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Investigation into the Use of Reclaimed Asphalt Pavement in Gap- and Open-Graded Asphalt Rubber Mixes: Phase 2: Laboratory Testing of Aggregate Replacement and CalME Simulation

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Investigation into the Use of Reclaimed Asphalt Pavement in Gap- and Open-Graded Asphalt Rubber Mixes: Phase 2: Laboratory Testing of Aggregate Replacement and CalME Simulation

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16. ABSTRACT This report presents data and analysis completed to evaluate changes in mix properties and simulated mix performance in pavement structures when using coarse reclaimed asphalt pavement (RAP) materials in new gap- and open-graded rubberized hot mix asphalt (HMA) (structural performance for gap-graded mixes only) and to prepare recommendations and suggested specification language, if considered appropriate, for allowing the use of coarse RAP in gap- and open-graded rubberized hot mix asphalt. This report includes laboratory binder and mix testing, as well as CalME fatigue and reflective cracking simulation results for four plant-produced gap-graded rubberized hot mix asphalt (RHMA-G) mixes used on the Heavy Vehicle Simulator test track at the UCPRC. The four mixes had the same base binder and two aggregate gradations, both with and without RAP. Six laboratory-produced mixes were also tested, using rubberized binders from two field projects and two RAP sources. Three mixes were produced with each base asphalt rubber binder—one with no RAP and two with 10% RAP by dry weight of aggregate from each of the two RAP sources. Testing of all mixes included stiffness frequency sweeps, flexural fatigue, rutting, and moisture sensitivity. Binder testing was performed on binder extracted from the test track mixes. Four open-graded rubberized hot mix asphalt (RHMA-O) mixes were also tested in this study for draindown and mechanical durability. Pavement fatigue and reflective cracking performance were simulated using the CalME mechanistic-empirical software and the flexural stiffness and fatigue laboratory test results. Simulations included all the different plant-produced and laboratory-produced RHMA-G mixes. The simulations addressed questions regarding the effect of adding 10% RAP to the mixes, the effects of maximum aggregate size gradation, the effects of different RAP sources, the effects of different asphalt rubber binders, the effects of different ratios of RHMA to HMA in new asphalt layers, and the effects of using full-depth RHMA compared to using an RHMA surface on new HMA in new asphalt layers. Simulations included new or reconstructed pavement, asphalt overlays on cracked asphalt pavement, and asphalt overlays on cracked concrete pavement.		
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PROJECT OBJECTIVES

A preliminary study investigating the use of reclaimed asphalt pavement (RAP) materials in new rubberized gap-graded hot mix asphalt (RHMA-G) and the use of rubberized RAP (RRAP) in new conventional dense-graded hot mix asphalt was completed by the University of California Transportation Center (UCPRC) in 2016. Considerable interest has since been expressed by both the California Department of Transportation (Caltrans) and paving industry contractors in extending the investigation to develop guidance on the topic.

The second phase of this research, part of PPRC SPE 4.79: Guidance, Tests, and Specifications for High Recycled Asphalt Pavement/Recycled Asphalt Shingle Contents in HMA and RHMA Mixes, has the following objectives:

1. Evaluate changes in mix properties and simulated mix performance in pavement structures when using coarse reclaimed asphalt pavement materials in new gap- and open-graded rubberized hot mix asphalt (structural performance for gap-graded mixes only).
2. Prepare recommendations and suggested specification language, if considered appropriate, for allowing the use of coarse RAP in gap- and open-graded rubberized hot mix asphalt.

These objectives will be achieved through the following tasks:

1. Literature review, detailed work plan, and sample collection
2. Laboratory testing
3. Mechanistic analysis
4. Preparation of a research report

This report completes the work of all four tasks.

The work presented in this report includes work funded by the California Department of Resources Recycling and Recovery (CalRecycle) and the California Department of Transportation (Caltrans). The sampling, laboratory testing, and mechanistic-empirical (using *CalME* software) simulations for the four RHMA-G mixes used in the Heavy Vehicle Simulator (HVS) test track were funded by CalRecycle. The sampling, laboratory testing, and *CalME* simulations for the mixes (RHMA-G and RHMA-O [laboratory testing only for the latter]) prepared using the asphalt rubber

binders sampled from the BUT 162 and IMP 186 projects were funded by Caltrans. The development of conclusions and writing of the report were supported by CalRecycle funding.

The laboratory testing of the mixes used in the HVS test track and the CalME simulations evaluating the use of thicker layers of RHMA-G in this report cover part of the scope of PPRC SPE 4.75, RHMA-G Layer Thickness Limits, which is a continuation of PPRC SPE 4.63. PPRC SPE 4.75 has the objective of developing updated criteria for determining thickness limits of RHMA-G layers, and the following tasks:

- Task 1: Complete HVS and associated laboratory testing of RHMA-G mixes that focus on nominal maximum aggregate size in 0.2 ft-thick layers, layer thickness, and the use of coarse RAP as aggregate replacement.
- Task 2: Complete *CalME* simulations using data collected during Task 1.
- Task 3: Revise life cycle cost analysis (LCCA) and life cycle assessment (LCA) information for RHMA-G applications and perform case study evaluations of the effects of implementing preliminary recommendations based on the results from Task 2.
- Task 4: Prepare a research report and, if justified, recommendations for updated Highway Design Manual language for RHMA-G design and use criteria.

This report completes the work of laboratory testing of Task 1 as well as Tasks 2 and 4.

EXECUTIVE SUMMARY

As asphalt concrete surface layers on highways and airfields reach the end of their service lives, they are milled off and replaced with new hot mix asphalt (HMA) or new rubberized hot mix asphalt (RHMA). The millings are added to reclaimed asphalt pavement (RAP) stockpiles, which in turn are reused in new conventional and polymer-modified HMA. The amount of RAP used in new dense-graded HMA in California varies between 0% and 25% by weight of the total mix under standard specifications, but Caltrans is now piloting the use of RAP contents up to 40%, an amount that could be even greater in the future. A few local governments have tried RAP mixes in the range of 0% to 100%.

Caltrans currently does not permit the use of any RAP in rubberized gap-graded (RHMA-G) mixes or in rubberized open-graded mixes (RHMA-O). However, there is increasing interest in allowing some RAP either as binder or aggregate replacement in RHMA mixes to reduce the amount of virgin materials required, which can potentially help reduce cost and environmental impact.

The University of California Pavement Research Center (UCPRC) completed a preliminary study for the California Department of Resources Recycling and Recovery (CalRecycle) in 2017 that investigated the potential effects of using RAP materials as partial binder and aggregate replacement in new RHMA-G mixes. Limited laboratory test results indicated that test results from the RHMA-G mixes containing RAP indicated that rutting performance is likely to improve and stiffness to increase, but that adding RAP could have a negative effect on fatigue at a given strain and on low temperature cracking performance, which would typically negate the benefits of using RHMA-G as a thin overlay (currently typically 0.2 ft. [60 mm] or thinner) with good resistance to reflective cracking, low temperature cracking, and top-down age-related cracking.

Since only limited testing on RHMA-G mixes containing RAP was undertaken in the Phase 1 study, further laboratory testing, followed by full-scale field testing in pilot projects or accelerated wheel load testing, was 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 Phase 2 study is therefore considered a continuation of the Phase 1 study and is being conducted in parallel with a separate accelerated pavement study that is testing RHMA-G

mixes with 10% RAP aggregate replacement under accelerated pavement testing with Heavy Vehicle Simulators (HVSs).

