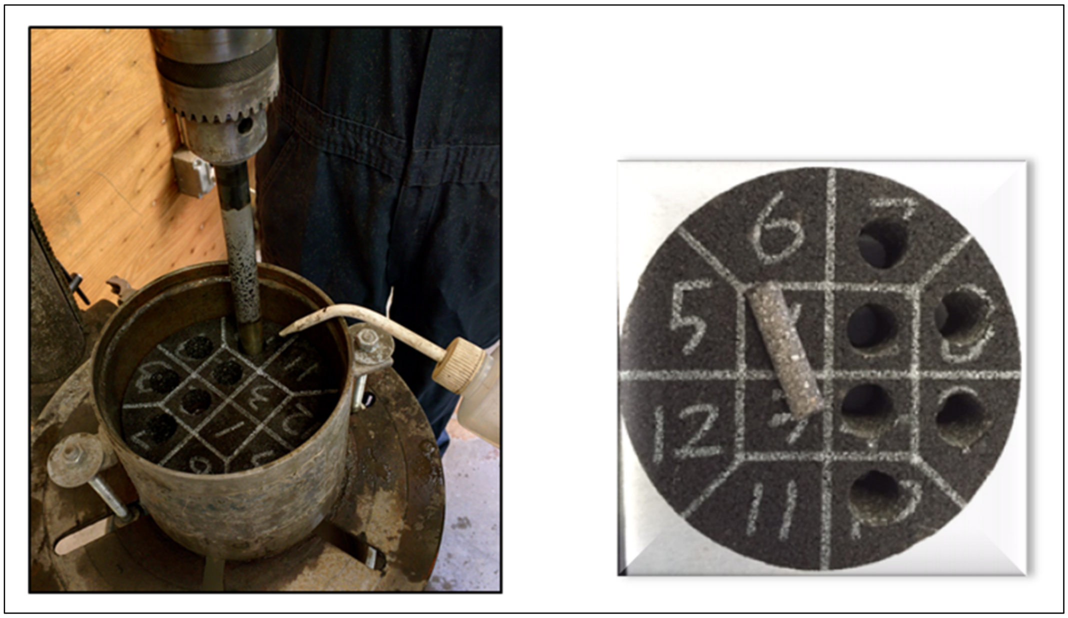

Figure 4.1: Cored FAM mix specimens (conventional binder).

Figure 4.2: Cut FAM mix specimens (asphalt rubber binder).

4.4.2 Full-Graded Mixes for Performance-Related Testing

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

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5. TEST RESULTS: PHASE 1a: ASPHALT BINDER RHEOLOGY

5.1 Experiment Plan

5.1.1 Materials

Table 5.1 lists the asphalt binders tested in Phase 1a. The methods for preparation of the asphalt rubber binder, and the simulated RAP and R-RAP binders are provided in Section 3.1.

Table 5.1: Asphalt Binders Evaluated in Phase 1a

Asphalt Binder	Mix Identification	Simulated RAP Content (%)	Simulated R-RAP Content (%)	Aging Conditions
Conventional	Conv.	0	0	Unaged, RTFO[1]-aged, and RTFO+PAV-aged
Asphalt rubber	AR	0	0	
Conventional + RAP	Conv. + RAP	15, 25, 40, 100	0	
Conventional + R-RAP	Conv. + RRAP	0	15, 25, 40, 100	
Asphalt rubber + RAP	AR + RAP	15, 25, 40, 100	0	

[1] RTFO = Rolling thin-film oven

5.1.2 Asphalt Binder Testing

The following tests were performed to characterize the rheological and performance-related properties of asphalt binders:

- Rotational viscosity testing to determine pumpability and workability of the binders
- High temperature performance grade determination (DSR)
- Multiple stress creep recovery (MSCR) determination to assess rutting performance (DSR)
- Complex shear modulus testing to determine the linear viscoelastic properties (DSR)
- Low-temperature performance grade (BBR) determination

Adjustments for Testing Asphalt Rubber Binder

According to AASHTO T 315, asphalt binders containing particulates can be tested in a DSR with parallel plate geometry provided that the largest particle size is a minimum of one fourth of the gap distance between the plates. This eliminates any dominating effects of the particles on the rheological measurements. The asphalt rubber binders used in this study contained rubber particles as large as 2.0 mm and thus determining the rheological properties using parallel plate geometry would theoretically require an 8.0 mm gap, which is not practical.

Earlier research *(79,80)* undertaken at the UCPRC showed that the concentric cylinder geometry (or cup and bob [Figure 5.1]) is a more appropriate method of measuring the rheological properties of asphalt rubber binder. This geometry provides a large gap (6.0 mm) that is more suited to testing binders with relatively large particulates. The UCPRC study compared concentric cylinder and parallel plate geometries for testing conventional, polymer-modified, and terminal-blended rubber binders with particles smaller than 150 µm. The results showed similar rheological measurements and repeatability from the two methods. When testing asphalt rubber binders with particle sizes up to 2.0 mm, the study showed that results started to differ when the particle size increased above 250 µm (i.e., equal to one quarter of the parallel plate gap size), consistent with the discussion in AASHTO T 315. Based on these findings, the concentric cylinder geometry was used in this UCPRC study to measure viscosity, determine performance grade, evaluate rutting performance, and to perform frequency sweeps of the composite binders containing unaged or age-hardened asphalt rubber binder.

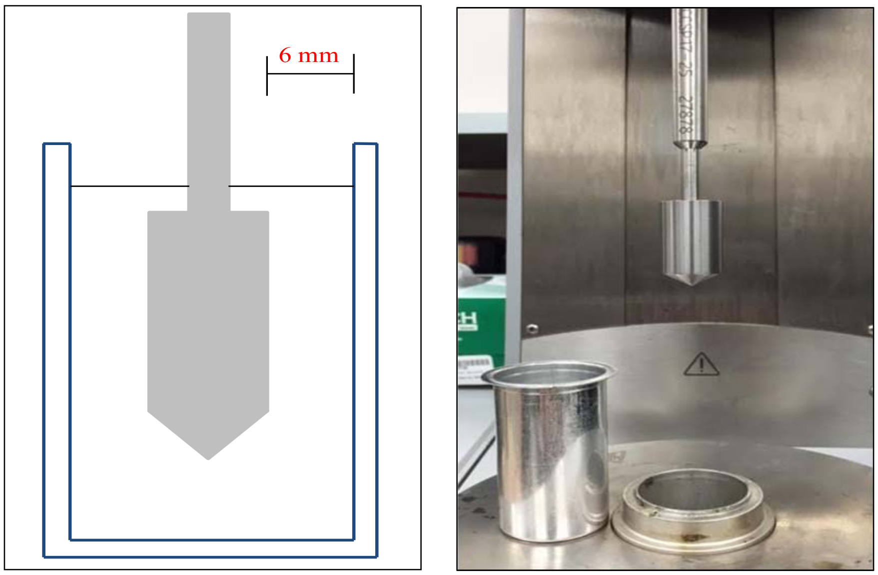

Figure 5.1: Concentric cylinder geometry.

When using the concentric cylinder geometry with a 6.0 mm gap, correction factors must be used to calculate the stress or strain response of materials under the applied strain or stress. The stress- and strain-related correction factors used in this study were recommended by the DSR manufacturer, and were determined by testing a standard fluid with properties similar to typical paving grade asphalt binders.

Determining the performance grade and rheological properties at intermediate temperatures of asphalt binders containing large rubber particles could not be performed since this test requires a modified version of the concentric cylinder geometry (10 mm diameter spindle diameter), which is still under development by the DSR manufacturer and was being tested by the UCPRC at the time of writing this report.

A prototype mold developed by the UCPRC study was used to cast asphalt rubber binder beams that can be tested in a BBR (Figure 5.2). The dimensions of this modified BBR beam are the same as a standard beam (6.25 × 12.5 × 127 mm [0.25 × 0.49 × 5.0 in.]), but the mold is assembled in a different orientation to provide a wider opening (12.5 mm instead of 6.25 mm) to facilitate pouring the more viscous binder and to obtain a uniform beam with regular shape and without trapped air bubbles.

Figure 5.2: Prototype BBR mold for testing asphalt rubber binder.

In previous UCPRC studies *(79,80)*, it was noted that the asphalt rubber binder, which is considerably more viscous than conventional binders, did not coat the entire rolling thin-film oven (RTFO) bottle after completion of the test (Figure 5.3). Segregation of asphalt rubber binders was also observed after PAV aging, with excess crumb rubber remaining in the middle of the pan, and the base asphalt binder drained to the edge of the pan (Figure 5.4). Consequently, it was concluded that RTFO and PAV aging of asphalt rubber binder might not be as effective as aging of conventional binder with this equipment, test configurations, and test parameters, and this was taken into consideration during analysis of the results. Modifications to the RTFO and PAV testing procedures to compensate for these issues are currently being investigated at the UCPRC in a separate study.

Figure 5.3: RTFO-aged sample.

Figure 5.4: PAV-aged sample.

5.2 Test Results for Control Asphalt Binders

The properties of the control conventional binder and the laboratory-prepared asphalt rubber binder are summarized in Table 5.2. In this phase of testing, comparisons were not made with plant-produced asphalt rubber binders (already undertaken in previous UCPRC studies); instead the focus was on ensuring that the preparation process was consistent for all binder samples. The performance grades of the extracted and recovered RAP binders from the R-RAP and RAP materials were also measured in accordance with the National Cooperative Highway Research Program (NCHRP) recommended procedure *(5)* and the results are listed in Table 5.3 (note that PAV aging is not recommended for RAP binders in the NCHRP procedure). Creep stiffness and m-value could not be determined for the conventional RAP and Source-B R-RAP binders as the stiffness of these binders exceeded the limits of the equipment at temperatures below 0°C (the BBR test should be performed at a temperature 10°C higher than the low PG temperature of the binder). The low PG grades of the RAP and R-RAP binders from Source-B were therefore reported as >-10°C. The recovered binder from R-RAP Source-A was softer than the recovered binder from Source-B. This was attributed to known contamination of the R-RAP with conventional RAP from the underlying layer during the milling operation.

Table 5.2: Control Binder Properties

Test Parameter	AASHTO Test Method	Binder Type	
		Control/Base Binder	Asphalt Rubber Binder
		Unaged	
Viscosity (PaS)	T 316	0.47	12.1
True PG temperature (°C)	T 315	68.6	92.3
G*/sin(δ) @ 64°C (kPa)	T 315	1.77	12.4
		RTFO-Aged	
True PG temperature (°C)	T 315	69.2	91.2
G*/sin(δ) @ 64°C (kPa)	T 315	4.32	23.3
		PAV-Aged	
Creep Stiffness @ -6°C (MPa)	T 313	100.0	N/A
m-value @ -6 °C	T 313	0.393	N/A
Creep Stiffness @ -12°C (MPa)	T 313	N/A	52.6
m-value @ -12°C	T 313	N/A	0.366

Table 5.3: Extracted R-RAP and RAP Binder Properties

Test Parameter	Binder Type				
	R-RAP Source-A		R-RAP Source-B		RAP
	≥2.36 mm	<2.36 mm	≥2.36 mm	<2.36 mm	
	Unaged				
True high PG temperature (°C)	72.2	78.2	102.9	98.4	106
G*/sin(δ) (kPa)	1.3 @ 70°C	1.3 @ 76°C	1.4 @ 100°C	1.2 @ 94°C	1.0 @ 106°C
	RTFO-Aged				
True high PG temperature (°C)	75.4	78.3	103.9	98.3	108
G*/sin(δ) (kPa)	4.3 @ 70°C	2.9 @ 76°C	3.5 @ 100°C	3.7 @ 94°C	2.8 @ 106°C
Intermediate PG temperature (°C)	22.2	24.1	47.3	41.8	48.3
True low PG temperature (°C)	-26.2	-26.9	> -10	>-10	>-10
Creep Stiffness @ -12°C (MPa)	155	199	Too stiff[1]	Too stiff[1]	Too stiff[1]
m-value @ -12°C	0.361	0.334	Too stiff[1]	Too stiff[1]	Too stiff[1]

[1] Binder was too stiff to test at temperatures below 0°C.

5.3 Test Results for Blended Binders

5.3.1 Viscosity

The viscosity of unaged binders containing different percentages of age-hardened binders from RAP was determined at 135°C (275°F) and 20 rpm using the concentric cylinder geometry in a DSR discussed in Section 5.1.2. Test results are shown in Figure 5.5. The following observations were made:

- Modification of asphalt binder with crumb rubber significantly increased the viscosity of the binder (i.e., more than 25 times), as expected.
- Aging both the conventional and asphalt rubber binders in a PAV for 40 hours at 100°C increased their viscosities by about 4 and 1.5 times respectively, compared to the unaged binders. This observation revealed the positive effect of crumb rubber in reducing the aging potential of the binder since the same PG 64-16 conventional binder was used as the base for the asphalt rubber binder. However, further study is required to exclude the possible influence of the extender oil on this result.
- Replacing 15, 25, and 40 percent of the conventional binder with RAP binder increased the binder viscosity, by 22, 33, and 68 percent, respectively, above that of the conventional binder with no RAP.
- Replacing conventional binder with R-RAP binder also increased the binder viscosity. The viscosities of composite binders containing 15, 25, and 40 percent R-RAP were approximately 1.5, 2.0, and 3.5 times the viscosity of the conventional binder with no R-RAP.
- Replacing 15, 25, and 40 percent of the asphalt rubber binder with RAP binder decreased the viscosity of the asphalt rubber binder by approximately 27, 40, and 56 percent, respectively.
- The change in the viscosity of unaged binders that results from adding age-hardened binder can be modeled using increasing or decreasing exponential functions as shown in Figure 5.5.

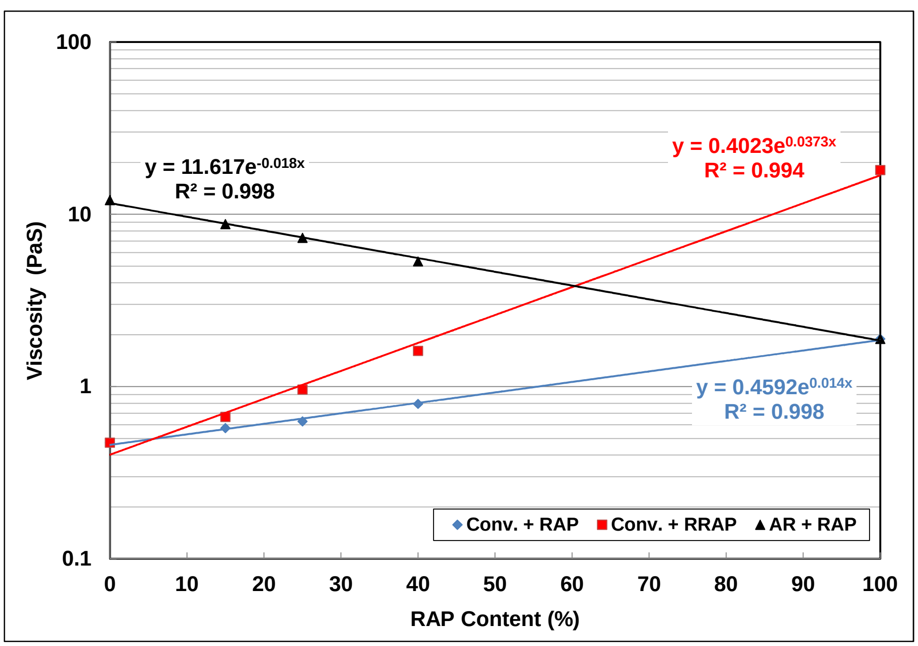

Figure 5.5: Viscosity of unaged composite binders (135°C).

5.3.2 High Performance Grade Limit

The high performance grade (PG) limit of the unaged binders and RTFO-aged binders are shown in Figure 5.6 and Figure 5.7, respectively.

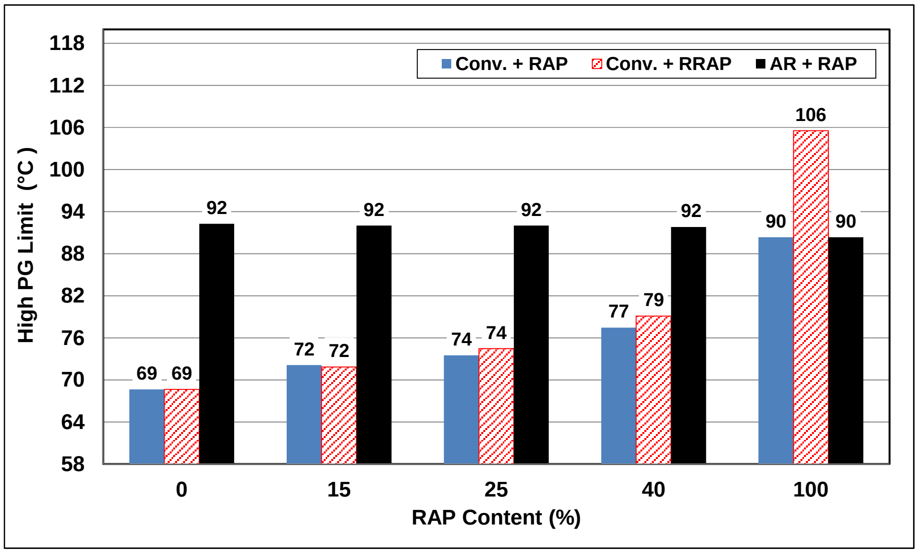

Figure 5.6: High PG limit of unaged binders.

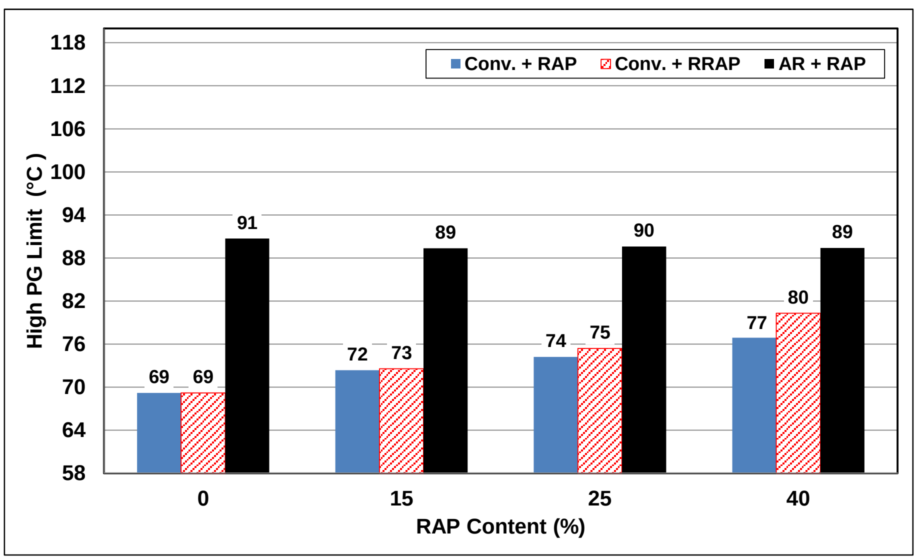

Figure 5.7: High PG limit of RTFO-aged binders.

The following observations were made:

- Extended long-term aging of conventional and asphalt rubber binder in a PAV increased the high PG limit of the conventional binder by about 21°C and the high PG limit of the asphalt rubber binder by about 14°C. This confirmed the findings from viscosity measurements that the rubber modification (including extender oil) could considerably reduce the aging potential of asphalt binders.

- Replacing 15, 25, and 40 percent of the conventional binder with RAP binder increased the high PG limit of the binder by 3°C, 5°C, and 8°C, respectively, compared to the control. Similar results were obtained when replacing 15, 25, and 40 percent of conventional binder with R-RAP binder. These results were expected given that the unaged asphalt rubber binders and simulated RAP binders had similar high PG limits. However, this observation could be limited to the types of materials tested in this study.
- Replacing 15, 25, and 40 percent of asphalt rubber binder with RAP binder had little effect on the high PG limit.
- Consistent results were obtained for both the unaged and RTFO-aged binders.

5.3.3 Rheological and Performance-Related Properties at High In-Service Temperatures

Complex Shear Modulus and Phase Angle

The complex shear modulus (G*) and phase angle (δ) of the composite unaged and RTFO-aged binders at 64°C are shown in Figure 5.8 through Figure 5.11. The following observations were made:

- For all the composite binders evaluated, complex shear modulus increased exponentially with increasing amounts of RAP or R-RAP binder, as expected. The rate of increase was relatively the same for the two, which implies that the aged base binder and the aged rubber particles had similar stiffness values. For the asphalt rubber binder, the complex shear modulus increased with increasing amounts of RAP but at a slower rate compared to the conventional binder with RAP or R-RAP binder.
- The phase angle of the conventional binder decreased with increasing amounts of RAP or R-RAP, but the rate of decrease was much faster in the binder containing R-RAP. This was attributed to the presence of the residual crumb rubber particles in the R-RAP, which appear to have added some elasticity to the base binder.
- The complex shear modulus of the asphalt rubber binder with RAP increased with increasing amounts of RAP, but at a slower rate than that of the conventional binder with RAP or R-RAP binders. The phase angle of the asphalt rubber binder also increased marginally with increasing RAP binder content.
- The complex shear modulus and phase angle followed similar trends for both unaged and RTFO-aged binders.

Frequency Sweep

Frequency sweep tests were conducted to understand the linear viscoelastic behavior of composite binders containing simulated RAP or R-RAP binders. Tests were performed at 64°C over a range of frequencies from 0.1 to 100 rad/sec. Figure 5.12 through Figure 5.14 show the relationship between complex shear modulus and phase angle for unaged conventional binders with RAP binder, unaged conventional binders with R-RAP binder, and asphalt rubber binder with RAP binder, respectively. The following observations were made:

- For the conventional binder, the complex shear modulus increased and the phase angle decreased with increasing RAP and R-RAP content.

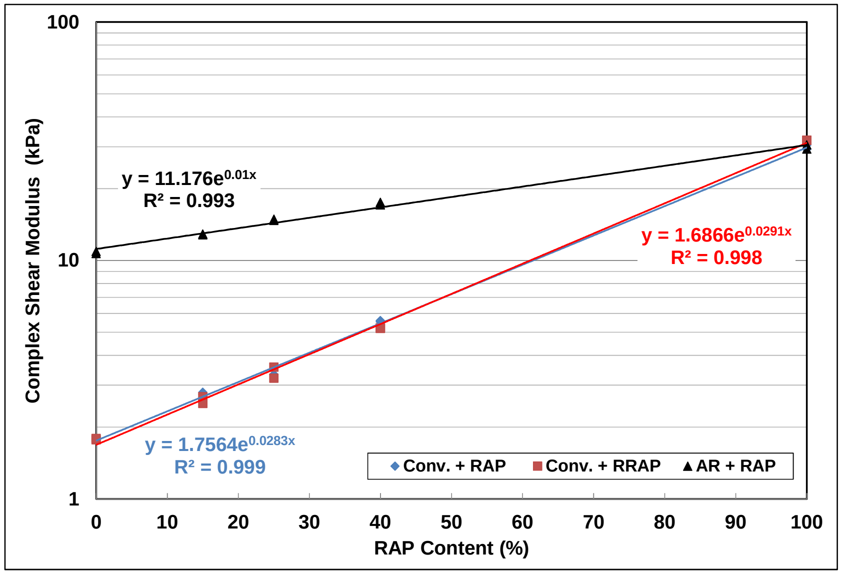

Figure 5.8: Complex shear modulus of unaged binders (64°C).

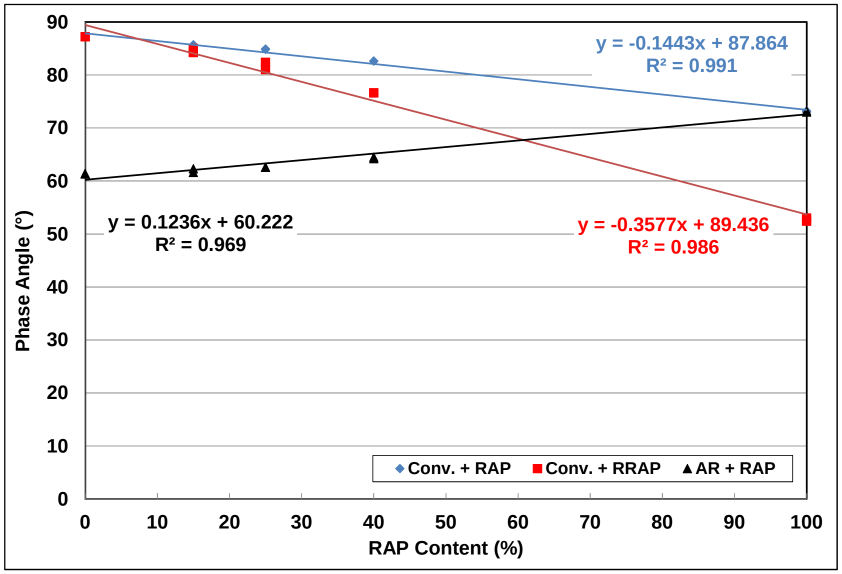

Figure 5.9: Phase angle of unaged binders (64°C).

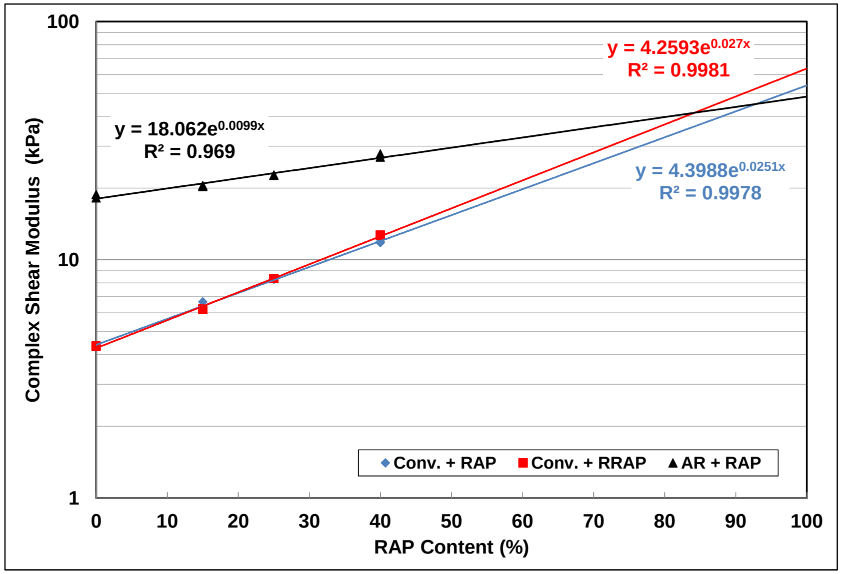

Figure 5.10: Complex shear modulus of RTFO-aged binders (64°C).

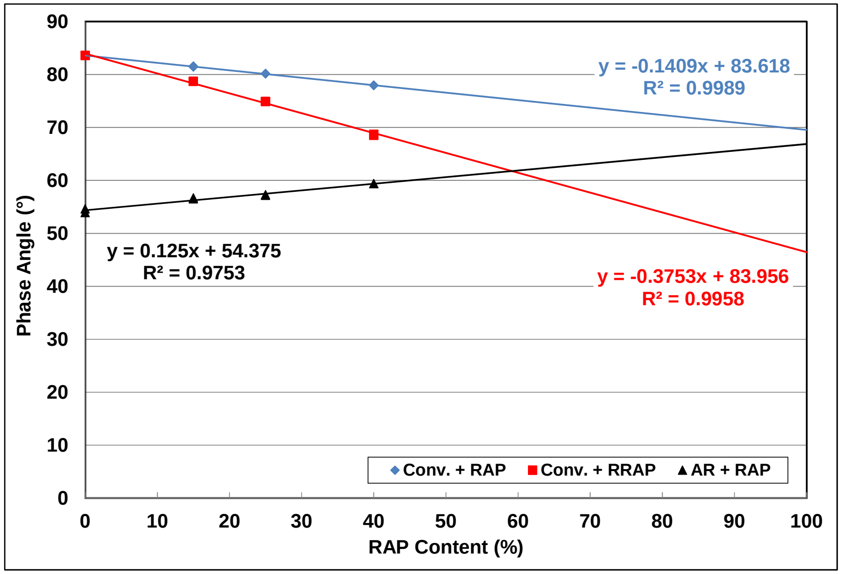

Figure 5.11: Phase angle of RTFO-aged binders (64°C).

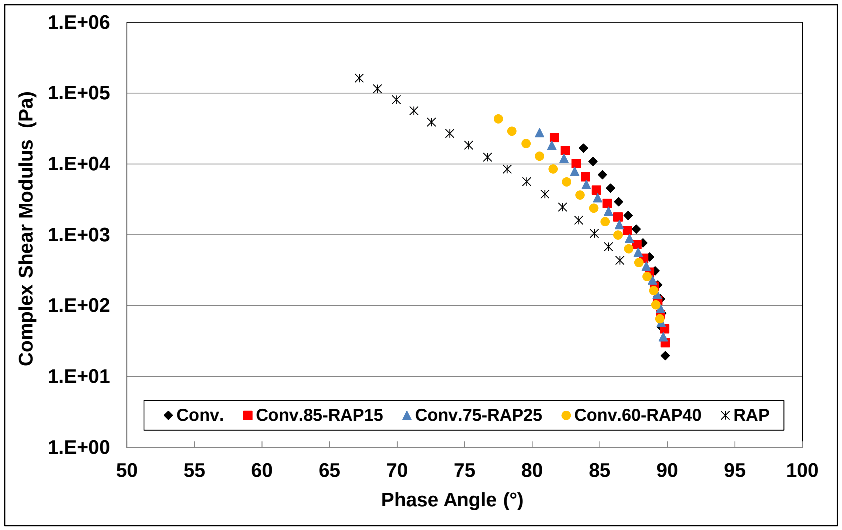

Figure 5.12: Black diagram of shear moduli of blended conventional and RAP binders (64°C).

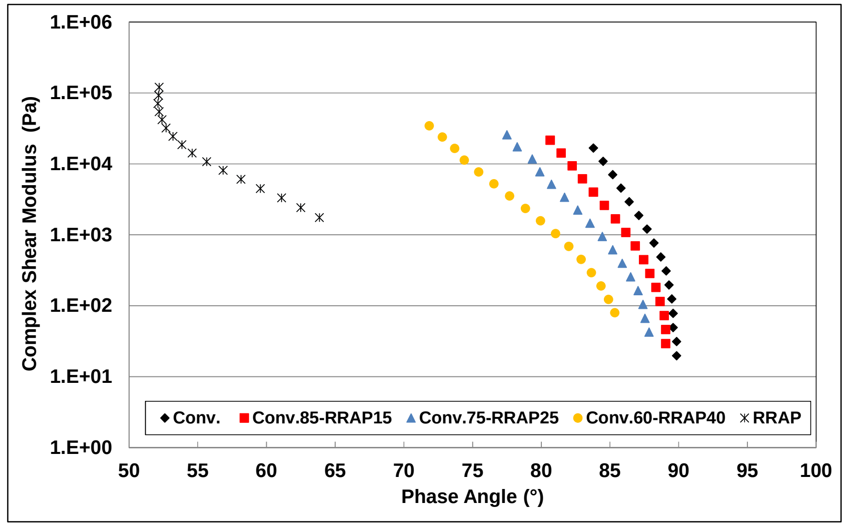

Figure 5.13: Black diagram of shear moduli of blended conventional and R-RAP binders (64°C).

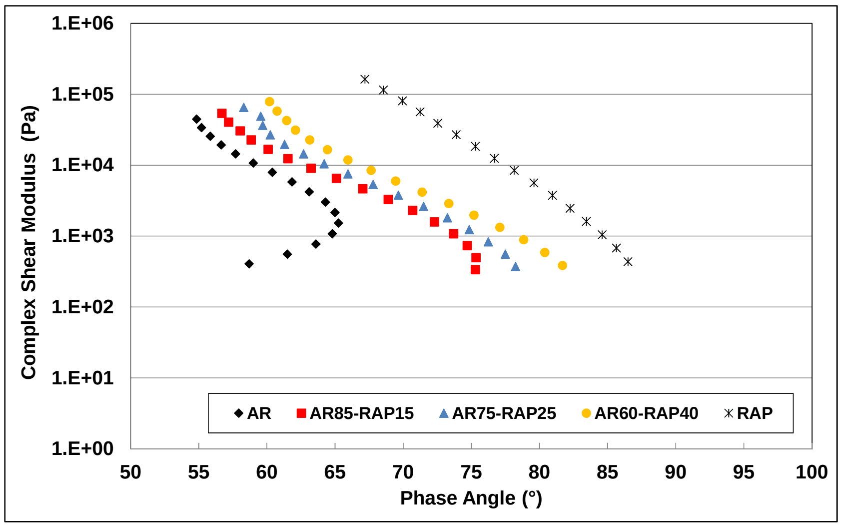

Figure 5.14: Black diagram of shear moduli of blended asphalt rubber and RAP binders (64°C).

- The complex shear moduli of the conventional binder with RAP binder and with R-RAP binder were similar across the different frequencies; however, the phase angle of the conventional binder with R-RAP binder was smaller than that of the conventional binder with RAP binder. This was attributed to the dominating elastic behavior of the rubber particles in the R-RAP binder.
- The bell-shaped shear modulus/phase angle curve for the asphalt rubber binder (Figure 5.14) clearly shows the viscoelastic solid behavior influenced by the presence of the rubber particles. However, when the stiffer RAP binder was added, the RAP properties dominated those of the rubber, resulting in the composite binder tending to behave more toward a viscoelastic liquid material, with the shear modulus/phase angle curve shifting to the right and gradually eliminating the bell-shape trend.

Multiple Stress Creep Recovery

MSCR tests were conducted on the RTFO-aged binders to evaluate rutting resistance properties. The test results recorded at 64°C under a 3.2 kPa stress level are shown in Figure 5.15 (average percent recovery versus recoverable creep compliance), Figure 5.16 (average percent recovery versus RAP content) and Figure 5.17 (recoverable creep compliance versus RAP content). The following observations were made:

- For the conventional binder with simulated RAP or R-RAP binder, the average percent recovery (APR) increased with increasing RAP or R-RAP content, and the recoverable creep compliance (J_{nr}) values decreased with increasing RAP or R-RAP content, as expected.
- Incorporating both RAP and R-RAP into the conventional binder improved its rutting resistance properties, with the R-RAP binder blend showing the best performance.
- The rate of increase in average percent recovery and decrease in recoverable creep compliance with R-RAP content were higher compared to the RAP binder. This was attributed to the presence of rubber particles in the R-RAP binder.
- The average percent recovery of the asphalt rubber binder decreased slightly with increasing RAP binder content, but the recoverable creep compliance barely changed. Consequently, the addition of RAP to the asphalt rubber binder did not cause any significant changes to rutting behavior.

Flexural Creep Stiffness at Low Temperature

Composite binders with different quantities of RAP and R-RAP binders were aged in a PAV for 20 hours at 100°C and then tested with a bending beam rheometer (BBR) to determine the low-temperature properties. The BBR tests were performed at -6°C since the low PG grade of the base binder was -16°C. The measured creep stiffness (S) and m-value are shown in Figure 5.18 and Figure 5.19, respectively. The following observations were made:

- In general, creep stiffness and m-value for all evaluated composite binders with different percentages of RAP and R-RAP binder replacement were lower than 300 MPa and higher than 0.30, respectively. This implies that adding simulated RAP or R-RAP binder did not adversely affect the low PG grade of the base binder.