The work presented in this report addresses the growing interest in adding some RAP to RHMA mixes. However, if binder replacement is the goal, then the amount of recycled tire rubber used will be reduced. Binder replacement in HMA mixes is typically achieved by using finer fractions of RAP (i.e., finer than 3/8 in. [9.5 mm]). Depending on plant operations, coarser RAP may be left over after removing the finer fractions for use in new HMA mixes. The coarse RAP can be used as an aggregate replacement with minimal binder replacement. Research is needed to assess using coarser RAP in RHMA mixes, with a focus on replacing virgin aggregate with minimal effect on binder properties and no binder replacement in the mix design calculations. This will allow some RAP addition to RHMA-G and potentially RHMA-O mixes, thereby using all processed RAP without reducing the recycled tires that are used in the mix or reducing the crack retardation benefits of these mixes.

The goal of this CalRecycle/Caltrans/UCPRC RAP initiative is the development of guidance for determining optimal replacement rates for virgin binder and aggregate with RAP in RHMA mixes. This second phase of the research has the following objectives:

1. Evaluate changes in mix properties and simulated mix performance in pavement structures when using coarse reclaimed asphalt pavement (RAP) materials in new gap- and open-graded RHMA (structural performance for gap-graded mixes only).
2. Prepare recommendations and suggested specification language, if considered appropriate, for allowing the use of coarse RAP in gap- and open-graded RHMA.

These objectives were achieved through the following tasks:

1. Literature review, detailed work plan, and sample collection
2. Laboratory testing
3. Mechanistic analysis
4. Preparation of a research report

This report completes the work of all four tasks.

The laboratory testing campaign documented in this report is intended to address the first objective of the study: Evaluate changes in mix properties and simulated mix performance in

pavement structures when using coarse RAP materials in new gap- and open-graded RHMA (structural performance for gap-graded mixes only).

To complete this objective, the experimental design, materials, and sampling and test methods are intended to answer the following questions:

1. What are the effects of using 10% coarse RAP by mass of mix on binder and RHMA-G mix performance-related properties for mixes with the same aggregate source compared with the same mixes with no RAP, checked for mixes with two different maximum aggregate sizes?
2. What are the effects of using 10% RAP by mass of mix on RHMA-G mix performance-related properties for mixes with the same aggregate source and maximum aggregate size, considering two RAP sources with different gradations (one coarse with a low binder content and one fine with a higher binder content) and different amounts of aging, and asphalt rubber (AR) base binders with different performance grades (PGs) and sources, compared with control mixes with no RAP?
3. What are the effects of using 10% coarse RAP by dry mass of aggregate on RHMA-O mix performance-related properties for mixes with different binder sources and the same aggregate source and aggregate gradation, compared with the same mixes with no RAP?

The experimental design to answer the first question consisted of four plant-produced mixes. These mixes were also used on the HVS test track, where they were tested for rutting under accelerated pavement testing with full-scale wheel loads at high temperatures. The mixes had the same AR binder and the same aggregate source. One pair of mixes, with and without 10% RAP by mass of mix, met Caltrans 1/2" maximum aggregate size gradation, and the other pair met the 3/4" gradation specification.

The experimental design to answer the second question used six laboratory-prepared mixes that had the same aggregate source and gradation as the plant mixes but used two different AR binders sampled from field projects in Butte County and Imperial County. The comparison included three mixes for each AR binder source, a control with no RAP, and two mixes with different RAP sources (RAP #1 and RAP #2).

The experiment to answer the third question about open-graded mixes included four laboratory-prepared mixes. The AR binders from the Butte County and Imperial County projects were used in mixes with the same aggregate source as was used for the gap-graded mixes, but with an open gradation. The same coarse RAP source used in the gap-graded plant mixes and as one of the two RAP sources in the gap-graded laboratory mixes was also used in the open-graded mixes, and the other was a fine RAP source with higher binder content. This experiment did not include binder testing.

The experimental design and test methods are presented in Chapter 4. Binder testing results are presented in Chapter 5. The laboratory test results for flexural stiffness and fatigue for RHMA-G mixes with no RAP and with 10% RAP were presented in Chapter 6. The results include testing for flexural and axial stiffness across a range of temperatures and frequencies (frequency sweep), flexural fatigue, fracture testing, and testing for rutting. The discussion in that chapter noted that the interactions of the stiffness and fatigue mix properties and the net effects of changes in both caused by adding RAP on fatigue and reflective cracking performance are best evaluated through mechanistic-empirical (ME) simulation. *CalME* is the ME simulation software used by Caltrans for the design of asphalt-surfaced pavements. Chapter 7 presents the results of the mix testing on open-graded mixes (RHMA-O).

Chapter 8 presents comparisons of pavement performance of mixes with and without RAP using *CalME* simulations and the stiffness and fatigue data presented in Chapter 6 for the four plant-produced test track mixes and six laboratory-produced mixes. A range of pavement structures with the RHMA-G mixes as surface layers were simulated for bottom-up fatigue cracking for new or reconstructed pavements and for reflective cracking for overlays on cracked asphalt pavement and cracked and seated concrete pavement.

The *CalME* simulations addressed questions regarding the effect of adding 10% RAP to the mixes, the effects of maximum aggregate size gradation, the effects of different RAP sources, the effects of different AR binders, the effects of different ratios of RHMA to HMA in new asphalt layers, and the effects of using full-depth RHMA compared to using an RHMA surface on new HMA in new

asphalt layers. Simulations included new or reconstructed pavement, asphalt overlays on cracked asphalt pavement, and asphalt overlays on cracked concrete pavement.

A summary, conclusions regarding all research questions addressed by the study, and preliminary recommendations are presented in Chapter 9. Based on the limited sets of mixes evaluated in this report, the following are preliminary recommendations for the use of RAP in RHMA-G and RHMA-O mixes:

- Allow the use of 10% RAP in RHMA-G without restriction on gradation.
 - + Keep the same aggregate gradation limits.
 - + Consider collecting data on the combined virgin and RAP binder blended low temperature PG grade based on binder blending charts for at least several years of implementation and monitoring the results of those projects for age-related cracking. This will provide a better indication regarding how much the different RAP sources in the state will change the low temperature performance of the combined binders. This may be a somewhat conservative recommendation; however, RHMA-G is used exclusively as a surface mix where aging and age-related and low temperature cracking are most important.
 - + Alternatively, implement the UCPRC recommendations for extracting the rubber from the binder before performing the bending beam rheometer test.
- Allow the use of 10% coarse RAP in RHMA-O.
 - + Develop a grading specification for coarse RAP that is practical but will not interfere with the open-graded gradation requirements.
 - + Consider collecting data on the combined virgin and RAP binder blended low temperature PG grade based on binder blending charts for at least several years of implementation and monitoring the results of those projects for age-related cracking. As noted for RHMA-G, this may be a conservative recommendation but is important for these mixes used exclusively on the surface.
 - + Alternatively, implement the UCPRC recommendations for extracting the rubber from the binder before performing the bending beam rheometer test.

Other preliminary recommendations drawn from the results of the project are:

- Continue work on a repeated load fatigue test for mix or fine aggregate mix test (FAM) for HMA and RHMA-G to identify and eventually develop specifications to minimize the use of binders with fatigue performance that is considerably worse than the current statewide median. It is important to identify mixes with poor laboratory fatigue performance that are likely contributing to poor performance in the state highway network. Fracture testing has

been shown in this study and other recent studies to provide a good indicator of flexural stiffness, but it is unable to identify mixes with poor fatigue performance.