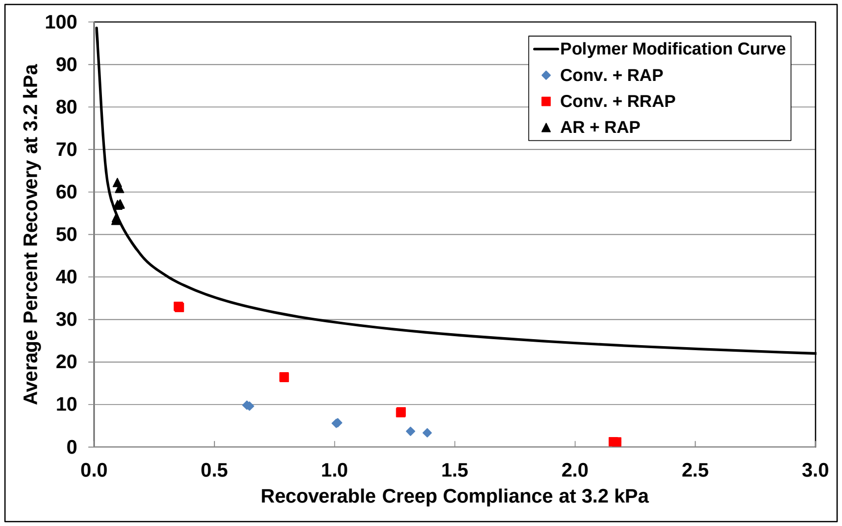

Figure 5.15: MSCR test results of RTFO-aged binders (64°C).

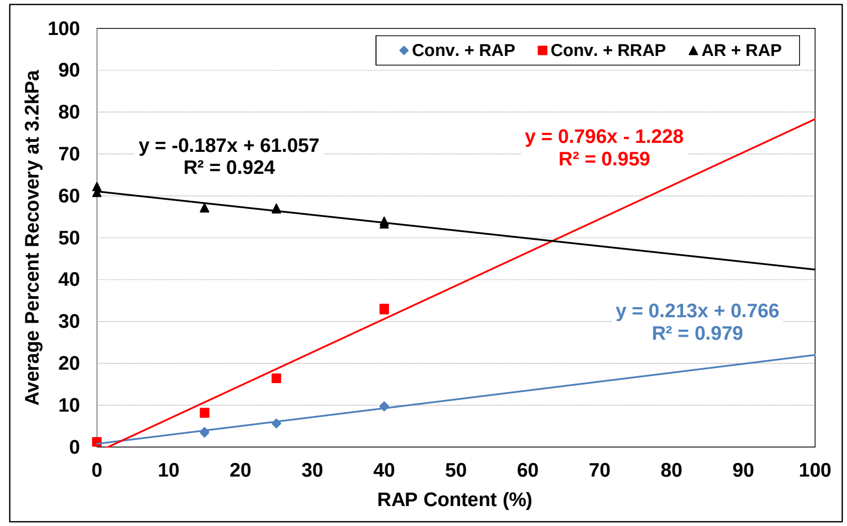

Figure 5.16: Average percent recovery for RTFO-aged composite binders (64°C and 3.2 kPa).

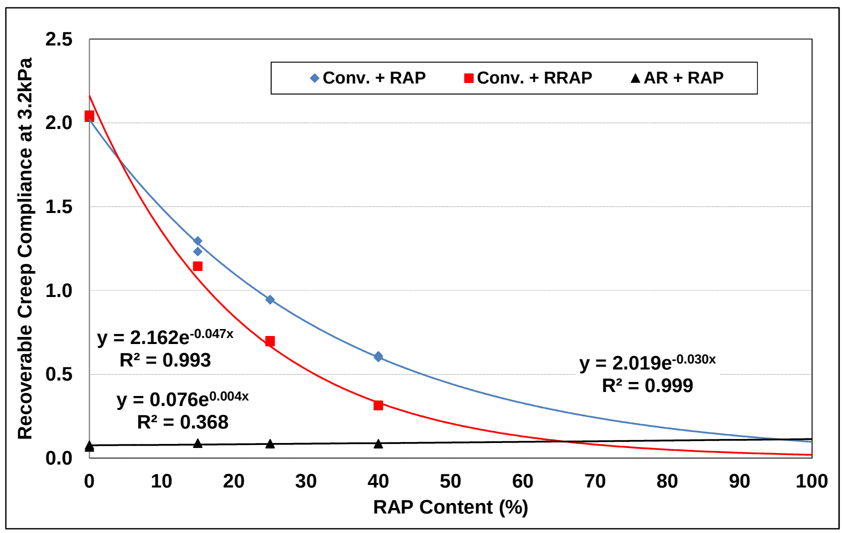

Figure 5.17: Recoverable creep compliance for RTFO-aged composite binders (64°C and 3.2 kPa).

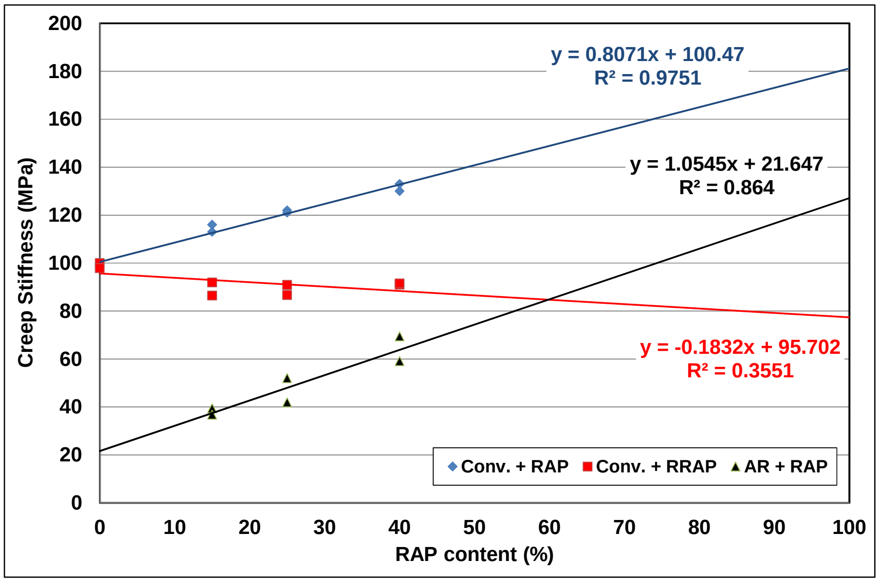

Figure 5.18: Creep stiffness of PAV-aged composite binders (-6°C).

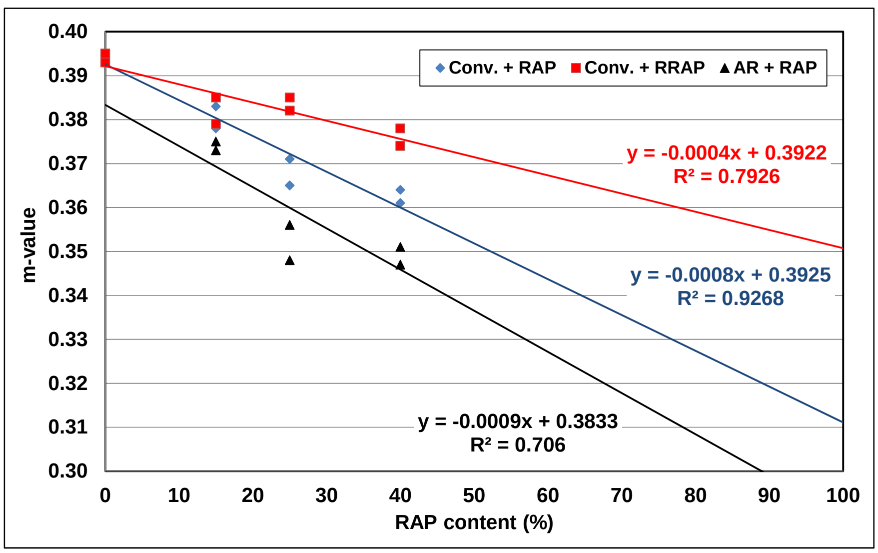

Figure 5.19: M-value of PAV-aged composite binders (-6°C).

- Replacing 15, 25, and 40 percent of the conventional binder with RAP binder increased the creep stiffness by about 15, 20, and 30 percent, respectively, and decreased the m-value by about 3, 7, and 8 percent, respectively, compared to the control.
- Incorporating up to 40 percent R-RAP into the conventional binder reduced the creep stiffness by about 10 percent and the m-value by about 5 percent.
- The creep stiffness and m-value of the asphalt rubber binder could not be measured at -6°C since the binder was too soft at this temperature and the creep deflection was beyond the acceptable limit that could be measured and recorded by the test setup.
- The asphalt rubber binder creep stiffness increased and the m-value decreased with increasing simulated RAP content.

- In general, adding RAP or R-RAP to conventional binder had a negative effect on low-temperature cracking resistance (by reducing the m-value). R-RAP had a lesser effect compared to RAP.

5.4 Phase 1a Test Summary

Three composite binders (i.e., conventional binder [PG 64-16] with RAP binder, conventional binder with R-RAP binder, and asphalt rubber binder with RAP binder) were characterized for viscosity and performance properties at high and low in-service temperatures using a DSR and BBR. The composite binders contained 15, 20, and 40 percent age-hardened binder (RAP or R-RAP) by binder replacement. The simulated RAP and R-RAP binders were produced in the laboratory by aging conventional and asphalt rubber binders for 40 hours in a PAV at 100°C and under 2.1 MPa air pressure. The following conclusions were drawn from the test results:

- The concentric cylinder geometry used on the DSR was able to effectively capture the changes in the rheological properties of composite binders containing RAP and R-RAP.
- Rubber modification appeared to reduce the aging susceptibility of asphalt binders in that less change was observed in their rheological properties than the rheology changes of the base binder after extended PAV aging for 40 hours at 100°C.
- The age-hardened asphalt rubber binder (R-RAP) was less temperature susceptible than the age-hardened conventional binder (RAP). At 64°C, the RAP and R-RAP binders had approximately the same stiffness; however, with an increase in temperature, the high PG limit of the R-RAP binder was 15°C higher than that of the RAP binder. The viscosity of the R-RAP binder (at 135°C) was 10 times higher than that of the RAP binder.
- Blending simulated RAP binder with conventional binder increased the viscosity (at 135°C) and stiffness of the composite binder at both high and low in-service temperatures. It also reduced the relaxation potential of the binder at low temperature, which was indicated by a reduction in m-value. In addition, the average percent recovery and the recoverable creep compliance of conventional asphalt binder decreased when RAP binder was added.
- Adding R-RAP binder to conventional binder increased the viscosity (at 135°C) and stiffness at high temperatures, which implies that these mixes could be less workable and more difficult to compact, but could have better rutting performance. At low temperatures (i.e., -6°C) the added R-RAP binder caused small reductions in the creep stiffness and relaxation potential (m-value), which implies that the R-RAP would have a limited effect on low-temperature cracking. The average percent recovery of the composite binder increased (indicating improved rutting performance) and the recoverable creep compliance decreased (indicating diminished cracking performance) with increasing R-RAP content.
- Adding simulated RAP binder to asphalt rubber binder reduced its viscosity, but barely changed the high PG grade, indicating no adverse impact to workability or rutting performance. At the low test temperature, the creep stiffness of the asphalt rubber binder increased and the m-value decreased with increasing RAP content, which indicates an increased potential for thermal cracking. The effect of RAP content on average percent recovery and recoverable creep compliance of asphalt rubber binders was minimal.

These results provide an initial indication that:

- Inclusion of R-RAP in conventional mixes will generally result in improved all-round performance at both high and low temperatures.
- Inclusion of RAP in asphalt rubber mixes will potentially negatively affect low-temperature performance, but will likely have limited effect on high-temperature performance.

6. TEST RESULTS: PHASE 1b: FINE AGGREGATE MATRIX MIX

6.1 Experiment Plan

6.1.1 Materials

Table 6.1 lists the fine aggregate matrix (FAM) mixes evaluated in this UCPRC study. The FAM mix design and specimen fabrication procedures were explained in Chapter 4.

Table 6.1: FAM Mixes Evaluated in Phase 1b

Mix Type	RAP Content (%)	RAP Source	Mix Identification
R-RAP in dense-graded HMA mix	0	Not applicable	FAM_HMA_Cont
	15 25	Laboratory-prepared (LP)	FAM_HMA_15RRAP_LP FAM_HMA_25RRAP_LP
	15 25	Road Source-A	FAM_HMA_15RRAP_A FAM_HMA_25RRAP_A
	15 25	Road Source-B	FAM_HMA_15RRAP_B FAM_HMA_25RRAP_B
RAP in gap-graded RHMA mix	0	Not applicable	FAM_RHMAG_Cont
	10 15	Laboratory-prepared (LP)	FAM_RHMAG_10RAP_LP FAM_RHMAG_15RAP_LP
	10	Asphalt plant (PS)	FAM_RHMAG_10RAP_PS

6.1.2 Equipment Configuration and Setup

FAM specimens were tested using a solid torsion bar fixture in an Anton Paar MCR302 dynamic shear rheometer (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 *(10-12,36)*, 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, and based on those results and discussions with the DSR manufacturer, this approach was not pursued given 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 6.1 shows the fixed specimen in the DSR-DMA used in this project

6.1.3 Frequency Sweep Tests

Frequency sweep tests measured the complex shear modulus at 0.002 percent strain for a range of frequencies (0.1 Hz to 25 Hz) at three different temperatures (4°C, 20°C, and 40°C). The 0.002 percent strain was selected, based on the results from a previous UCPRC study *(37,38,40)*, to ensure that the material was in the linear viscoelastic region. In that previous study, amplitude sweep tests were performed on FAM specimens to determine the linear viscoelastic range of material behavior. The shear modulus of each FAM specimen was measured at 4°C and a frequency of 10 Hz when the shear strain increased from 0.001 to 0.1 percent incrementally. The linear viscoelastic strain limit was determined as the strain at which the measured stiffness differed from the initial stiffness by five percent, when measured at 0.001 percent strain.

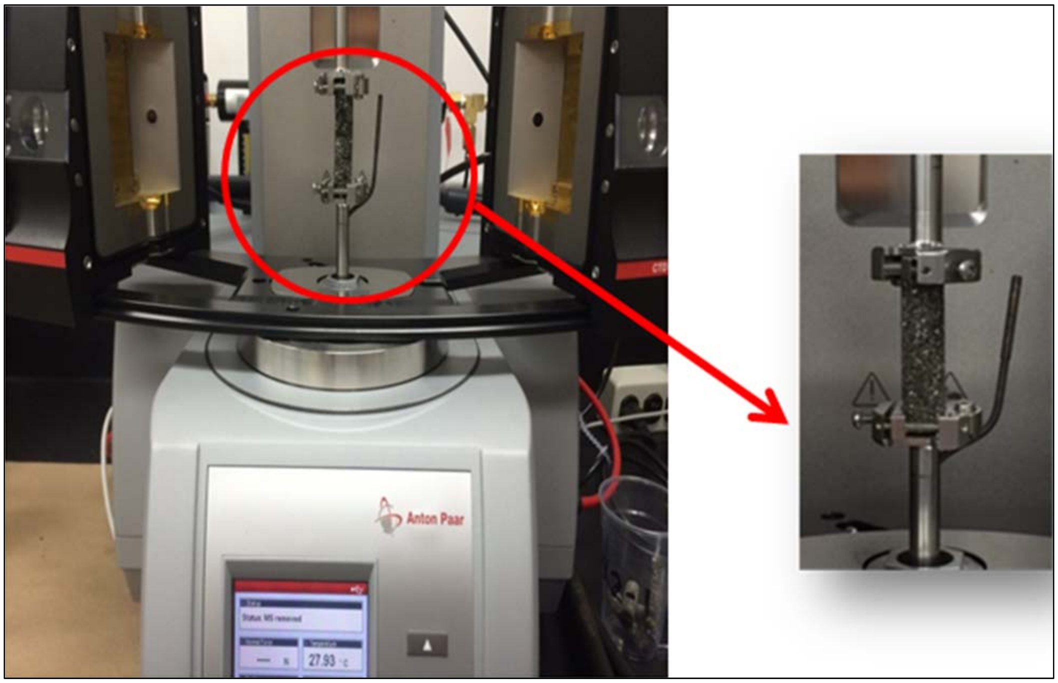

Figure 6.1: DSR-DMA torsion bar fixture used for FAM testing.

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 measured complex shear modulus values (G*) were used to construct asphalt binder master curves at the reference temperature (20°C) by fitting the data to the sigmoidal function shown in Equation 6.1. The testing frequencies at any testing temperature were converted to the reduced frequency at the reference temperature using the time-temperature superposition principle (Equation 6.2) with the aid of an Arrhenius shift factor (Equation 6.3).

$$log(|G^*(f_r)|) = \delta + \frac{\alpha}{1+e^{\beta+\gamma\times log(f_r)}} \quad \textbf{(6.1)}$$

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

$$log(f_r) = log\big(a_T(T)\big) + log(f) \quad \textbf{(6.2)}$$

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

$$\log(a_T(T)) = \frac{E_a}{Ln(10)\times R}\left(\frac{1}{T} - \frac{1}{T_r}\right) \quad \textbf{(6.3)}$$

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

The parameters of the sigmoidal function as well as the activation energy term in the Arrhenius shift factor equation were estimated using the *Solver* feature in *Microsoft Excel*® by minimizing the sum of square error between predicted and measured values. Examples of the measured shear modulus and the corresponding master curve at 20°C for a FAM mix are shown in Figure 6.2 and Figure 6.3, respectively.

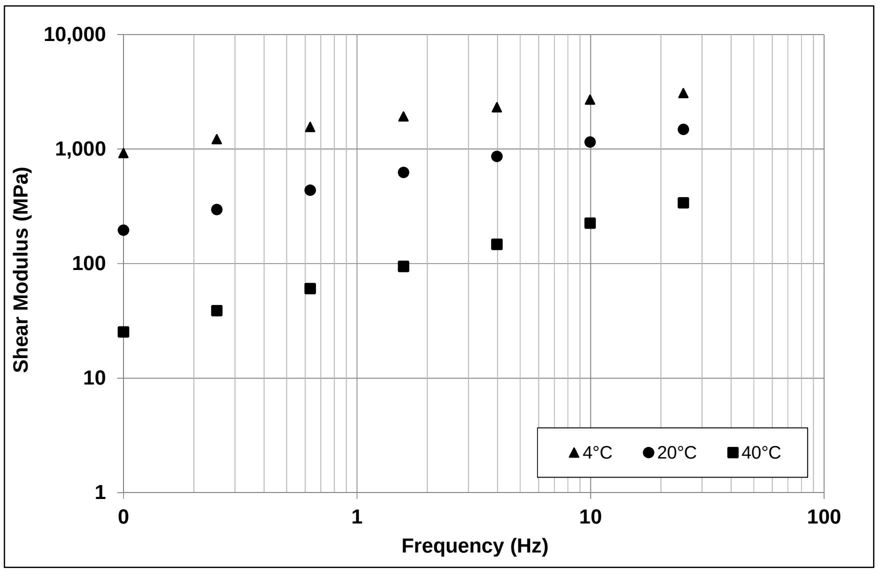

Figure 6.2: Example of measured shear modulus of a FAM specimen at 20°C.

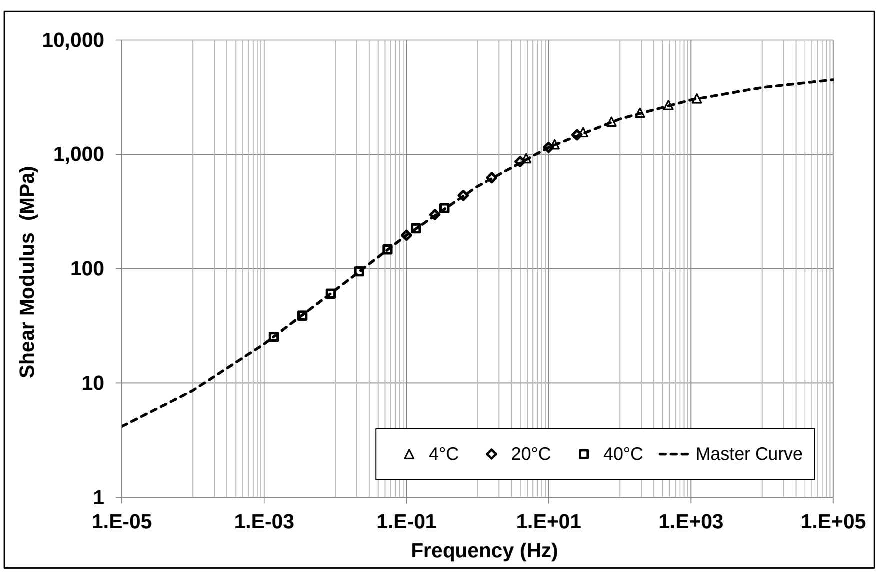

Figure 6.3: Example of a shear modulus master curve of a FAM specimen at 20°C.

6.2 Test Results

6.2.1 FAM Specimen Air-Void Content

Figure 6.4 and Figure 6.5 show the air-void contents measured on the seven dense-graded HMA and four gap-graded RHMA specimens, respectively. The air-void contents ranged between 10 and 12 percent, which was within the target range and considered acceptable for this study. The influence of air-void content (within an acceptable range) was negligible on the FAM test results since the mixes were tested at very low strain levels, which generally only quantifies the properties of the asphalt binder and not the aggregate skeleton.

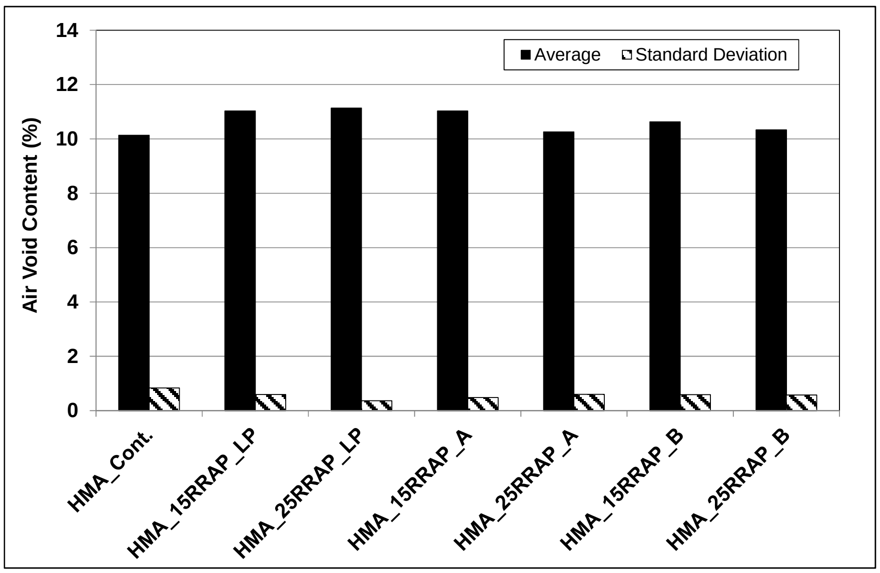

Figure 6.4: Air-void contents of dense-graded HMA FAM mix specimens.

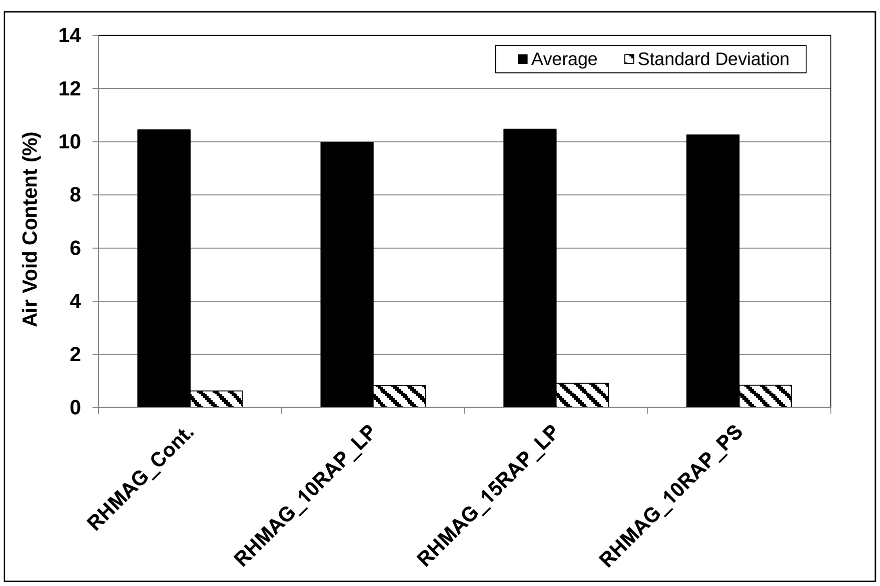

Figure 6.5: Air-void contents of gap-graded RHMA FAM mix specimens.

6.2.2 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 6.1) and activation energy in terms of the Arrhenius shift factor (Equation 6.3) for the FAM mixes are provided in Table 6.2.

Table 6.2: Phase 1b Master Curve Parameters

Mix Type	RAP Source	RAP Content (%)	Mix Identification	Master Curve Parameters				
				δ (kPa)	α	β	γ	Ea (kJ/mol)
Dense-graded HMA	NA	0	FAM_HMA_Cont	2.41	4.45	-0.65	-0.46	210,549
	Lab-prepared	15	FAM_HMA_15RRAP_LP	1.26	6.24	-0.90	-0.30	215,276
		25	FAM_HMA_25RRAP_LP	0.71	6.55	-1.17	-0.30	227,087
	Road-A	15	FAM_HMA_15RRAP_A	1.92	5.73	-0.68	-0.31	219,547
		25	FAM_HMA_25RRAP_A	4.11	3.24	-0.41	-0.40	221,519
	Road-B	15	FAM_HMA_15RRAP_B	1.39	5.90	-1.06	-0.31	220,764
		25	FAM_HMA_25RRAP_B	2.37	4.67	-1.18	-0.37	242,162
Gap-graded RHMA	NA	0	FAM_RHMAG_Cont	1.74	5.18	-1.05	-0.34	211,324
	Lab-prepared	10	FAM_RHMAG_10RAP_LP	0.45	6.37	-1.39	-0.30	210,822
		15	FAM_RHMAG_15RAP_LP	1.25	5.71	-1.30	-0.31	225,551
	Plant	10	FAM_RHMAG_10RAP_PS	2.76	4.15	-0.86	-0.37	223,133

The shear modulus master curves for the dense- and gap-graded mixes are shown in Figure 6.6 through Figure 6.9 along with their normalized modulus curves, which better illustrate the effect of the R-RAP and RAP on FAM mix behavior. The normalized curves were obtained by dividing the moduli of the FAM mixes containing RAP by the corresponding moduli of the control mixes at each respective frequency.

The following observations were made:

- Dense-graded HMA mixes
  + Adding R-RAP (simulated and actual) increased the stiffness of all the mixes at all frequencies, as expected. The maximum increase in stiffness occurred at about 0.001 Hz, with the degree of increase in stiffness reducing at higher and lower frequencies (i.e., increasing and decreasing temperatures), regardless of R-RAP source. The mix stiffness values merged at high frequencies (> 100 Hz corresponding to low temperatures, with temperature dominating performance).
  + Stiffness increased with increasing R-RAP content, but the degree of stiffness increase depended on the source of the R-RAP.
  + The degree of change in stiffness was least on the mixes containing laboratory-prepared R-RAP (up to four times that of the control mix [observed at 0.001 Hz]), with only a marginal difference in stiffness between the mix containing 15 percent R-RAP and the mix containing 25 percent R-RAP.

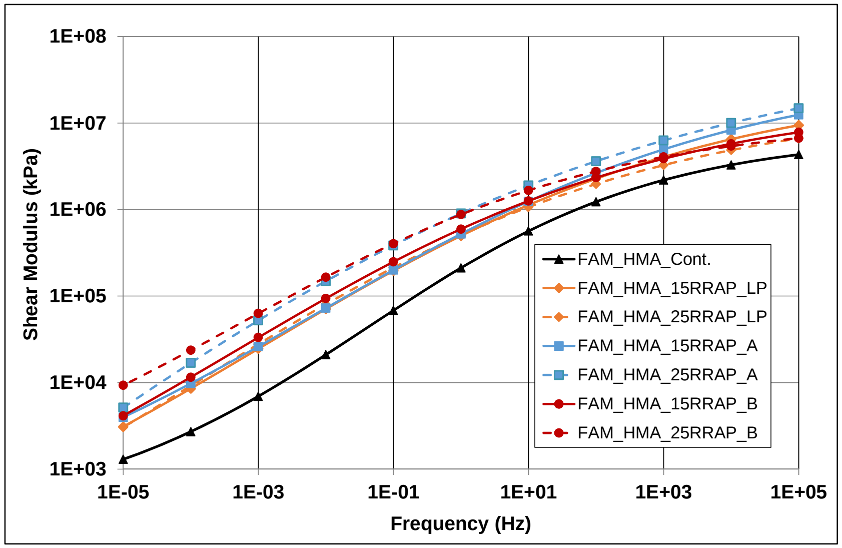

Figure 6.6: Shear modulus master curves for dense-graded HMA mixes.

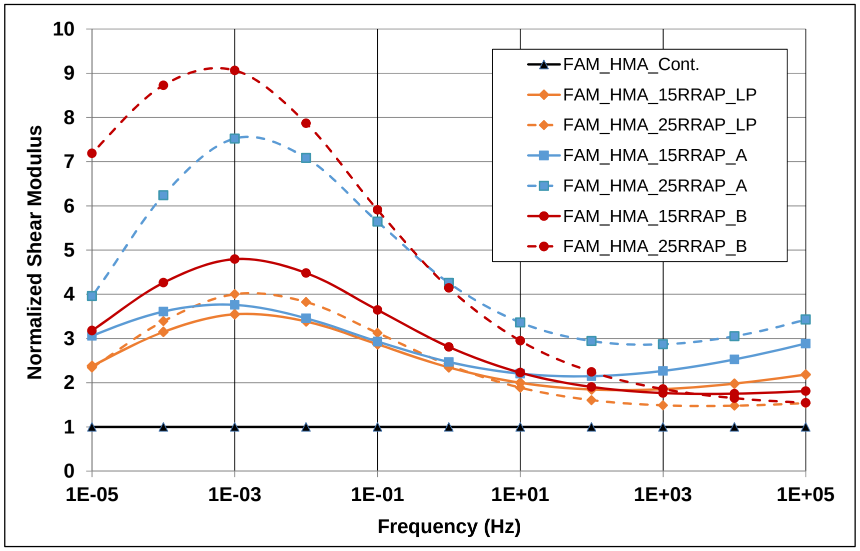

Figure 6.7: Normalized shear modulus master curves for dense-graded HMA mixes.

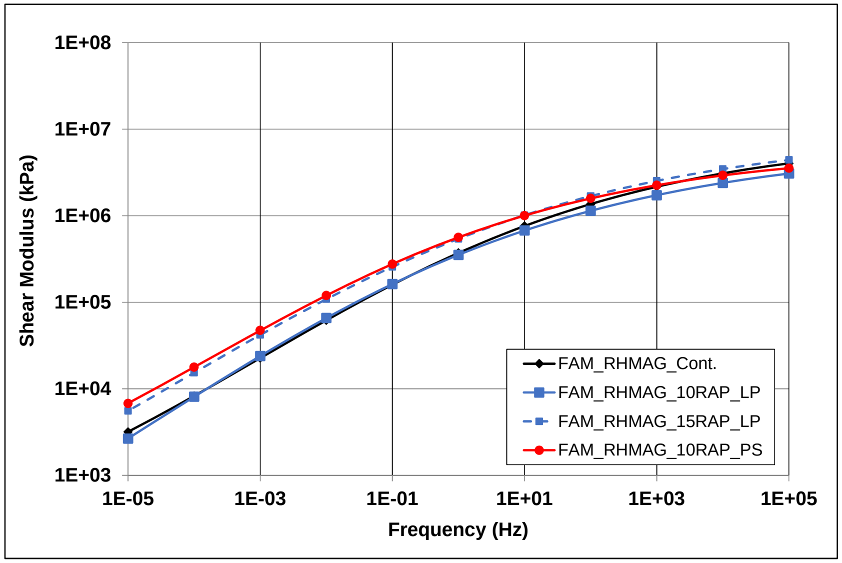

Figure 6.8: Shear modulus master curves for gap-graded RHMA mixes.

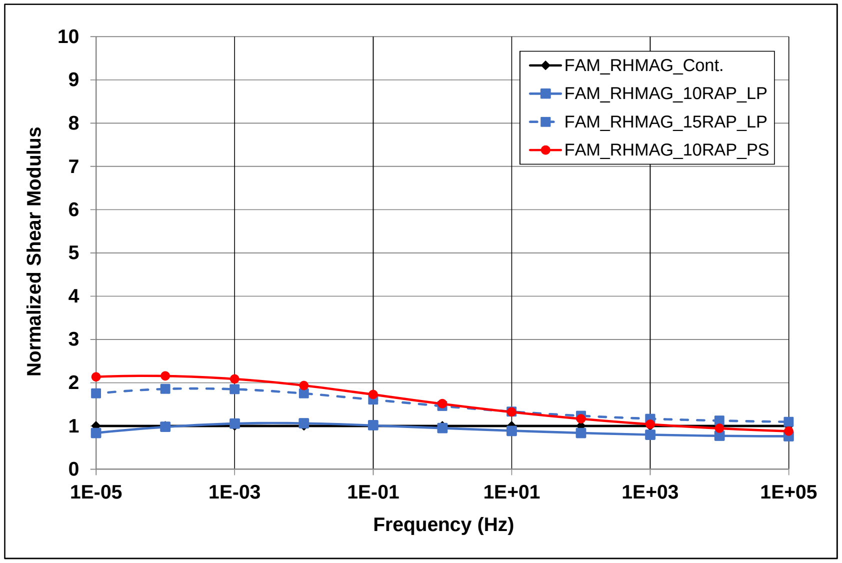

Figure 6.9: Normalized shear modulus master curves for gap-graded RHMA mixes.

  + Adding 15 and 25 percent R-RAP from Source-A increased the mix stiffness by 3.8 and 7.5 times that of the control (at 0.001 Hz), respectively, while adding the same R-RAP quantities from Source-B increased the mix stiffness by 4.8 and 9.2 times that of the control. The difference was attributed to known contamination of the Source-B R-RAP with conventional RAP from the underlying layer during the milling operation.
  + Performance between the laboratory-prepared R-RAP and the R-RAP sampled from two highway projects was considerably different, indicating that the laboratory aging procedures used in this study were not necessarily representative of field conditions.
- Gap-graded RHMA mixes
  + Adding RAP (simulated and actual) increased the stiffness of two of the three mixes at all frequencies. The performance of the mix containing 10 percent laboratory-prepared RAP was similar to that of the control mix.
  + Once again, performance differed considerably between the laboratory-prepared RAP and the RAP sampled from a stockpile, further supporting the conclusion that the laboratory aging procedures used in this study were not necessarily representative of field conditions.
  + The trends in change of stiffness over the range of frequencies were similar to those observed on the dense-graded HMA mixes; however, the RHMA mixes appeared to be less sensitive to changes in frequency (i.e., less sensitive to changes in temperature).
  + Adding 10 percent RAP, sourced from a stockpile at an asphalt plant, to the gap-graded RHMA mix increased the stiffness to a maximum almost twice that of the control (recorded at about 0.001 Hz, corresponding to a higher than median temperature).

6.3 Phase 1b Test Summary

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

- The stiffness of the mixes increased with increasing R-RAP or RAP content, as expected.
- The behavior of mixes prepared with laboratory-prepared R-RAP and RAP was inconsistent with that of the mixes prepared with field-sampled RAP and R-RAP materials, indicating that the laboratory aging procedures used in this study were not necessarily representative of field conditions. This contradicts findings reported in the literature.
- The trends in change of stiffness over the range of frequencies were similar for both types of mix; however, the gap-graded RHMA mixes appeared to be less sensitive to changes in frequency (i.e., less sensitive to changes in temperature) than the dense-graded HMA mixes.
- Adding 15 and 25 percent R-RAP sourced from two road projects increased the mix stiffness by up to 3.8 and 9.2 times that of the control (at 0.001 Hz), respectively. Mix behavior was dependent on the R-RAP source, with the source known to be contaminated with conventional RAP millings having a greater effect on the stiffness increase.
- Adding 10 percent RAP, sourced from a stockpile at an asphalt plant, to the gap-graded RHMA mix increased the stiffness to a maximum almost twice that of the control (recorded at about 0.001 Hz, corresponding to a higher than median temperature).