- Identify whether there is sufficient data in the Caltrans job mix formula data identifying binder sources to evaluate whether the high sensitivity of fatigue performance to binder source, as opposed to the binder grade identified in laboratory testing and *CalME* simulations, is also evident in pavement management system (PMS) field performance data.
- Implement a medium-term oven aging protocol for mix design to capture the effects of silo aging and early to medium-term aging in place.
- Consider the use of full-depth RHMA with or without 10% RAP in overlays and new pavement up to 0.5 ft. thick.
- Continue work on characterizing the effect of 10% to 25% RAP on RHMA-G material performance-related properties, including consideration of recycling agents.

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LIST OF ABBREVIATIONS

AC	Asphalt concrete
AMPT	Asphalt mixture performance tester
AR	Asphalt rubber
BBR	Bending beam rheometer
CA	Carbonyl
COV	Coefficient of variation
CRM	Crumb rubber modifier
DF	Degrees of freedom
DM	Dynamic modulus
DSR	Dynamic shear rheometer
ESAL	Equivalent single axle loads
FAM	Fine aggregate matrix
FAT	Beam fatigue
FI	Flexibility index
FM	Flexural modulus
FS	Frequency sweep
FTIR	Fourier transform infrared
FTIR-ATR	Fourier transform infrared spectroscopy with attenuated total reflective
HMA	Hot mix asphalt
HVS	Heavy Vehicle Simulator
LCA	Life cycle assessment
LCCA	Life cycle cost analysis
ME	Mechanistic empirical
MSCR	Multiple stress creep recovery
NMAS	Nominal maximum aggregate size
OGFC	Open-graded friction course
PAS	Permanent axial strain
PAV	Pressure aging vessel
PCC	Portland cement concrete
PG	Performance grade

PG-AR	Performance grade of asphalt rubber binders
PMS	Pavement management system
PSP	Proficiency sample program
RAP	Reclaimed asphalt pavement
RHMA	Rubberized hot mix asphalt
RHMA-G	Rubberized hot mix asphalt–gap-graded
RHMA-O	Rubberized hot mix asphalt–open-graded
RLT	Repeated load triaxial
RRAP	Reclaimed rubberized asphalt pavement
RTFO	Rolling thin film oven
SCB	Semicircular bend
SE	Standard error
SG	Subgrade
SSD	Saturated surface dry
SUL	Sulfoxide
Superpave	SUperior PERforming Asphalt PAVement
WIM	Weigh-in-motion

LIST OF TEST METHODS CITED IN THIS REPORT

AASHTO

- M 320 Standard Specification for Performance-Graded Asphalt Binder
- M 323 Standard Specification for Superpave Volumetric Mix Design
- PP 3 Standard Practice for Preparing Hot Mix Asphalt (HMA) Specimens by Means of the Rolling Wheel Compactor
- R 28 Standard Practice for Accelerated Aging of Asphalt Binder Using a Pressurized Aging Vessel (PAV)
- R 30 Standard Practice for Mixture Conditioning of Hot Mix Asphalt (HMA)
- T 84 Standard Method of Test for Specific Gravity and Absorption of Fine Aggregate
- T 85 Standard Method of Test for Specific Gravity and Absorption of Coarse Aggregate
- T 164 Standard Method of Test for Quantitative Extraction of Asphalt Binder from Hot Mix Asphalt (HMA)
- T 166 Standard Method of Test for Bulk Specific Gravity (Gmb) of Compacted Hot Mix-Asphalt (HMA) Using Saturated Surface-Dry Specimens
- T 209 Standard Method of Test for Theoretical Maximum Specific Gravity (Gmm) and Density of Hot Mix Asphalt (HMA)
- T 240 Standard Method of Test for Effect of Heat and Air on a Moving Film of Asphalt Binder (Rolling Thin-Film Oven Test)
- T 308 Standard Method of Test for Determining the Asphalt Binder Content of Hot Mix-Asphalt (HMA) by the Ignition Method
- T 312 Standard Method of Test for Preparing and Determining the Density of Asphalt Mix Specimens by Means of the Superpave Gyratory Compactor
- T 313 Standard Method of Test for Determining the Flexural Creep Stiffness of Asphalt Binder Using the Bending Beam Rheometer
- T 315 Standard Method of Test for Determining the Rheological Properties of Asphalt Binder Using a Dynamic Shear Rheometer
- T 316 Standard Method of Test for Viscosity Determination of Asphalt Binder Using Rotational Viscometer
- T 321 Standard Method of Test for Determining the Fatigue Life of Compacted Asphalt Mixtures Subjected to Repeated Flexural Bending
- T 331 Bulk Specific Gravity (Gmb) and Density of Compacted Hot Mix Asphalt (HMA) Using Automatic Vacuum Sealing Method
- T 350 Standard Method of Test for Multiple Stress Creep Recovery (MSCR) Test of Asphalt Binder Using a Dynamic Shear Rheometer (DSR)

- T 378 Standard Method of Test for Determining the Dynamic Modulus and Flow Number for Asphalt Mixtures Using the Asphalt Mixture Performance Tester (AMPT)
- TP 124 Provisional Standard Method of Test for Determining the Fracture Potential of Asphalt Mixtures Using Semicircular Bend Geometry (SCB) at Intermediate Temperature

ASTM

- D 7064 Standard Practice for Open-Graded Friction Course (OGFC) Asphalt Mixture Design

CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS				
Symbol	When You Know	Multiply By	To Find	Symbol
LENGTH				
in.	inches	25.40	millimeters	mm
ft.	feet	0.3048	meters	m
yd.	yards	0.9144	meters	m
mi.	miles	1.609	kilometers	km
AREA				
in ²	square inches	645.2	square millimeters	mm ²
ft ²	square feet	0.09290	square meters	m ²
yd ²	square yards	0.8361	square meters	m ²
ac.	Acres	0.4047	hectares	ha
mi ²	square miles	2.590	square kilometers	km ²
VOLUME				
fl. Oz.	fluid ounces	29.57	milliliters	mL
gal.	gallons	3.785	liters	L
ft ³	cubic feet	0.02832	cubic meters	m ³
yd ³	cubic yards	0.7646	cubic meters	m ³
MASS				
oz.	ounces	28.35	grams	g
lb.	pounds	0.4536	kilograms	kg
T	short tons (2000 pounds)	0.9072	metric tons	t
TEMPERATURE (exact degrees)				
°F	Fahrenheit	(F-32)/1.8	Celsius	°C
FORCE and PRESSURE or STRESS				
lbf	pound-force	4.448	newtons	N
lbf/in ²	pound-force per square inch	6.895	kilopascals	kPa
APPROXIMATE CONVERSIONS FROM SI UNITS				
Symbol	When You Know	Multiply By	To Find	Symbol
LENGTH				
mm	millimeters	0.03937	inches	in.
m	meters	3.281	feet	ft.
m	meters	1.094	yards	yd.
km	kilometers	0.6214	miles	mi.
AREA				
mm ²	square millimeters	0.001550	square inches	in ²
m ²	square meters	10.76	square feet	ft ²
m ²	square meters	1.196	square yards	yd ²
ha	hectares	2.471	acres	ac.
Km ²	square kilometers	0.3861	square miles	mi ²
VOLUME				
mL	milliliters	0.03381	fluid ounces	fl. Oz.
L	liters	0.2642	gallons	gal.
m ³	cubic meters	35.31	cubic feet	ft ³
m ³	cubic meters	1.308	cubic yards	yd ³
MASS				
g	grams	0.03527	ounces	oz.
kg	kilograms	2.205	pounds	lb.
t	metric tons	1.102	short tons (2000 pounds)	T
TEMPERATURE (exact degrees)				
°C	Celsius	1.8C + 32	Fahrenheit	°F
FORCE and PRESSURE or STRESS				
N	newtons	0.2248	pound-force	lbf
kPa	kilopascals	0.1450	pound-force per square inch	lbf/in ²