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7. TEST RESULTS: PHASE 2: FULL-GRADED MIX PERFORMANCE

7.1 Experiment Plan

7.1.1 Materials

Table 7.1 lists the mixes evaluated in Phase 2 of this study. The mix design and specimen fabrication procedures were explained in Chapter 4. This phase only included mixes with RAP sourced from a stockpile at an asphalt plant and R-RAP sourced from two road projects, and did not consider simulated RAP and R-RAP binders.

Table 7.1: Full-Graded Mixes Evaluated in Phase 2

Mix Type	RAP Content (%)	RAP Source	Mix Identification
R-RAP in dense-graded mix	0	Not applicable	HMA_Cont
	15 25	Road Source-A	HMA_15RRAP_A HMA_25RRAP_A
	15 25	Road Source-B	HMA_15RRAP_B HMA_25RRAP_B
RAP in gap-graded mix	0	Not applicable	RHMAG_Cont
	10	Asphalt plant	RHMAG_10RAP

7.1.2 Testing Program

Table 7.2 lists the test methods and brief details about the test parameters used to conduct performance-related testing on the dense-graded HMA and gap-graded RHMA mixes.

Table 7.2: Tests Performed in Phase 2

Test	Replicates	Air Voids (%)	Test Variables
Stiffness • Dynamic modulus - AASHTO TP 79 and AASHTO PP 61	2	7.0 ± 1.0	• 1 temperature sequence (4, 25, 40°C for HMA and 4, 20, 45°C for RHMA) • 1 stress level[1] • No confining pressure
Stiffness • Beam flexural frequency sweep - AASHTO T 321	2	6.0 ± 0.5	• 3 temperatures (10, 20, 30°C) • 2 strain levels (100 µstrain at 10 and 20°C; 200 µstrain at 30°C)
Rutting Performance • Flow number from repeated load triaxial results - AASHTO TP 79	2	7.0 ± 1.0	• 1 temperature (52°C) • 1 deviator stress (600 kPa [87 psi]) • 1 contact stress (30 kPa [4 psi]) • No confining pressure
Cracking Performance • Beam fatigue - AASHTO T 321	3	6.0 ± 0.5	• 1 temperature (20°C) • 3 strain ranges (high, medium, low) based on the mix stiffness • 1 frequency (10 Hz)

[1] Deviator stress controlled by AMPT software to get 75 to 125 µstrain peak-to-peak axial strain.

Asphalt Mix Performance Tester (AMPT) tests were conducted on specimens 100 mm (4 in.) in diameter and 150 mm (6 in.) high, cored from gyratory-compacted specimens with a target air-void content of 7.0 ± 1.0 percent. The beam specimens were cut from ingots compacted with a steel-wheel roller to target air-void contents of 6.0 ± 0.5 percent. The beams were 380 mm (15 in.) in length, 50 mm (2 in.) in height and 63 mm (2.5 in.) in width.

7.2 Test Results

7.2.1 Air-Void Content

Air-void contents of the specimens compacted in a Superpave gyratory compactor (cylindrical AMPT specimens) and with a rolling-wheel compactor (beam specimens) are shown in Figure 7.1 and Figure 7.2, respectively.

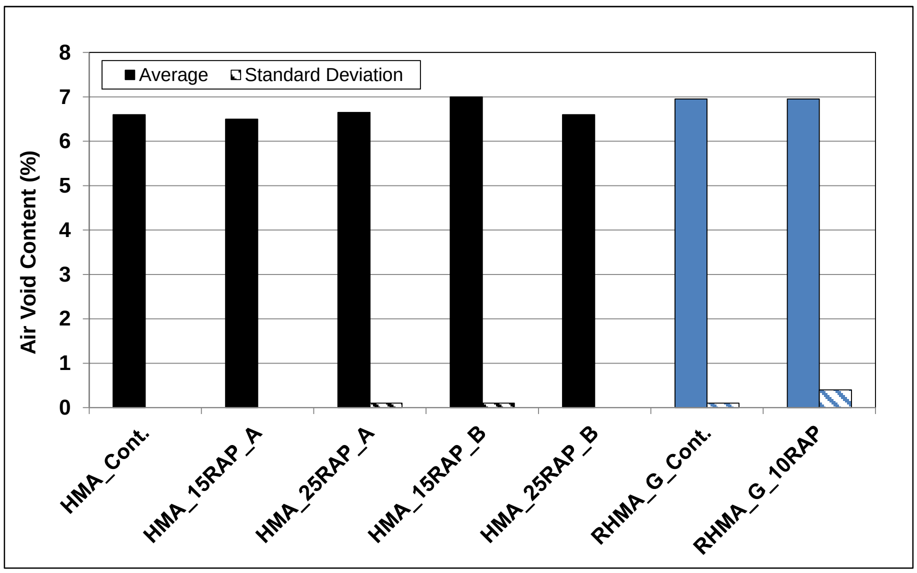


Figure 7.1: Air-void contents of gyratory-compacted specimens.

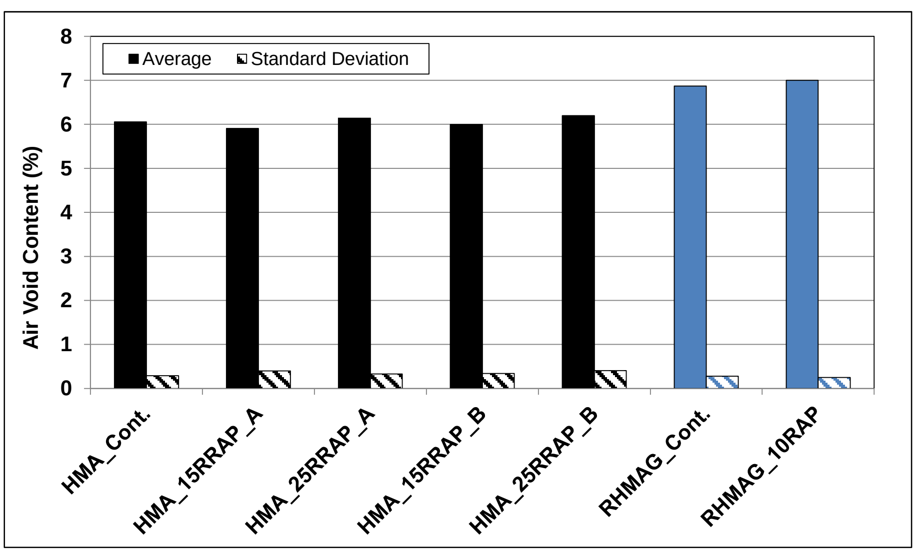


Figure 7.2: Air-void contents of rolling wheel–compacted specimens.

All the gyratory-compacted specimens and all the dense-graded specimens compacted with the rolling-wheel were within the target limits. The gap-graded RHMA specimens compacted with the rolling wheel were slightly above the target limits, but a decision was made to continue with testing these beams due to the limited availability of materials and time constraints for compacting additional beams, and because the performance of the HMA and RHMA mixes would not be directly compared. Variation in air-void content between beams from the same mix was again larger than that achieved with the gyratory-compacted specimens, but was still acceptable, indicating that consistent compaction was achieved. Any potential influences of air-void content were considered during analysis of the results.

7.2.2 Effect of RAP Addition on Mix Stiffness: AMPT Dynamic Modulus

Dynamic modulus (E*) tests were performed using an AMPT. In this test, the specimen is subjected to a haversine axial-compressive load with fixed amplitude under controlled strain conditions. The axial deformation of the specimen during cyclic loading is measured using three linear variable displacement transducers (LVDTs) mounted around the specimen 120° apart. The dynamic modulus is calculated by dividing the peak stress (σ_max) by the peak strain (ε_max) during each loading cycle. Two replicate specimens from each mix were tested. The dynamic modulus and phase angle of the dense-graded HMA mixes were measured at 10 Hz, 1 Hz, and 0.1 Hz when testing at 4°C and 20°C (39°F and 68°F) and at 10 Hz, 1 Hz, 0.1 Hz, and 0.01 Hz when testing at 40°C (104°F). The same parameters were measured on the gap-graded RHMA mixes, but at temperatures of 4°C, 25°C, and 45°C (39°F, 77°F, and 113°F).

Dynamic modulus master curves were developed using Equations 6.1 through 6.3. Table 7.3 lists the function parameters (Equation 6.1) and activation energy term used in the Arrhenius shift factor equation (Equation 6.3) for the evaluated mixes.

Table 7.3: Phase 2 Dynamic Modulus Master Curve Parameters

Mix Type	RAP Source	RAP Content (%)	Mix Identification	Master Curve Parameters				
				δ (kPa)	α	β	γ	Ea (kJ/mol)
Dense-graded HMA	NA	0	HMA_Cont	3.55	3.95	-0.48	-1.40	200,000
	Road-A	15	HMA_15RRAP_A	4.08	3.30	-0.51	-1.40	200,000
		25	HMA_25RRAP_A	4.01	3.43	-0.50	-1.49	199,999
	Road-B	15	HMA_15RRAP_B	4.00	3.33	-0.52	-1.72	200,000
		25	HMA_25RRAP_B	3.98	3.31	-0.47	-1.74	200,000
Gap-graded RHMA	NA	0	RHMAG_Cont	3.64	3.63	-0.41	-1.27	199,999
	Plant	10	RHMAG_10RAP	3.89	3.41	-0.42	-1.38	199,999

Figure 7.3 shows the dynamic shear modulus master curves for the dense-graded HMA and gap-graded RHMA mixes. Modulus curves normalized to their corresponding control mix are shown in Figure 7.4 and Figure 7.5. The normalized values were obtained by dividing the stiffnesses of each mix with binder replacement by the corresponding value of the control mix.

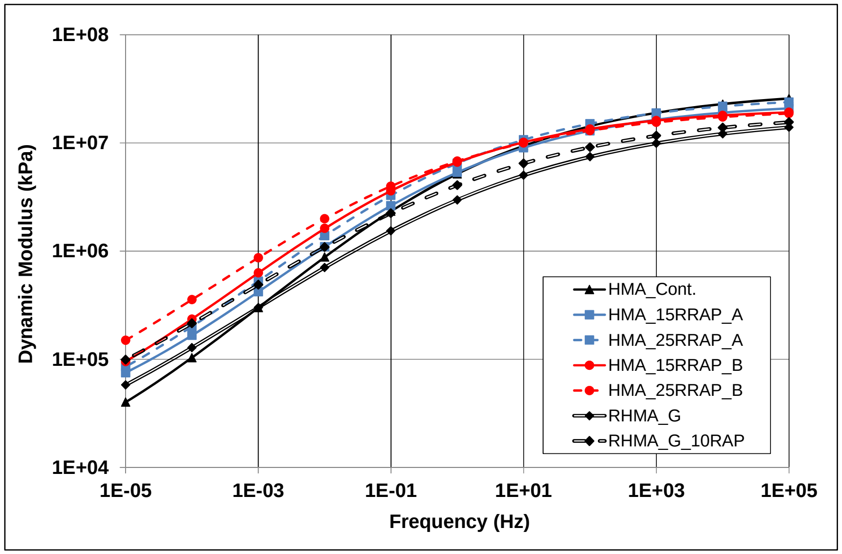


Figure 7.3: Phase 2 dynamic shear modulus master curves.

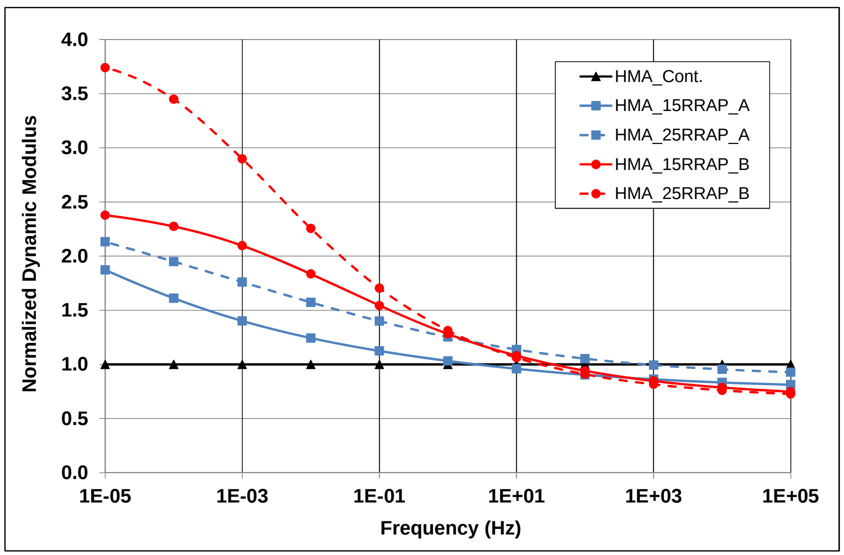


Figure 7.4: Normalized dynamic shear modulus master curves for dense-graded HMA mixes.

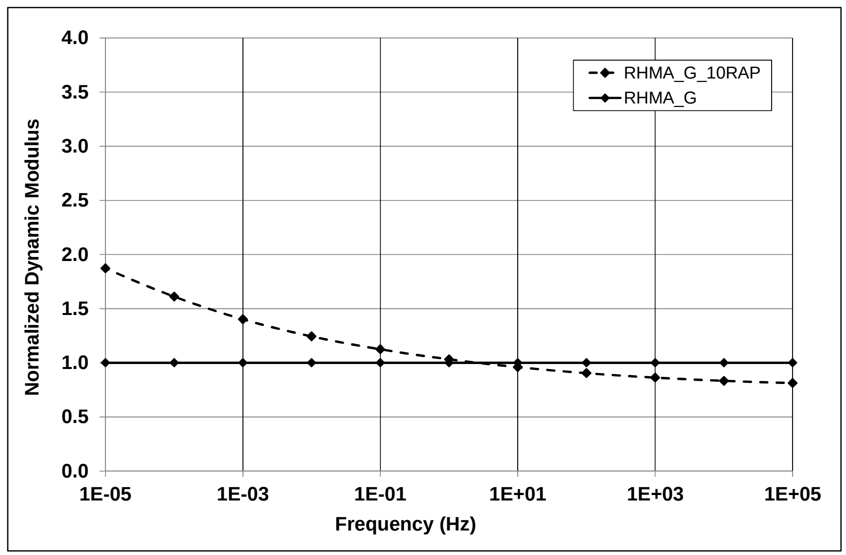


Figure 7.5: Normalized dynamic shear modulus master curves for gap-graded RHMA mixes.

The following observations were made:

- The stiffnesses of the control mixes were lower than the mixes with RAP, as expected. The gap-graded RHMA mixes generally had lower stiffnesses than the dense-graded HMA mixes, but the stiffness-change trends were similar for all mixes across the different test frequencies.
- Dense-graded HMA mixes:
  + The stiffness of the HMA mixes increased with increasing R-RAP content; however, the degree of stiffness change varied between the two R-RAP sources, which was consistent with the observations from the FAM testing made in Phase 1b. There was no significant difference in the increase in stiffness when adding 15 or 25 percent R-RAP from Source-A (up to 1.9 and 2.1 times higher than the control mix, respectively). However, adding 15 and 25 percent R-RAP from Source-B increased the stiffness by up to 2.4 and 3.7 times, respectively, compared to the control. This was again attributed to the contamination of the R-RAP from Source-B with RAP millings from the underlying layer.
  + The dense-graded HMA mix with 25 percent RAP from Source-B had the highest stiffness at frequencies below 10 Hz. At higher frequencies (equating to colder temperatures), the control mix and mixes containing R-RAP from Source-A were slightly stiffer.
- Gap-graded RHMA mixes:
  + Adding RAP to the RHMA mix to replace 10 percent of the required binder increased the stiffness of the mix up to twice that of the control mix at the lower frequencies (i.e., warmer temperatures), but the effect diminished with increasing frequency, which was consistent with the HMA mixes.

7.2.3 Effect of RAP Addition on Mix Stiffness: Flexural Dynamic Modulus

Four point-bending frequency sweep tests were conducted to measure the stiffness (flexural dynamic modulus) of the dense-graded HMA and gap-graded RHMA beams under different frequencies and various loading rates. Two replicates were tested at temperatures of 10°C, 20°C, and 30°C and over frequencies of 15, 10, 5, 2, 1, 0.5, 0.2, 0.1, 0.05, 0.02 and 0.01 Hz. Tests were performed in strain control mode (100 µstrain at 10°C and 20°C; 200 µstrain at 30°C).

A sigmoidal function similar to that used to determine the FAM mix shear modulus and dynamic modulus was used to construct the flexural dynamic modulus master curve at a reference temperature of 20°C. The shift factor equation used for generating the master curves is shown in Equation 7.1. Table 7.4 lists the sigmoidal function parameters and the shift factor equation constant used for the evaluated mixes.

$$Log\ a_T(T) = C \times (T - T_r) \qquad \textbf{(7.1)}$$

where:

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

Figure 7.6 shows the flexural dynamic modulus master curves for the different mixes. Flexural modulus curves and curves normalized to their corresponding control mix are shown in Figure 7.7 and Figure 7.8, respectively, for the dense-graded HMA and gap-graded RHMA mixes. The normalized values were obtained by dividing the stiffness of each mix with binder replacement by the corresponding value of the control mix.