*SI is the abbreviation for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
(Revised April 2021)

1 INTRODUCTION

1.1. Background to the Study

As asphalt concrete surface layers on highways and airfields reach the end of their service lives, they are milled off and replaced with new hot mix asphalt (HMA) or new rubberized hot mix asphalt (RHMA). The millings are added to reclaimed asphalt pavement (RAP) stockpiles, which in turn are reused in new conventional and polymer-modified HMA. The amount of RAP used in new dense-graded HMA in California varies between 0% and 25% by weight of total mix under standard specifications, but Caltrans is now piloting the use of RAP contents up to 40%, an amount that could be even greater in the future. A few local governments have tried mixes with RAP contents up to 100%, and the City of Los Angeles has routinely used RAP contents of 40% and 50%. Caltrans currently does not permit the use of any RAP in rubberized gap-graded (RHMA-G) mixes or in rubberized open-graded mixes (RHMA-O). However, there is increasing interest in allowing some RAP either as binder or aggregate replacement in RHMA mixes to reduce the amount of virgin materials required.

1.2. Phase 1 Study

The University of California Pavement Research Center (UCPRC) completed a preliminary study (1) for the California Department of Resources Recycling and Recovery (CalRecycle) in 2017 that investigated the potential effects of using reclaimed rubberized asphalt pavement (RRAP) materials as partial binder and aggregate replacement in new conventional dense-graded HMA mixes and using RAP materials as partial binder and aggregate replacement in new RHMA-G mixes.

Limited laboratory test results indicated that adding RRAP to dense-graded HMA could potentially yield some improvement in overall rutting performance and an increase in stiffness, but it could also have a potentially overall negative effect on mix fatigue at a fixed strain level and on low temperature cracking performance. These findings were consistent with those from tests where conventional RAP was used. The net effect on the fatigue of a pavement structure of the increased stiffness and decrease of mix fatigue life at a given strain will depend on the thickness of the asphalt layers and where in those asphalt layers the HMA is used. The degree of change in rutting and cracking resistance in the HMA mixes was dependent on the RRAP source,

with mixes containing only RRAP millings performing slightly better than mixes containing both RRAP and RAP. These findings indicate that there is no reason or justification for separating RRAP and RAP millings or maintaining separate stockpiles at asphalt plants unless the specific properties of a given RRAP or RAP are desired to engineer the properties of the HMA.

Test results from the RHMA-G mixes containing RAP indicated that rutting performance is likely to improve and stiffness to increase, but that adding RAP could have a negative effect on fatigue at a given strain and on low temperature cracking performance, which would typically negate the benefits of using RHMA-G as a thin overlay (currently typically 0.2 ft. [60 mm] or thinner) with good resistance to reflective cracking, low temperature cracking, and top-down age-related cracking. Since only limited testing on RHMA-G mixes containing RAP was undertaken in the Phase 1 study, further laboratory testing, followed by full-scale field testing in pilot projects or accelerated wheel load testing, was 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 Phase 2 study is therefore considered a continuation of the Phase 1 study and is being conducted in parallel with a separate accelerated pavement study that is testing RHMA-G mixes with 10% RAP aggregate replacement under accelerated pavement testing with Heavy Vehicle Simulators (HVSs) (2).

1.3. Problem Statements Pertinent to Adding RAP to RHMA Mixes

There is growing interest in adding some RAP to RHMA mixes. However, if binder replacement is the goal, then the amount of recycled tire rubber used will be reduced. Binder replacement in HMA mixes is typically achieved by using finer fractions of RAP (i.e., finer than 3/8 in. [9.5 mm]). Depending on plant operations, coarser RAP may be left over after removing the finer fractions for use in new HMA mixes. The coarse RAP can be used as an aggregate replacement with minimal binder replacement. Research is needed to assess using coarser RAP in RHMA mixes, with a focus on replacing virgin aggregate with minimal effect on binder properties and no binder replacement in the mix design calculations. This will allow some RAP addition to RHMA-G and potentially RHMA-O mixes, thereby using all processed RAP without reducing the recycled tires that are used in the mix or reducing the crack retardation benefits of these mixes.

1.4. Project Objectives

The goal of this CalRecycle/Caltrans/UCPRC RAP initiative is the development of guidance for determining optimal replacement rates for virgin binder and aggregate with RAP in RHMA mixes.

The second phase of this research (part of PPRC SPE 4.79) has the following objectives:

1. Evaluate changes in mix properties and simulated mix performance in pavement structures when using coarse RAP materials in new RHMA-G and RHMA-O (structural performance for gap-graded mixes only).
2. Prepare recommendations and suggested specification language, if considered appropriate, for allowing the use of coarse RAP in RHMA-G and RHMA-O.

These objectives will be achieved through the following tasks:

1. Literature review, detailed work plan, and sample collection
2. Laboratory testing
3. Mechanistic analysis
4. Preparation of a research report

This report completes the work of all four tasks. The work presented in this report includes work funded by the California Department of Resources Recycling and Recovery (CalRecycle) and the California Department of Transportation (Caltrans). The sampling, laboratory testing, and mechanistic-empirical (ME) (using *CalME* software) simulations for the four RHMA-G mixes used in the Heavy Vehicle Simulator (HVS) test track were funded by CalRecycle. The sampling, laboratory testing, and *CalME* simulations for the mixes (RHMA-G and RHMA-O [laboratory testing only for the latter]) prepared using the asphalt rubber (AR) binders sampled from the BUT 162 and IMP 186 projects were funded by Caltrans. The development of conclusions and writing of the report were supported by CalRecycle funding.

The goal of laboratory testing of the mixes used in the HVS test track and the *CalME* simulations looking at RHMA-G thickness included in this research report is the development of updated criteria for determining thickness limits of RHMA-G layers. The project (PPRC SPE 4.75) has the following tasks:

- Task 1: Complete HVS and associated laboratory testing of RHMA-G mixes that focus on nominal maximum aggregate size in 0.2 ft. thick layers, layer thickness, and the use of coarse RAP as aggregate replacement.

Task 2: Complete *CalME* simulations using data collected during Task 1.

Task 3: Revise LCCA and LCA information for RHMA-G applications and perform case study evaluations of the effects of implementing preliminary recommendations based on the results from Task 2.

Task 4: Prepare a research report and, if justified, recommendations for updated Highway Design Manual language for RHMA-G design and use criteria.

This report completes the work of laboratory testing of Task 1 as well as Tasks 2 and 4.

1.5. Report Structure

This report includes the following chapters and appendices, which address the tasks discussed in Section 1.4:

- Chapter 2 summarizes the findings from the Phase 1 study.
- Chapter 3 summarizes recent published literature relevant to the use of RAP in RHMA mixes, addressing Task 1.
- Chapter 4 details the experimental design, materials, sampling and test methods, and mix designs, addressing Task 1.
- Chapter 5 to Chapter 7 discuss the results from the testing of binders and RHMA-G and RHMA-O mixes, addressing Task 2.
- Chapter 8 covers the *CalME* simulations using the results presented in Chapter 5 to Chapter 7, addressing Task 3.
- Chapter 9 presents the conclusions and recommendations, including recommended specification language.
- Appendix A includes binder testing results, and Appendix B includes mix testing results.

1.6. Measurement Units

Although Caltrans recently returned to the use of US standard measurement units, metric units have always been used by the UCPRC in the design and layout of test tracks, as well as for laboratory, Heavy Vehicle Simulator (HVS), and field measurements and data storage. In this report, both US and metric units (provided in parentheses after the US units) are provided in the general discussion. In keeping with convention, metric units are used in laboratory data analyses

and reporting, with some US units, where appropriate, to assist the reader. A conversion table is provided on page xii.

2 SUMMARY OF THE PHASE 1 STUDY

2.1. Introduction

The use of 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. No published information or experience documenting whether the use of RAP containing rubber could influence mix performance was located. 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 and/or aggregate replacement in gap- and open-graded mixes to reduce the amount of virgin materials required.

The Phase 1 study (1), published in 2017, investigated the effects of using RRAP 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 AR mixes. A literature survey was completed, and a small number of mixes were evaluated for performance-related properties using laboratory-prepared mixes.

2.2. Literature Review

Key points from the literature review conducted as part of the 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 PGs 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. AR 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.

- Adding RAP to a new asphalt mix can alter the volumetrics and performance-related properties of the mix. However, volumetric requirements can still be met with relatively high RAP contents (i.e., up to 25%). Compared to equivalent mixes without RAP, rutting performance and stiffness were generally improved by the addition of RAP, but cracking performance was generally worse as measured by fatigue tests at a constant strain and fracture tests. Conflicting results from 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% binder replacement), specifically regarding 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 pavement (RRAP) in new asphalt mixes was located.
- 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% 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. Limited published work was found on long-term field assessments that compared mixes containing RAP with equivalent control mixes containing no RAP.

2.3. Mix Designs

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 mixes with RRAP materials. Mixes with 15% and 25% RAP binder replacement were

prepared, and they met all volumetric requirements listed in the Caltrans 2015 specifications.

- Gap-graded RHMA mixes:
 - + The initial workplan proposed evaluating mixes with 15% and 25% RAP binder replacement. Initial gap-graded mix design experimentation revealed that a maximum of only 10% RAP binder replacement could be achieved while still meeting the aggregate gradation specifications for gap-graded mixes. 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% passing the 4.75 mm [#4] sieve), and the gap gradation specifications having small amounts of those sizes. 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 for air-void content under standard gyratory compaction. 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 small deviations in this parameter.

2.4. Binder Testing

The following key observations were made during the analysis of the results of binder testing:

- Rubber modification appeared to reduce the aging susceptibility of asphalt binders in that less change was observed in their rheological properties than the rheological changes of the base binder after extended aging in a pressure aging vessel (PAV) for 40 hours at 100°C.
- The age-hardened AR binder, RRAP, was less temperature-susceptible than the age-hardened conventional binder, RAP. At 64°C, the RAP and RRAP binders had approximately the same stiffness; however, the high performance grade (PG) limit of the RRAP binder was 15°C higher than that of the RAP binder. The viscosity of the RRAP 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 temperatures, 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 RRAP 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 RRAP binder caused small reductions in the creep stiffness and relaxation potential (m-value), which implies that the RRAP 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 RRAP content.
- Adding simulated RAP binder to AR binder reduced its viscosity but barely changed the high PG, indicating no adverse impact on workability or rutting performance. At the low temperature test, the creep stiffness of the AR binder increased, and the m-value decreased with increasing RAP content, which indicates an increased potential for low temperature cracking. The effect of RAP content on average percent recovery and recoverable creep compliance of AR binders was minimal.

2.5. Fine Aggregate Matrix Mix Testing

The following key observations were made during the analysis of the results of FAM mix testing:

- The stiffness of the mixes increased with increasing RRAP or RAP content, as expected.
- The behavior of mixes prepared with laboratory-prepared RRAP and RAP was inconsistent with that of the mixes prepared with field-sampled RAP and RRAP materials, indicating that the laboratory aging procedures used in this study were not necessarily representative of field conditions in creating RAP and RRAP. This contradicts findings reported in the literature.
- The trends in the change of stiffness over the range of frequencies were similar for both types of mixes; however, the gap-graded RHMA mixes appeared to be less sensitive to changes in frequency, which also means they are less sensitive to changes in temperature than the dense-graded HMA mixes.
- Adding 15% and 25% RRAP sourced from two different road projects to the HMA 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 RRAP. Mix behavior was dependent on RRAP source, with the source known to be contaminated with conventional RAP millings having a greater effect on stiffness increase.

- Adding 10% 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).

2.6. Full-Graded Mix Testing

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

- 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 RRAP and RAP. However, all testing was undertaken on newly prepared laboratory specimens and, consequently, does not necessarily reflect long-term performance of the mixes or the longer-term effects of the RAP and RRAP binder on the rate of aging of the mix containing a blend of RAP or RRAP and virgin binder.
- Adding RAP and RRAP 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 RRAP to dense-graded HMA could potentially yield some improvement in overall rutting performance, but it could also have a potentially overall negative effect on low temperature cracking performance and on fatigue and reflective cracking performance when used in thinner asphalt layers or overlays. 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 RRAP source, with mixes containing millings only from RHMA layers performing slightly better than mixes containing both RRAP and RAP, but with test results for each source ranking consistently across the different tests.
- Adding RAP to gap-graded RHMA mixes appeared to improve rutting performance but diminish fatigue and reflective cracking performance of structures 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 reflective cracking. The potential effects of the higher-than-target mix design air-void content were considered during the analysis of the results.

2.7. Conclusions

The results from the Phase 1 testing led to the following conclusions:

- Adding RAP milled from RHMA pavement layers to new conventional dense-graded HMA will generally result in better rutting performance at high temperatures, diminished low temperature cracking performance at low temperatures, and diminished fatigue and reflective cracking performance when evaluated in mechanistic structural analysis. Although mixes containing conventional RAP were not included in HMA as additional controls to compare the performance of RRAP and RAP in dense-graded HMA mixes, the difference in behavior between the two different RRAP sources (one contaminated with conventional RAP from the underlying layer) provides an indication that there could be a negligible difference between mixes prepared with RRAP and mixes prepared with conventional RAP, although mixes containing RRAP are likely to have marginally better performance than mixes containing conventional RAP resulting from the previous rubber modification. Based on these findings, there appears to be no reason or justification for separating RRAP and RAP or maintaining separate RRAP 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 RHMA mixes used in overlays will potentially cause 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, does 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.

3 UPDATED LITERATURE REVIEW

A literature review of research undertaken on incorporating RAP materials in RHMA was completed in 2021. Research on both RAP binder replacement and RAP aggregate replacement was considered. Literature searches focused on the interactions of the aged binder in the RAP and the new asphalt rubber (AR) binder, mix design procedures to minimize any negative effects of this interaction, and any laboratory or field performance data from projects where RAP has been used in rubberized gap-graded (RHMA-G) or rubberized open-graded asphalt (RHMA-O) mixes.