Table 7.4: Phase 2 Flexural Modulus Master Curve Parameters

Mix Type	RAP Source	RAP Content (%)	Mix Identification	Master Curve Parameters				
				δ (kPa)	α	β	γ	Ea (kJ/mol)
Dense-graded HMA	NA	0	HMA_Cont	3.82	3.46	-1.24	-0.57	0.1847
	Road-A	15	HMA_15RRAP_A	3.91	3.30	-1.36	-0.59	0.0206
		25	HMA_25RRAP_A	3.87	3.32	-1.43	-0.58	0.0446
	Road-B	15	HMA_15RRAP_B	3.88	3.33	-1.46	-0.57	0.0119
		25	HMA_25RRAP_B	4.11	3.10	-1.55	-0.58	0.0208
Gap-graded RHMA	NA	0	RHMAG_Cont	3.62	3.47	-1.14	-0.45	0.0677
	Plant	10	RHMAG_10RAP	4.16	3.01	-1.02	-0.47	0.0803

The following observations were made:

- Results from the flexural dynamic modulus testing showed similar trends to those from the AMPT dynamic modulus testing discussed in Section 7.2.2. Adding R-RAP or RAP to the mixes increased the flexural stiffness, as expected.
- Dense-graded HMA mixes:
  + The stiffening effect of the R-RAP on the HMA mixes was most notable at the lower frequencies (i.e., corresponding to warmer temperatures), with the largest increase in stiffness observed at about 0.001 Hz. The master curves of these mixes merged at frequencies higher than 10 Hz (i.e., corresponding to colder temperatures) indicating that addition of the R-RAP would have little effect on mix stiffness at lower temperatures compared to the control mix.
  + Adding 15 and 25 percent R-RAP from Source-A increased the stiffness of the HMA mix by up to 1.2 and 1.4 times that of the control, respectively. Adding the same percentages of R-RAP from Source-B increased the mix stiffness by up to 1.6 and 2.4 times that of the control mix, respectively, considerably higher than the mix containing R-RAP from Source-A.
- Gap-graded RHMA mixes:
  + Adding 10 percent RAP to the RHMA mix increased the mix stiffness to a maximum of about twice that of the control (at a frequency of 10^{-5} Hz). The stiffening effect of the RAP addition was notable at all frequencies, but most notable at the lower frequencies.

7.2.4 Effect of RAP Addition on Rutting Performance: Flow Number

The flow number test provides an indication of the resistance of an asphalt mix to permanent deformation (rutting). The accumulation of permanent deformation is assumed to occur in three phases, namely: primary, secondary, and tertiary. Permanent strain typically accumulates rapidly in the primary phase, then follows a more constant rate through the secondary phase, and then accumulates rapidly again in the tertiary phase. The flow number is defined as the cycle at which the tertiary phase starts. A higher flow number values implies that a mix has better rutting (permanent deformation) resistance. In this study, unconfined specimens were subjected to a repeated compressive deviator stress of 600 kPa (87 psi) and a 30 kPa (4.4 psi) contact stress. The resulting cumulative permanent deformation versus the number of loading cycles was recorded with flow number calculations performed automatically by the AMPT software. The numbers of cycles to 100, 200, and 300 μstrain of permanent deformation were also analyzed to obtain a better understanding of the rutting behavior of each of the mixes.

According to the test method, testing temperature should be selected based on the adjusted high PG temperature of the binder selected for the pavement location. Since testing for specific project locations was not included as part of the workplan, all tests were performed at 52°C to obtain a good understanding of how damage accumulated during the test. Running the test at higher temperatures (e.g., 64°C) could have resulted in accelerated evolution of permanent deformation, which would not provide a comprehensive indication of how damage accumulated with load repetition. Running the test at lower temperatures would extend the testing time, but would probably not provide any additional useful information with regard to the effect of RAP on rutting performance.

Figure 7.9 shows the relationship between cumulative permanent deformation and the number of load cycles for all mixes evaluated. The following observations were made:

- The repeatability of the test results met the single-operation precision specified in AASHTO TP 79 for all mixes, but showed some variability between the replicate specimens in each mix, which is consistent with repeated load testing.
- The evolution rate of cumulative permanent deformation with increasing loading cycles was fastest for the control mixes. The rate decreased with increasing RAP content, indicating a likely improvement in rutting performance.

Figure 7.10 shows the flow number values for the different mixes, and Figure 7.11 shows these values normalized to the respective control mixes. The normalized values were obtained by dividing the flow number of each mix with binder replacement by the corresponding value of the control mix. The following observations were made:

- The control mixes had the lowest flow number values.
- The flow number results for the two HMA mixes with 15 percent R-RAP were similar. However, when the R-RAP content was increased to 25 percent, the mix containing R-RAP from Source-B outperformed the mix with R-RAP from Source-A, which was consistent with the stiffness test results.
- The addition of RAP to the RHMA mix had a significant effect on the flow number, indicating a considerable potential improvement in expected rutting performance. The RHMA mix with 10 percent RAP had the highest flow number of all mixes.

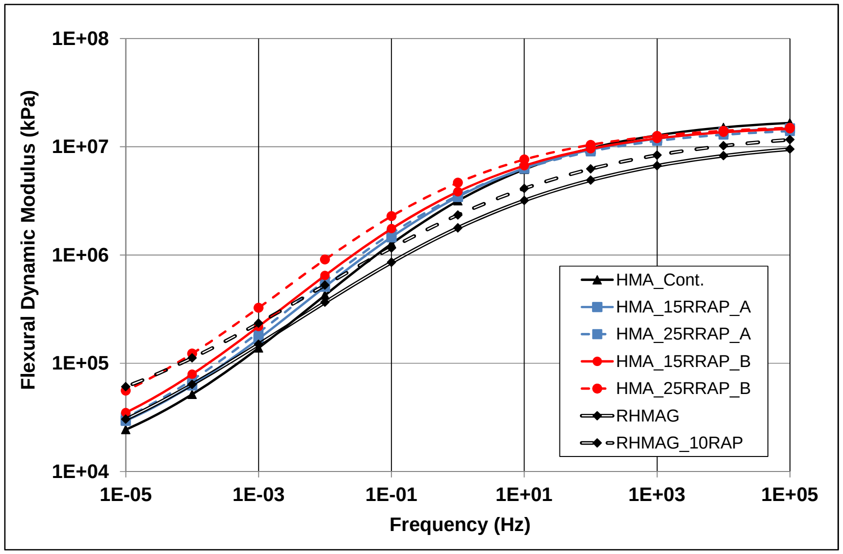


Figure 7.6: Phase 2 flexural modulus master curves.

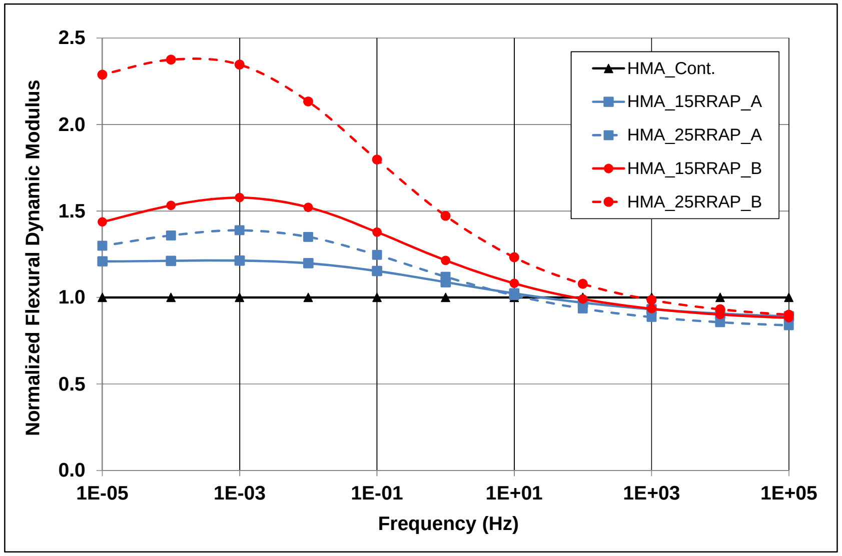


Figure 7.7: Normalized flexural modulus master curves for dense-graded HMA mixes.

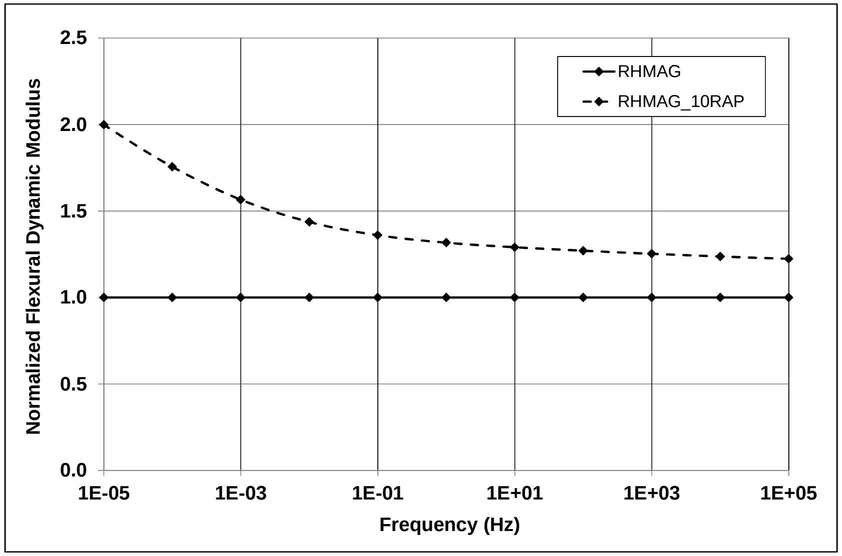


Figure 7.8: Normalized flexural modulus master curves for gap-graded RHMA mixes.

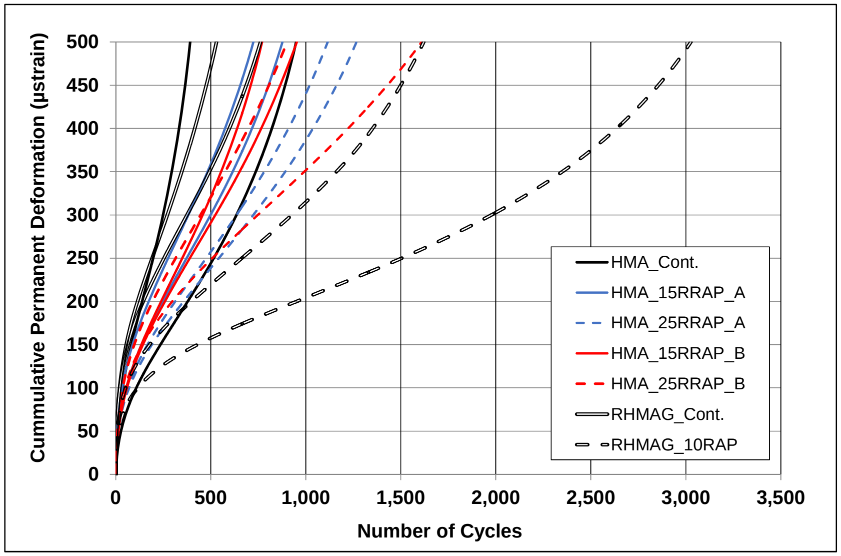


Figure 7.9: Cumulative permanent deformation versus number of cycles (52°C).

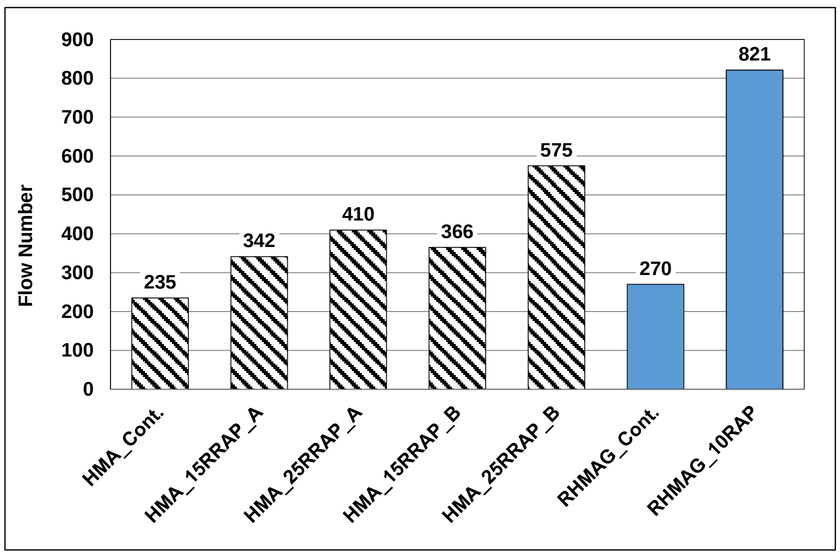


Figure 7.10: Flow number values for evaluated mixes (52°C).

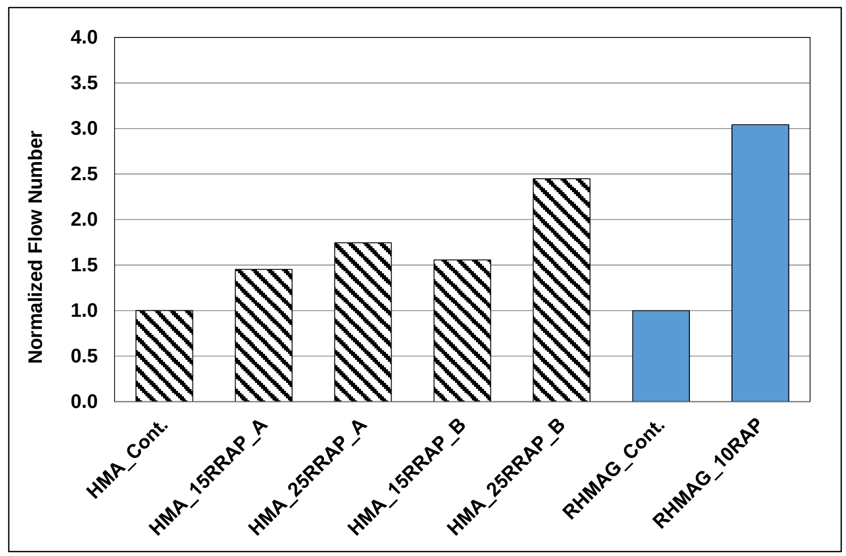


Figure 7.11: Normalized flow number values (52°C).

Figure 7.12 shows the number of cycles to 1, 3, and 5 percent permanent axial strain (note that the y-axis is on a log scale). Trends observed for the number of cycles to 5 percent permanent axial strain were similar to those observed for the flow number results. At lower strain levels, the difference in the number of cycles required to reach the selected strain level was much closer between the mixes (also clearly shown in Figure 7.9), with the rankings of some of the mixes different to those for the 5 percent strain level.

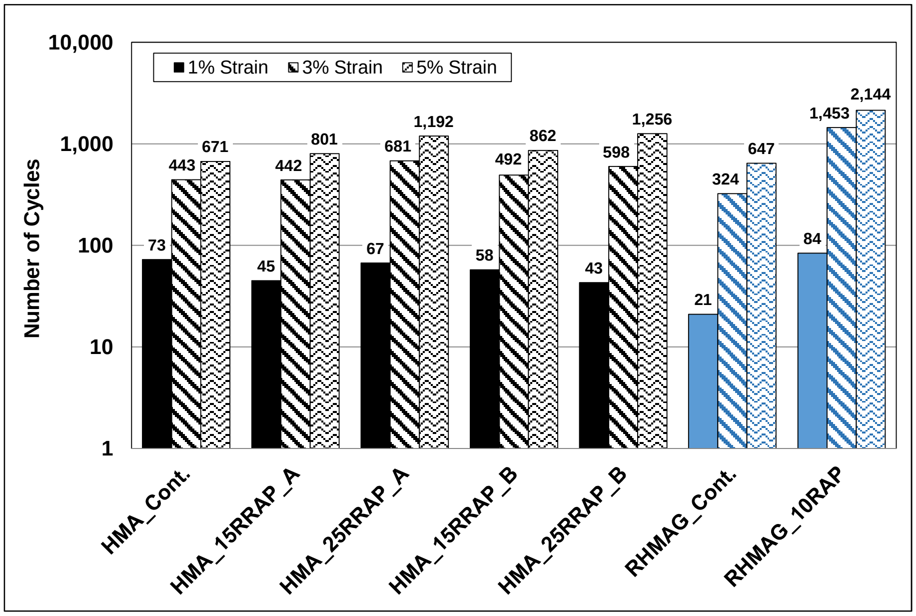


Figure 7.12: Number of cycles to 1, 3, and 5% permanent axial strain.

7.2.5 Effect of RAP Addition on Cracking Performance: Beam Fatigue

The beam fatigue test provides an indication of the resistance of an asphalt mix to fatigue cracking at a constant deformation (strain). Beam specimens are subjected to four-point bending by applying sinusoidal loading at three different strain levels (high, intermediate, and low) at a frequency of 10 Hz and temperature of 20°C (68°F). The fatigue life at each strain level was selected as the cycle at which maximum values of stiffness multiplied by the number of cycles occurs. Laboratory test results will generally rank with field fatigue or reflection cracking performance for overlays thinner than about 75 mm (0.25 ft) but may not rank with expected field performance for thicker layers of asphalt. For thicker layers, the interaction of the pavement structure, traffic loading, temperature, and mix stiffness with the controlled strain beam fatigue results needs to be simulated using mechanistic analysis in order to rank mixes for expected field performance.

In this UCPRC study, the testing approach currently specified in AASHTO T 321 was modified to optimize the quantity and quality of the data collected. Replicate specimens were first tested at high and medium strain levels to develop an initial regression relationship between fatigue life and strain (Equation 7.2), with strain levels selected, based on experience, to achieve fatigue lives between 10,000 and 100,000 load cycles and between 300,000 and 500,000 load cycles, respectively. Additional specimens were then tested at lower strain levels selected based on the results of the initial linear regression relationship to achieve a fatigue life of about 1 million load repetitions. The regression relationship was then refined to accommodate the measured stiffness at the lower strain level.