Apart from the research previously undertaken by the UCPRC for CalRecycle (1), only limited new published research on the use of RAP in new RHMA mixes was located, with most of it focused on laboratory testing of dense-graded mixes produced with terminal-blended binders containing completely digested rubber particles smaller than 0.4 mm (passing the #40 sieve) in size (3–10), which is not applicable to the scope of this study.

One Canadian study investigated adding 20% RAP (by weight of the mix) into RHMA-G mixes produced with asphalt rubber binder containing 20% rubber by weight of the binder (11) and compared with a control dense-graded mix. Stiffness, rutting performance, and low temperature 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 low temperature cracking tests, while the dense-graded control mix performed better in rutting tests. Mixes 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 low temperature cracking.

No documented research involving pilot field studies or accelerated pavement testing of RHMA mixes containing RAP was located.

4 EXPERIMENT DESIGN, MATERIALS, TEST METHODS, SAMPLING, AND MIX DESIGNS

4.1. Overview

The laboratory testing campaign documented in this report is intended to address the first objective of the study: Evaluate changes in mix properties and simulated mix performance in pavement structures when using coarse RAP materials in new RHMA-G and RHMA-O (structural performance for gap-graded mixes only).

To complete this objective, the experimental design, materials, and sampling and test methods are intended to answer the following questions:

1. What are the effects of using 10% coarse RAP by mass of mix on binder and RHMA-G mix performance-related properties for mixes with the same aggregate source compared with the same mixes with no RAP, checked for mixes with two different maximum aggregate sizes?
2. What are the effects of using 10% RAP by mass of mix on RHMA-G mix performance-related properties for mixes with the same aggregate source and maximum aggregate size, considering two RAP sources with different gradations (one coarse with a low binder content and one fine with a higher binder content) and different amounts of aging, and AR base binders with different PGs and sources, compared with control mixes with no RAP?
3. What are the effects of using 10% coarse RAP by dry mass of aggregate on RHMA-O mix performance-related properties for mixes with different binder sources and the same aggregate source and aggregate gradation, compared with the same mixes with no RAP?

4.2. Experimental Design

The experimental designs deviated from the original workplan because an opportunity arose during another UCPRC project to sample two plant-produced RHMA-G mixes containing 10% RAP aggregate replacement along with two control mixes produced with the same AR binder and aggregates but no RAP. Discussions with industry partners also indicated that 10% aggregate replacement was an appropriate target to minimize any binder replacement. Based on these discussions, only one target aggregate replacement rate (10%) was evaluated instead of the two rates (10% and 15%) originally proposed. Laboratory testing covered both binder and mix testing.

The experimental design to answer the first question consisted of four plant-produced mixes, shown at the top of Table 4.1. Binder testing was performed for the control and RAP #1 binders and their blends in this experiment. These mixes were also used on the HVS test track, where they were tested for rutting under accelerated pavement testing with full-scale wheel loads at high temperatures. As shown in the table, the mixes had the same AR binder and the same aggregate source. One pair of mixes, with and without 10% RAP by mass of mix, met Caltrans 1/2" maximum aggregate size gradation, and the other pair met the 3/4" gradation specification.

The experimental design to answer the second question used six laboratory-prepared mixes that had the same aggregate source and gradation as the plant mixes but, as shown in Table 4.1, used two different AR binders sampled from field projects in Butte County and Imperial County. The comparison included three mixes for each AR binder source, a control with no RAP, and two mixes with different RAP sources (RAP #1 and RAP #2). RAP #1 came from a source in the Inland Valley climate region, and RAP #2 came from a source in the North Coast climate region. This experiment did not include true grade binder testing; instead, testing was performed on the virgin AR base binders and the two RAP sources to develop blending charts to estimate blended properties.

The experiment to answer the third question included four laboratory-prepared mixes, shown in Table 4.2. The AR binders from the Butte County and Imperial County projects were used in mixes with the same aggregate source as that used for the gap-graded mixes but with an open gradation. The same coarse RAP source used in the gap-graded plant mixes and as one of the two RAP sources in the gap-graded laboratory mixes was also used in the open-graded mixes. This experiment did not include binder testing.

Table 4.1: List of RHMA-G Mixtures

Mix Production Type	Description	Aggregate Source	RAP Source	Asphalt Rubber Binder Source
Plant	Mix A (1/2", 0% RAP, 64-16 AR) for test track	George Reed Clements	—	VSSI West Sacramento (PG 64-16AR); base binder from unknown refinery
Plant	Mix B (3/4", 0% RAP, 64-16 AR) for test track			
Plant	Mix C (1/2", 10% 3/4" RAP, 64-16 AR) for test track		RAP #1	
Plant	Mix D (3/4", 10% 3/4" RAP, 64-16 AR) for test track			
Lab	Mix 10B (1/2", 0% RAP, 64-16 AR)		—	BUT 162 (PG 64-16AR); base binder from Bay Area refinery
Lab	Mix 2B (1/2", 10% 1/2" RAP #1, 64-16 AR)		RAP #1	
Lab	Mix 4 (1/2", 10% 1/2" RAP #2, 64-16 AR)		RAP #2	
Lab	Mix 11 (1/2", 0% RAP, 70-10 AR)		—	IMP 86 (PG 70-10AR); base binder from Southern California refinery
Lab	Mix 3 (1/2", 10% 1/2" RAP #1, 70-10 AR)		RAP #1	
Lab	Mix 5 (1/2", 10% 1/2" RAP #2, 70-10 AR)		RAP #2	

Table 4.2: List of RHMA-O Mixes

Mix ID	Rubberized Binder Source	RAP Content (% by Mass of Aggregate)	RAP Source
O-I-OR	IMP 86	0	—
O-I-10R	IMP 86	10	RAP #1 (Inland Valley)
O-B-OR	BUT 162	0	—
O-B-10R	BUT 162	10	RAP #1 (Inland Valley)

4.3. Test Methods

4.3.1. Binder Test Methods

Binder testing included the following (an overview of the methods and data interpretation is discussed below):

- Performance grading
- Multiple stress creep and recovery (MSCR) tests to characterize permanent deformation resistance
- Frequency sweep tests to evaluate binder stiffness
- Fourier transform infrared (FTIR) spectroscopy tests to track any changes in binder chemistry after aging

Table 4.3 summarizes the conditions and replicates for these tests.

Table 4.3: Summary of Laboratory Binder Test Conditions and Replicates

Test	Equipment Used	Aging Condition	Spindle Geometry	Temperature (°C)	Testing Parameters and/or Failure Criteria	Replicates
Binder high PG	Dynamic shear rheometer (DSR)	Unaged	Concentric cylinder	Starting from 64°C with 6°C increment/reduction	$G^*/\sin(\delta) \geq 1 \text{ kPa}$	3
Binder high PG	Dynamic shear rheometer (DSR)	RTFO aged	Concentric cylinder	Starting from 64°C with 6°C increment/reduction	$G^*/\sin(\delta) \geq 2.2 \text{ kPa}$	3
Binder intermediate PG	Dynamic shear rheometer (DSR)	PAV aged	Concentric cylinder	Starting from 19°C with 3°C increment/reduction	$G^*\sin(\delta) \leq 5000 \text{ kPa}$	3
Binder low PG	Bending beam rheometer (BBR)	PAV aged	Not applicable	-12°C and -36°C	Creep stiffness (S) $\leq 300 \text{ Mpa}$ Creep slope (m) ≥ 0.3	3
MSCR	Dynamic shear rheometer (DSR)	RTFO aged	Concentric cylinder	64°C	Jnr and percent recovery	3
Frequency sweep test	Dynamic shear rheometer (DSR)	RTFO aged	Concentric cylinder	20°C, 40°C, and 50°C	Complex shear modulus (G^*) and phase angle (δ)	3
Chemical properties	Fourier transform infrared (FTIR) spectroscopy	Unaged, RTFO aged, and PAV aged	Not applicable	Room temperature	Carbonyl (CA) area index Sulfoxide (SUL) area index	9

Performance Grading

A dynamic shear rheometer (DSR) was used to determine the binder PG following a modified Superpave PG method (AASHTO T 315) based on concentric cylinder geometry, currently being developed by the UCPRC (12) for asphalt rubber binders, performance grade of asphalt rubber binders (PG-AR). Incompletely digested rubber particles (greater than 500 μm) were not removed prior to testing and, consequently, the results may have been influenced by the presence of these particles, given that asphalt binder and rubber particles age differently.

Short-term aging of the binders was simulated in a rolling thin film oven (RTFO) following a modified AASHTO T 240 method, which better simulates aging during RHMA mix production (12). In the modified method, RTFO aging is done at 190°C (instead of 163°C) using 45 g specimens (instead of 35 g). Long-term aging of the binder was simulated in a pressure aging vessel (PAV) following a modified AASHTO R 28 method. In the modified method, specimen weights were increased to 63 g (instead of 50 g) to account for the rubber (12).

The low temperature PGs were determined for the PAV-aged binders using a bending beam rheometer (BBR) following AASHTO T 313. Specimens were prepared using the proposed PG-AR modified BBR mold (12), which allows pouring of the binder in the width dimension instead of the thickness dimension.

Multiple Stress Creep Recovery

Multiple stress creep recovery tests were performed on RTFO-aged binders following AASHTO T 350, but using the concentric cylinder geometry. The test temperature was set to 64°C based on the high-temperature PG of the base binder. The non-recoverable creep compliance was calculated as an indicator of the rutting resistance, and the average percent recovery was used to evaluate the effects of rubber modification.

Frequency Sweep

Frequency sweep tests were performed on RTFO-aged binders using concentric cylinder geometry with a 10 mm bob and 9.5 mm gap at intermediate temperatures of 20°C, 40°C, and 50°C and frequencies between 25.1 and 0.1 radians/second. Tests could not be run at 4°C because the concentric cylinder geometry used has not been calibrated at this low temperature (12). A constant 0.01% strain was applied to prevent any non-linear viscoelastic behavior in the binder.

A symmetric sigmoidal fit function was used to convert the frequency sweep data into a master curve at the reference temperature using the fit function in Equation 4.1 (13). The reference temperature was selected as 20°C.

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

Where:

- $|E^*|$: magnitude of complex modulus (kPa)
- α : fitting parameter (the high asymptote of the master curve)
- δ : fitting parameter (the lower asymptote of the master curve)
- β, γ : fitting parameters (the slope of the transition region of the master curve)
- ω : frequency (Hz)
- f_r : reduced frequency, which is the shifted frequency at the reference temperature from the frequency at the test temperature (Hz)

Equation 4.1 can be used to generate a binder master curve by substituting the complex modulus (E^*) with the shear complex modulus (G^*). The reduced frequency can be calculated using the Arrhenius equations (Equation 4.2 and Equation 4.3), which are based on the time-temperature superposition (13):

$$\log f_r = \log f + \log \alpha_T \quad (4.2)$$

$$\log \alpha_T = \frac{E_a}{R(\ln 10)} \left(\frac{1}{T} - \frac{1}{T_r} \right) \quad (4.3)$$

Where:

f : frequency sweep test loading frequency (Hz)

α_T : shift factor as a function of temperature in Kelvin ($^{\circ}\text{K}$)

E_a : activation energy (Jol/Molar)

T : test temperature ($^{\circ}\text{K}$)

T_r : reference temperature ($^{\circ}\text{K}$)

R : ideal gas constant, 8.314 J/ $^{\circ}\text{K}$ -molar

Measured dynamic moduli can be horizontally shifted into a single master curve at the reference temperature using the above equations. The shift factor (α_T) can be determined using the solver function in Microsoft Excel by minimizing the sum of squares error between the predicted and measured dynamic moduli. Figure 4.1 and Figure 4.2 show examples of the fitting procedure.

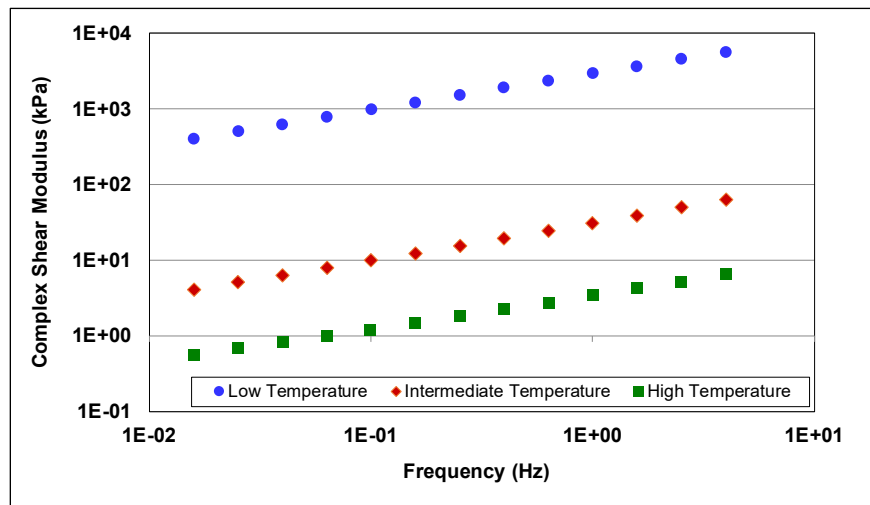


Figure 4.1: Example of modulus master curves: Plotted by frequency at tested temperature.

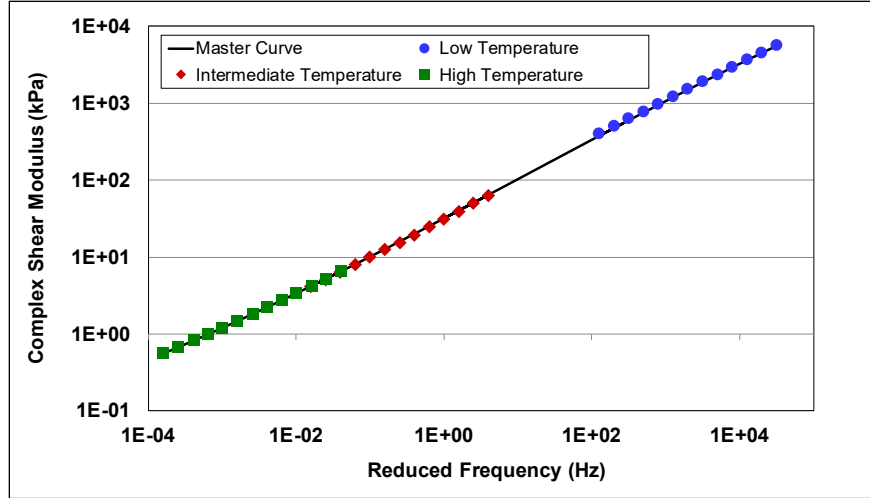


Figure 4.2: Example of modulus master curves: Plotted by shifted frequency.