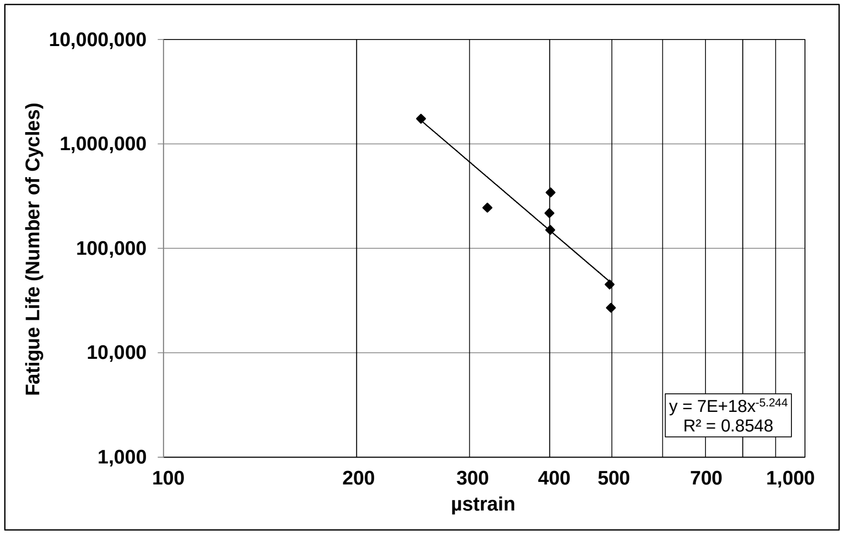
$$LnN = A + B \times \varepsilon \quad \textbf{(7.2)}$$

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

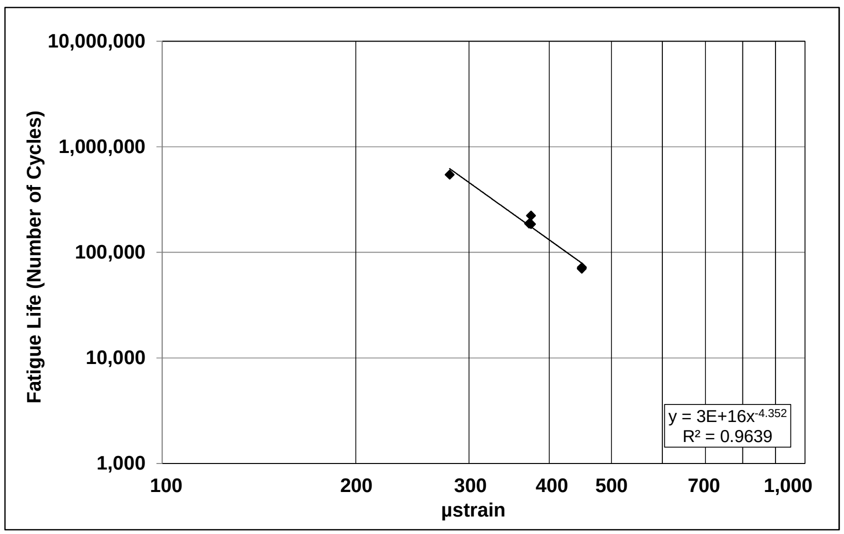
Plots of the fatigue models for each dense-graded HMA mix are shown in Figure 7.13 and for each gap-graded RHMA mix in Figure 7.14. The models were considered to be appropriate based on the mostly high r-squared values of the model fitting and the repeatability of the test results at each strain level. The reasons for the variability of the results for the dense-graded HMA control mix and the dense-graded HMA mix with 25 percent R-RAP from Source-A (i.e., slightly lower r-squared values) compared to the other mixes was not clear, and not large enough to justify additional testing.

Calculated fatigue lives at 200 µstrain, 400 µstrain, and 600 µstrain of all the mixes are compared in Figure 7.15. Note that no mixes were tested at 200 µstrain and that fatigue life at this strain level was extrapolated. The following observations were made:

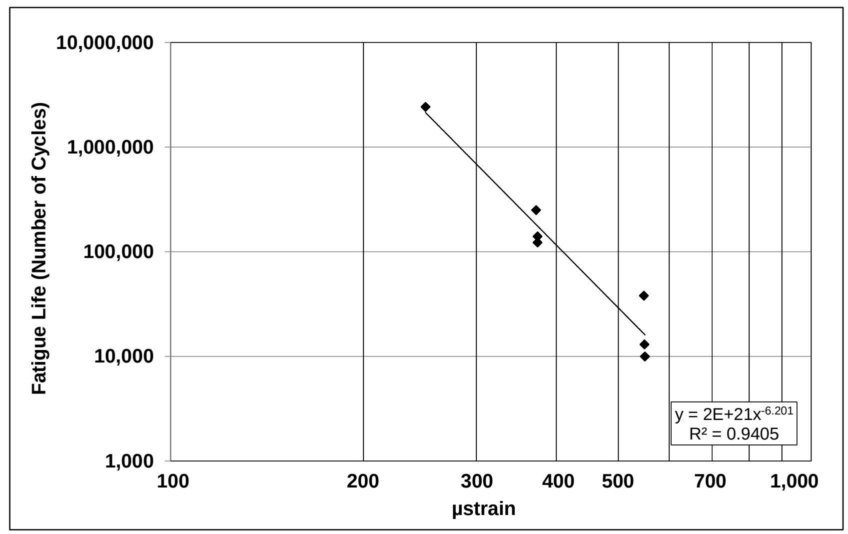
- Dense-graded HMA mixes:
  + Fatigue life decreased with increasing strain level, as expected.
  + At low strain levels (i.e., 200 and 300 µstrain), the fatigue lives of the different mixes were similar, as expected, given that mix stiffness dominates behavior and the low strain levels do not effectively differentiate cracking behavior in the test beams.
  + At the intermediate and higher strain levels (400 and 600 µstrain), the control mix and mixes with 15 and 25 percent R-RAP from Source-A and 15 percent R-RAP from Source-B had similar fatigue performance. The mix with 25 percent R-RAP from Source-B showed a shorter fatigue life, indicating poorer performance.
  + The effect of increased strain level on the behavior of the mix containing R-RAP from Source-B was notably different than that of the other mixes, with increasing strain level having an increasingly larger impact on fatigue life, which indicates that although the R-RAP (that was known to be contaminated with conventional RAP from the underlying layer) could potentially improve rutting performance, it could also potentially diminish fatigue cracking performance when used under high strain conditions.



Control

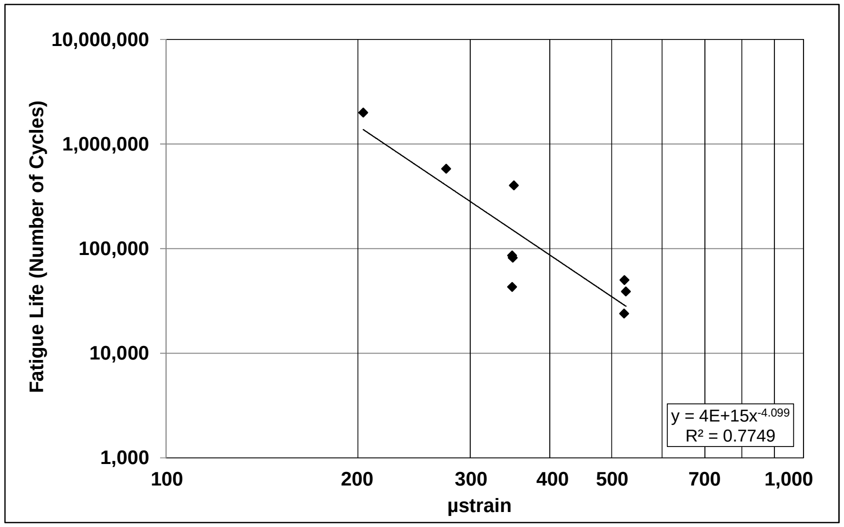


15% R-RAP from Source-A

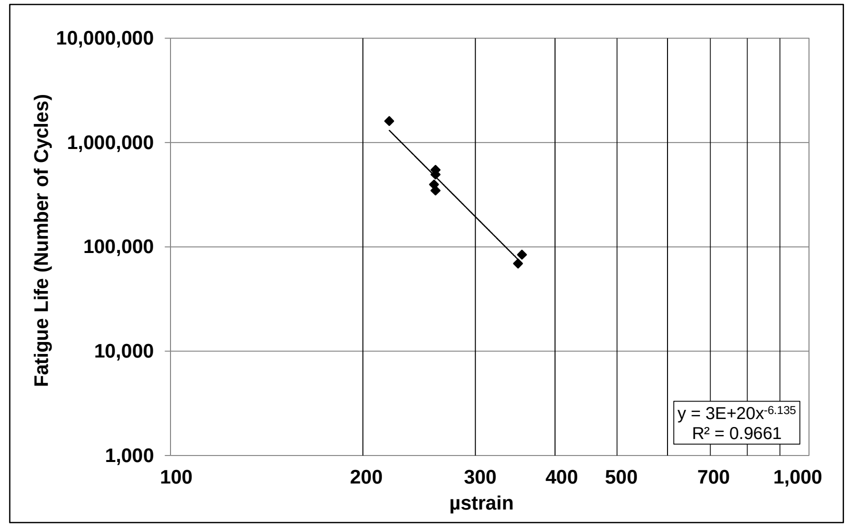


15% R-RAP from Source-B

Figure 7.13: Fatigue regression models for dense-graded HMA mixes.

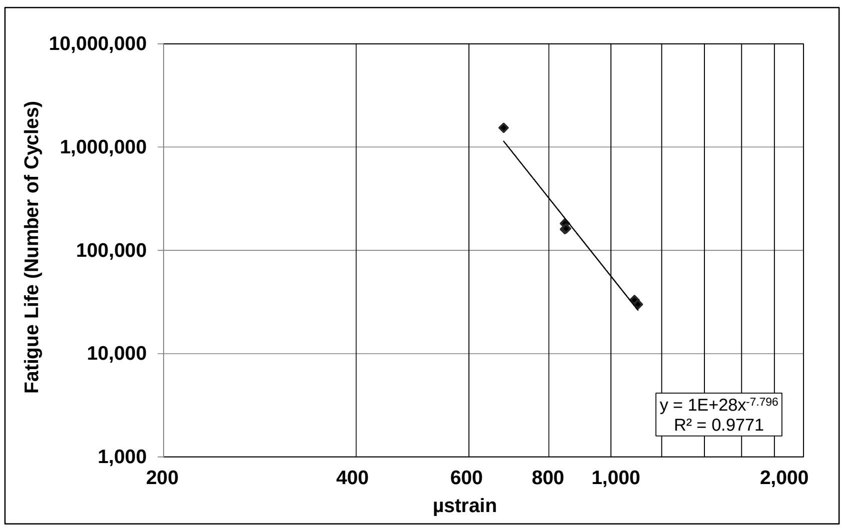


25% R-RAP from Source-A

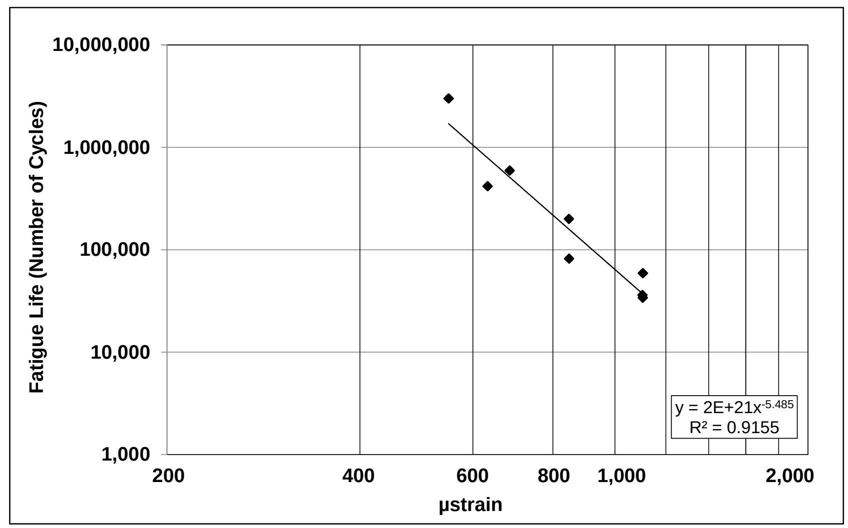


25% R-RAP from Source-B

Figure 7.13: Fatigue regression models for dense-graded HMA mixes *(continued)*.

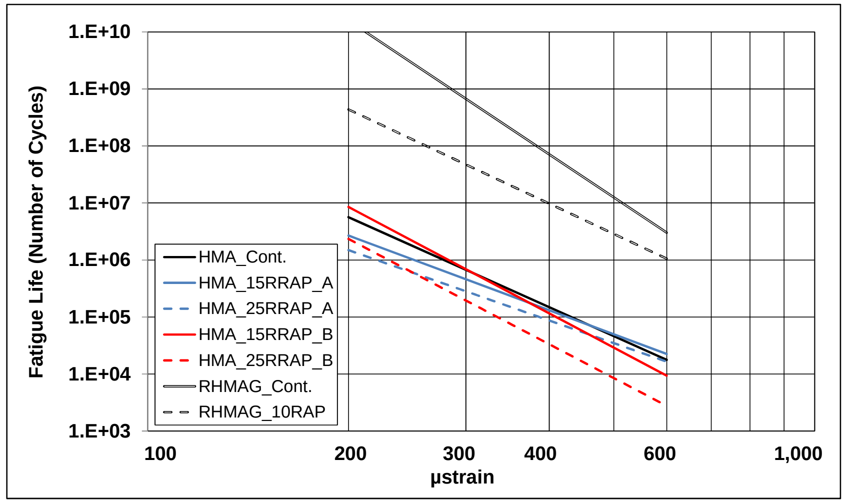


Control

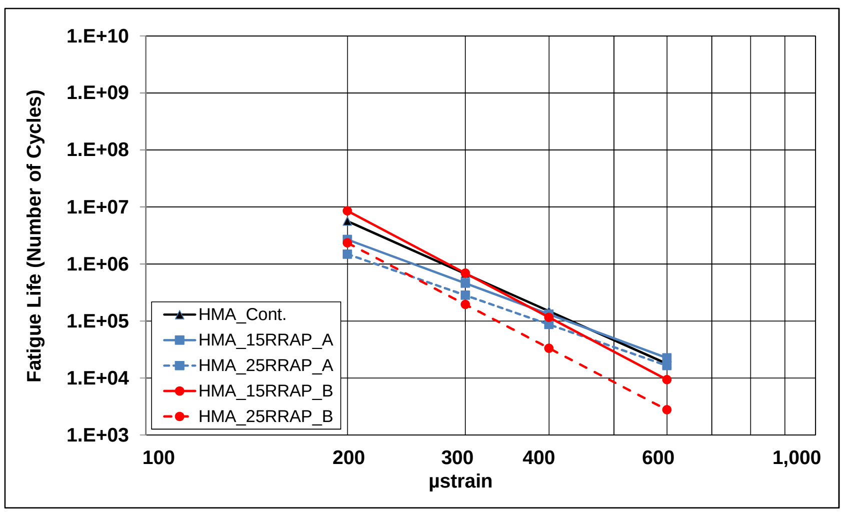


10% RAP

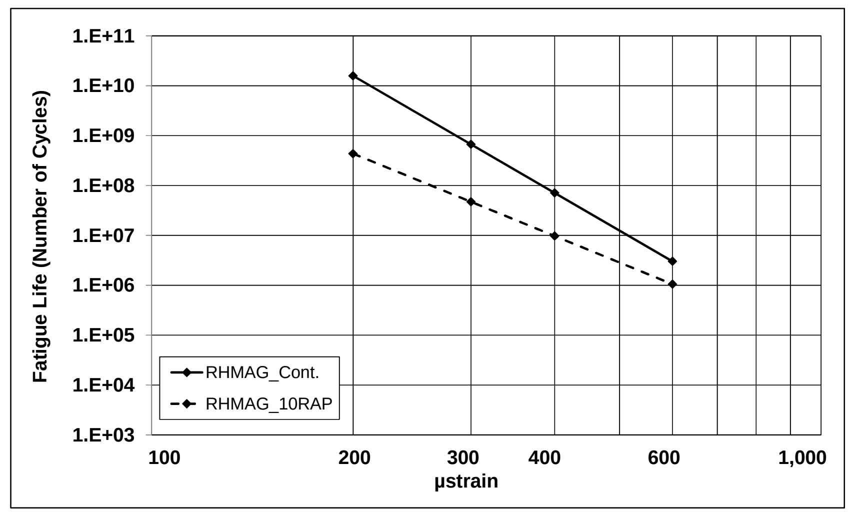
Figure 7.14: Fatigue regression models for gap-graded RHMA mixes.



All mixes



Dense-graded HMA mixes



Gap-graded RHMA mixes

Figure 7.15: Calculated fatigue life at 200, 400, and 600 µstrain.

- Gap-graded RHMA mixes:
  + Fatigue life decreased with increasing strain level, as expected.
  + Adding 10 percent RAP to the mix significantly reduced the fatigue life of the mix, thereby potentially negating the benefits of selecting RHMA-G as an overlay to retard the rate of reflection cracking. The difference in fatigue life between the two mixes decreased with increasing strain level. Since the air-void content in the beams prepared from the two mixes was essentially the same, the addition of the RAP clearly dominated performance throughout the range of strain levels.

<u>Mechanistic Analysis of Fatigue Performance</u>

To account for the interaction of fatigue life at a given strain and mix stiffness, load, and structure, the above observations were verified with a mechanistic analysis. The fatigue performance of an asphalt mix is a function of many factors including but not limited to the pavement structure, mix stiffness, mix strength, ambient temperature, wheel load, wheel configuration, and tire pressure. The maximum tensile strength at the bottom of the asphalt concrete layers (or at the bottom of individual asphalt concrete layers if debonding has occurred) is the critical pavement response for fatigue cracking. Therefore, to obtain a realistic evaluation of fatigue performance, the critical pavement responses must be calculated based on known asphalt stiffness and traffic load configurations.

Two pavement structures (Table 7.5) with two different overlay thicknesses were considered in the analysis; a thin 60 mm (0.2 ft) overlay and a thick 120 mm (0.4 ft) overlay (note that a 120 mm-thick [0.4 ft] gap-graded RHMA layer would usually not be considered by Caltrans as 60 mm [0.2 ft] is generally the current maximum thickness used). A truck with a 60 kN single axle load and 700 kPa (101 psi) tire pressure travelling at 88 km/h (55 mph) was used for the analysis.

Table 7.5: Pavement Structures Used in the Fatigue Performance Analysis

<table>
<tr><th rowspan="2">Layer</th><th colspan="4">Thickness
(mm)</th><th colspan="4">Stiffness
(MPa)</th><th colspan="4">Poisson's
Ratio</th></tr>
<tr><th>OL</th><th>AC</th><th>Base</th><th>SG</th><th>OL</th><th>AC</th><th>Base</th><th>SG</th><th>OL</th><th>AC</th><th>Base</th><th>SG</th></tr>
<tr><td>Structure #1
(Thin AC overlay)</td><td>60</td><td rowspan="2">200</td><td rowspan="2">300</td><td rowspan="2">Inf</td><td rowspan="2">Calc</td><td rowspan="2">600</td><td rowspan="2">300</td><td rowspan="2">100</td><td rowspan="2">0.4</td><td rowspan="2">0.4</td><td rowspan="2">0.35</td><td rowspan="2">0.35</td></tr>
<tr><td>Structure #2
(Thick AC overlay)</td><td>120</td></tr>
<tr><td colspan="13">OC = overlay AC = old asphalt concrete SG = subgrade Calc. = calculated from master curve Inf. = infinite</td></tr>
</table>

Loading time was calculated using Equation 7.3.

$$\textit{Loading time} = 2 \times \textit{radius of wheel loading area} \times \textit{AC overlay thickness} \quad \textbf{(7.3)}$$

The inverse of the loading time was used as the loading frequency (in radian frequency [$\omega = 2\pi \times f\ (Hz)$]). The loading frequencies were determined to be 9.96 Hz for Structure #1 and 9.10 Hz for Structure #2. Mix stiffnesses at a pavement temperature of 20°C were selected from the flexural stiffness master curves (Figure 7.6).

The *Openpave*™ software program was used to calculate the maximum principal tensile strains at the bottom of the asphalt concrete layers. The responses were calculated under the center point of one tire where the maximum principal strain typically occurs. This calculated critical strain at the bottom of the asphalt concrete layer for each overlay was used with the respective fatigue models discussed above to estimate the fatigue life. Table 7.6 summarizes the critical maximum principal tensile strains and fatigue lives for the different mixes for both overlay thicknesses.

Table 7.6: Tensile Strains and Corresponding Fatigue Lives

Mix ID	Structure #1 (Thin AC overlay)			Structure #2 (Thick AC overlay)		
	Max. Tensile Strain (µstrain)	Fatigue Life (Nf)	% Change From Control	Max. Tensile Strain (µstrain)	Fatigue Life (Nf)	% Change From Control
HMA_Cont.	159	1.86E+07	0	110	1.27E+08	0
HMA_15RRAP_A	158	7.40E+06	-60	108	3.76E+07	-70
HMA_25RRAP_A	159	3.83E+06	-79	110	1.76E+07	-86
HMA_15RRAP_B	156	3.93E+07	112	106	4.37E+08	243
HMA_25RRAP_B	151	1.32E+07	-29	99	1.74E+08	37
RHMAG_Cont.	175	4.48E+10	0	146	1.87E+11	0
RHMAG_10RAP	171	1.02E+09	-98	132	4.22E+09	-98

The following observations were made:

- The ranking of the mixes based on fatigue performance was independent of the pavement structure. Fatigue performance increased with increasing pavement thickness, as expected.
- Dense-graded HMA mixes:
  + Adding 15 and 25 percent R-RAP from Source-A to the HMA mix significantly reduced the fatigue life in both overlay thickness scenarios; adding 15 percent R-RAP from Source-B improved the performance in both scenarios, while adding 25 percent R-RAP from Source-B increased fatigue life if the thicker overlay was placed, but shortened it if a thinner overlay was used. The results show that the laboratory fatigue test results alone should not be used to rank fatigue performance independent of the pavement structure and loading except for very thin overlays, and that a combination of initial stiffness and fatigue life will dictate fatigue cracking behavior under traffic.
- Gap-graded RHMA mixes:
  + Both RHMA mixes outperformed the HMA mixes, but adding RAP to the RHMA mix significantly reduced the fatigue life, which was consistent with the results discussed above.

7.3 Phase 2 Summary

Key observations from Phase 2 testing on full-graded mixes include the following:

- The test methods used in this phase of the study were sufficiently sensitive to distinguish the behavior of the different mixes and to consistently distinguish the differences in performance of mixes containing no RAP (i.e., control mixes) and mixes containing R-RAP and RAP. However, all testing was undertaken on newly prepared laboratory specimens, and consequently do not necessarily reflect long-term performance of the mixes or the longer-term effects of the RAP and R-RAP binder on the rate of aging of the virgin binder.
- Adding RAP and R-RAP increased the stiffness of the mixes, which in most instances improved the rutting resistance of the mix, but diminished the cracking resistance.
- Adding R-RAP to dense-graded HMA mixes does not appear to have any significant negative effects on performance. However, the degree of change in rutting and cracking resistance was dependent on the R-RAP source, with test results for each source ranking consistently across the different laboratory tests, but not in a mechanistic analysis of cracking where stiffness, which affects tensile strain, and cracking resistance at a given strain interact.
- Given that the mixes had the same gradation and binder content and similar volumetric properties, RAP should not be considered as a generic material with consistent properties. This contradicts the findings from earlier UCPRC research on RAP materials sampled from processed stockpiles at northern California asphalt plants reported in Section 3.1 *(37),* but supports the findings from a more recent UCPRC study *(82)*, which tested RAP materials sampled from stockpiles in three different states and noted that RAP source had a consistent influence on test results. Although mixes containing conventional RAP were not included as additional controls to compare performance of the R-RAP and RAP in dense-graded HMA mixes, the difference in behavior between the Source-A and Source-B (contaminated with conventional RAP from the underlying layer) materials indicates that there would likely be a difference in performance between mixes prepared with conventional RAP and mixes prepared with R-RAP, due to the earlier rubber modification.
- Adding RAP to gap-graded RHMA mixes appears to improve rutting performance but diminish cracking performance, thereby potentially negating the benefits of selecting RHMA-G as an overlay to retard the rate of reflection cracking.
- The trends observed in the test results discussed in this chapter are unlikely to have been significantly influenced by the use of the gap-graded mix design with higher-than-target air-void content. Additional testing using a wider range of virgin binder, virgin aggregate, and RAP sources in mix designs that meet Caltrans specifications should be considered before any decision to allow RAP in gap-graded asphalt rubber mixes is considered.

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8. CONCLUSIONS AND PRELIMINARY RECOMMENDATIONS

8.1 Summary

This report describes a study that investigated the potential implications of using reclaimed rubberized asphalt pavement materials as partial binder and aggregate replacement in new conventional dense-graded asphalt concrete mixes, and using reclaimed conventional asphalt pavement materials as partial binder and aggregate replacement in new gap-graded asphalt rubber mixes.

The use of rubberized hot mix asphalt (RHMA) in pavements in California has been increasing since the early 1990s. As these RHMA layers reach the end of their design lives they are being milled off and replaced with new hot mix asphalt (HMA) or new RHMA. The millings are being added to reclaimed asphalt pavement (RAP) stockpiles, which in turn are reused in new conventional HMA. There is no published information or experience documenting whether the use of RAP containing rubber could influence mix performance. Although Caltrans currently does not permit the use of any RAP in open-graded mixes or in rubberized gap-graded (RHMA-G) mixes, there is increasing interest in allowing some RAP as binder replacement in gap-graded mixes in order to reduce the amount of virgin binder required.

Key points from the literature review conducted as part of this study include the following:

- The asphalt binder in RAP can blend appreciably with virgin binder in new mixes. The level of blending between the aged and new binders depends on numerous factors including the chemical composition of the individual binders. To ensure the optimal performance of asphalt mixes containing high percentages of reclaimed asphalt, the compatibility of reclaimed and virgin asphalt binders from different sources and with different performance grades needs to be well understood.
- Appropriate methods for extracting aged binder from reclaimed asphalt materials are still being developed, with a focus on examining the effects of extraction solvents on the properties of recovered binders. The solvents in current use are aggressive enough to fully blend the binders extracted from new mixes containing aged and virgin binders, which is problematic because the forced blending can lead to potentially misleading binder replacement values and nonrepresentative performance gradings of the blended binders. Asphalt rubber binders cannot be chemically extracted because the rubber is separated from the base binder during the process. Alternative methods to the use of extraction and recovery are being explored to better characterize the performance properties of blended virgin and RAP binders. Further testing on mortar and fine aggregate matrix (FAM) mixes is warranted. Tests on mortar and fine aggregate matrix (FAM) mixes warrant further investigation.
- Adding RAP to a new asphalt mix can alter the volumetrics and performance of the mix. However, volumetric requirements can still be met with relatively high RAP contents (i.e., up to 25 percent). Compared to equivalent mixes without RAP, rutting performance was generally improved by the

addition of RAP, but cracking performance was generally worse. Conflicting results with regard to laboratory testing performance were reported.

- Given that the use of RAP for binder replacement and not just for aggregate replacement is a relatively new practice, there is limited knowledge on the long-term field performance of mixes containing high RAP contents (i.e., above 25 percent binder replacement), specifically with regard to the rate of binder aging and its effect on stiffness and susceptibility to cracking. Conventional laboratory aging procedures have not been verified for high RAP mixes.
- No published literature on the use of reclaimed rubberized asphalt concrete in new asphalt mixes was located.
- Only limited published research on the use of RAP in rubberized asphalt concrete was located, and all of it referred to binders containing less than 10 percent rubber by weight of the binder and used in dense-graded mixes.
- Most of the research reported in the literature covered laboratory testing under controlled conditions. Only limited published work was found on long-term field assessments that compared mixes containing RAP with equivalent control mixes containing no RAP.

The following key observations were made during the development of mix designs used to prepare mixes for laboratory testing:

- Dense-graded HMA mixes:
  + No concerns were identified during the development of the conventional dense-graded mix with reclaimed rubberized asphalt pavement materials. Mixes with 15 and 25 percent RAP binder replacement were prepared, and they met all volumetric requirements listed in the Caltrans 2015 specifications.
- Gap-graded RHMA mixes:
  + Initial gap-graded mix design experimentation revealed that a maximum of only 10 percent RAP binder replacement could be achieved while still meeting the specified gradation requirements for gap-graded mixes; mixes with greater than 10 percent RAP binder replacement did not meet those requirements (the initial workplan proposed evaluating mixes with 15 and 25 percent RAP binder replacement). This was attributed to the processed RAP materials used in this study (and considered representative of RAP materials in California in general) having relatively high percentages of small and fine aggregate (74 percent passing the 4.75 mm [#4] sieve), much of which is not permitted in a gap-gradation. An attempt to use higher proportions of coarse RAP to compensate for the lower proportions of fine RAP resulted in a lower-than-target binder content, as coarse RAP fractions tend to have limited asphalt binder coating.
  + The mix design met all Caltrans specification requirements except air-void content. Due to time and funding constraints, a decision was made to proceed with the preliminary tests despite not meeting the air void target given that general performance trends were unlikely to be significantly affected by this parameter.

The following key observations were made during the analysis of the results of binder testing (Phase 1a):

- Rubber modification appeared to reduce the aging susceptibility of asphalt binders in that less change was observed in their rheological properties than the rheology changes in the rheology of the base binder after extended PAV aging for 40 hours at 100°C.
- The age-hardened asphalt rubber binder (R-RAP) was less temperature susceptible than the age-hardened conventional binder (RAP). At 64°C, the RAP and R-RAP binders had approximately the same stiffness; however, with an increase in temperature, the high PG limit of the R-RAP binder was 15°C higher than that of the RAP binder. The viscosity of the R-RAP binder (at 135°C) was 10 times higher than that of the RAP binder.
- Blending simulated RAP binder with conventional binder increased the viscosity (at 135°C) and stiffness of the composite binder at both high and low in-service temperatures. It also reduced the relaxation potential of the binder at low temperature, which was indicated by a reduction in m-value. In addition, the average percent recovery and the recoverable creep compliance of conventional asphalt binder decreased when RAP binder was added.
- Adding R-RAP binder to conventional binder increased the viscosity (at 135°C) and stiffness at high temperatures, which implies that these mixes could be less workable and more difficult to compact, but could have better rutting performance. At low temperatures (i.e., -6°C) the added R-RAP binder caused small reductions in the creep stiffness and relaxation potential (m-value), which implies that the R-RAP would have a limited effect on low-temperature cracking. The average percent recovery of the composite binder increased (indicating improved rutting performance) and the recoverable creep compliance decreased (indicating diminished cracking performance) with increasing R-RAP content.
- Adding simulated RAP binder to asphalt rubber binder reduced its viscosity, but barely changed the high PG grade, indicating no adverse impact to workability or rutting performance. At the low test temperature, the creep stiffness of the asphalt rubber binder increased and the m-value decreased with increasing RAP content, which indicates an increased potential for thermal cracking. The effect of RAP content on average percent recovery and recoverable creep compliance of asphalt rubber binders was minimal.

The following key observations were made during the analysis of the results of fine aggregate matrix mix testing (Phase 1b):

- The stiffness of the mixes increased with increasing R-RAP or RAP content, as expected.
- The behavior of mixes prepared with laboratory-prepared R-RAP and RAP was inconsistent with that of the mixes prepared with field-sampled RAP and R-RAP materials, indicating that the laboratory aging procedures used in this study were not necessarily representative of field conditions. This contradicts findings reported in the literature.
- The trends in change of stiffness over the range of frequencies were similar for both types of mix; however, the gap-graded RHMA mixes appeared to be less sensitive to changes in frequency (i.e., less sensitive to changes in temperature) than the dense-graded HMA mixes.
- Adding 15 and 25 percent R-RAP sourced from two different road projects increased the mix stiffness by up to 3.8 and 9.2 times that of the control (at 0.001 Hz), respectively. This implies better rutting performance than the mixes containing no R-RAP. Mix behavior was dependent on

R-RAP source, with the source known to be contaminated with conventional RAP millings having a greater effect on stiffness increase.
- Adding 10 percent RAP, sourced from a stockpile at an asphalt plant, to the gap-graded RHMA mix increased the stiffness by a maximum of almost two times that of the control (recorded at about 0.001 Hz, corresponding to a higher than median temperature).

The following key observations were made during the analysis of the results of full-graded mix testing (Phase 2):

- The test methods used in this phase of the study were sufficiently sensitive to distinguish the behavior of the different mixes and to consistently distinguish the differences in performance of mixes containing no RAP (i.e., control mixes) and mixes containing R-RAP and RAP. However, all testing was undertaken on newly prepared laboratory specimens, and consequently do not necessarily reflect long-term performance of the mixes or the longer-term effects of the RAP and R-RAP binder on the rate of aging of the virgin binder.
- Adding RAP and R-RAP increased the stiffness of the mixes, which in most instances improved the rutting resistance of the mix, but diminished the fatigue cracking resistance at a given strain.
- Adding R-RAP to dense-graded HMA could potentially yield some improvement in overall rutting performance, but it could also have a potentially overall negative effect on fatigue and low-temperature cracking performance. These findings are consistent with those from tests where conventional RAP was used. However, the degree of change in rutting and cracking resistance was dependent on the R-RAP source, with mixes containing millings only from RHMA layers performing slightly better than mixes containing both R-RAP and RAP, but with test results for each source ranking consistently across the different tests.
- Adding RAP to gap-graded RHMA mixes appears to improve rutting performance but diminish cracking performance (when evaluated in a mechanistic analysis considering structure and load), thereby potentially negating the benefits of selecting RHMA-G as an overlay to retard the rate of reflection cracking.

8.2 Conclusions

The results of tests conducted in this UCPRC study led to the following conclusions:

- Adding RAP milled from rubberized asphalt concrete pavement layers to new conventional dense-graded mixes will generally result in better rutting performance, but diminished cracking performance, at both high and low temperatures. Although mixes containing conventional RAP were not included as additional controls to compare performance of the R-RAP and RAP in dense-graded HMA mixes, the difference in behavior between the two different R-RAP sources (one contaminated with conventional RAP from the underlying layer) provides an indication that there could be a negligible difference between mixes prepared with R-RAP and mixes prepared with conventional RAP resulting from the earlier rubber modification (i.e., mixes containing R-RAP are likely to have marginally better performance than mixes containing conventional RAP). Based on these findings, there appears to be no reason or justification for separating R-RAP and RAP or maintaining separate R-RAP and RAP stockpiles at asphalt plants. Given that the mixes tested had the same gradation and binder content and similar volumetric properties, RAP should not be considered as a generic material with consistent properties.

- Adding RAP to gap-graded asphalt rubber mixes used in overlays will potentially have some improvement in overall rutting performance, but a potentially overall negative effect on fatigue cracking performance (based on a mechanistic analysis considering structure and load). More comprehensive testing should be carried out before any changes to current practice are considered.
- All testing in this study was undertaken on newly prepared laboratory specimens (with and without accelerated aging), and consequently do not necessarily reflect long-term field performance of the mixes or the longer-term effects of the RAP binder on the rate of aging of the virgin binder.

8.3 Recommendations

The following recommendations are made:

- Only limited testing on asphalt rubber mixes containing RAP was undertaken in this study. Therefore further laboratory testing and mechanistic analyses, followed by full-scale field testing in pilot projects or accelerated load testing is recommended on a wider range of virgin binder, virgin aggregate, and RAP material sources to confirm the findings before any changes to current practice are considered. This future testing should also investigate the potential use of these mixes in intermediate layers in long-life pavement designs, where an optimal combination of rutting and cracking resistance might offer an appropriate alternative to conventional mixes in this type of structure.
- Additional investigation to assess the effect of replaced binder from RAP on the rate of aging of virgin binders and of potential consequential effects on cracking (low-temperature, top-down, and fatigue) is required as this parameter has not been adequately quantified.

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