Fourier Transform Infrared Spectroscopy

Chemical component changes in the control and blended binders were evaluated using Fourier transform infrared spectroscopy with attenuated total reflective (FTIR-ATR).

The spectra measured by the FTIR are recorded in a reflective mode, from 4,000 to 400 cm^{-1} , at a resolution of 4 cm^{-1} . Each measurement entails 24 scans, and an average value is recorded. Nine replicate measurements are taken to ensure that representative measurements of each binder sample are collected. The carbonyl component was used to track oxidative aging, which is usually defined by the peak at 1,680 cm^{-1} (14-17). The tangential integration of the component area index was calculated between the upper and lower wavenumbers (1,675 cm^{-1} and 1,750 cm^{-1}).

The spectra were normalized using the aliphatic band at 2,923 cm^{-1} to eliminate any variability introduced by the operator and any background impacts between repeat measurements. This aliphatic band structure is not affected by aging over time (17,18). The chemical component area index was then integrated from the normalized spectra using Equation 4.4 (17). Figure 4.3 shows an example of a spectrum and the respective component.

$$I_i = \int_{w_{l,i}}^{w_{u,i}} a(w)dw - \frac{a(w_{u,i}) + a(w_{l,i})}{2} \times (w_{u,i} - w_{l,i}) \quad (4.4)$$

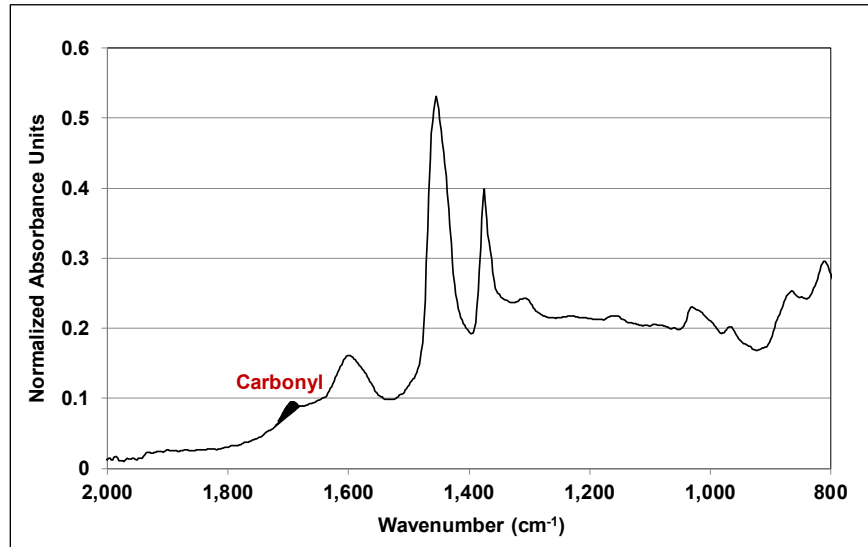
Where:

i : index of area i

$w_{l,i}$: lower wavenumber integral limit of area i

$w_{u,i}$: upper wave number integral limit of area i

$a(w)$: absorbance as a function of wavenumber



Note: Plot shows tangential integration with carbonyl areas.

Figure 4.3: Example of normalized FTIR absorbance spectrum.

4.3.2. Mix Test Methods for Gap-Graded Mixes

Mix testing for the gap-graded mixes included the following (an overview of the methods and data interpretation is discussed below):

- Dynamic modulus (DM, AASHTO T 378; specimens prepared in a gyratory compactor)
- Flexural modulus (FM, AASHTO T 321; specimens prepared using a rolling wheel compactor)
- Repeated load triaxial (RLT, flow number, AASHTO T 378; specimens prepared in a gyratory compactor)
- Beam fatigue (FAT, AASHTO T 321; specimens prepared using a rolling wheel compactor)
- Semicircular bend cracking test (SCB, AASHTO TP 124; specimens prepared in a gyratory compactor)

Table 4.4 summarizes the conditions and replicates for these tests.

Table 4.4: Summary of Mix Test Factors

Test	Air-Void Content (%)	Temperature (°C)	Testing Parameters	Replicates
DM	7.0 ± 0.5	4, 21, 38, 54	Strain controlled (100 µstrain) at 0.1-25 Hz	3
FM	7.0 ± 1.0	10, 20, 30	Strain controlled (100 µstrain) at 0.01-15 Hz	3
RLT	7.0 ± 0.5	50	Unconfined specimen	4
FAT	7.0 ± 1.0	20	3 strain levels (450 – 950 µstrain) at 10 Hz	3/strain level
SCB	7.0 ± 1.0	25	Loading rate of 50 mm/min	5

Air-void contents of the beam and SCB specimens were determined according to AASHTO T 166 (saturated surface-dry [SSD] method). The air-void contents of the AMPT specimens were determined according to AASHTO T 331 (CoreLok). Theoretical maximum specific gravity was determined according to AASHTO T 209.

Dynamic Modulus

Dynamic modulus testing followed AASHTO T 378 using an asphalt mix performance tester (AMPT) with specimens prepared in a gyratory compactor.

Specimens were tested at 4°C, 21°C, 38°C, and 54°C at frequencies between 25 and 0.1 Hz. Measured dynamic moduli and phase angles were horizontally shifted into a master curve at 20°C using Equation 4.2, Equation 4.3, and the Williams-Landel-Ferry shift function (19) in Equation 4.5.

$$\log(\alpha_T) = \frac{-C_1(T-T_r)}{C_2+(T-T_r)} \quad (4.5)$$

Where:

α_T : shift factor as a function of temperature T

T: test temperature in Kelvin (°K)

T_r : reference temperature in Kelvin (°K)

C1 and C2: fitting parameters

Flexural Modulus

Flexural beam frequency sweep testing followed AASHTO T 321 using a beam fatigue apparatus and beams prepared using a rolling wheel compactor.

Specimens were tested at 10°C, 20°C, and 30°C at frequencies between 15 and 0.01 Hz. A sine wave frequency was applied to produce a tensile strain of 100 µstrain on the longitudinal surface

of the beam. The measured stiffnesses and phase angles were horizontally shifted into master curves at 20°C using Equation 4.2 and Equation 4.5. Flexural stiffnesses were used in the *CalME* simulations discussed in Chapter 8.

Rutting Resistance

Permanent deformation resistance testing followed AASHTO T 378 using an AMPT with specimens prepared in a gyratory compactor. The RLT parameters assessed included flow number and the number of cycles to reach 5% permanent axial strain (PAS). Specimens were tested with no confinement under a deviator stress of 483 kPa and also with a confining stress of 5 psi (35 kPa) and the same deviator stress of 70 psi (483 kPa) (20–22). Given that the addition of RAP tends to stiffen mixes and therefore improve rutting resistance, Hamburg Wheel-Track tests were not conducted in addition to the RLT tests.

Fatigue Cracking Resistance

Fatigue cracking resistance testing followed AASHTO T 321 on beams prepared using a rolling wheel compactor. 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 a temperature of 20°C. The fatigue life for each strain level was selected by multiplying the maximum stiffness value for that strain level by the number of cycles at which that stiffness value occurred.

In this 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 4.6). Strain levels were 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 for high and medium strains, 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 final regression relationship was then refined to accommodate the measured stiffness at the lower strain level.

$$\ln(N) = A + B \times \ln(\epsilon) \quad (4.6)$$

Where:

N : fatigue life (number of cycles)

ϵ : strain level (μ strain)

A and B : model parameters

Test results were also used to generate the material fatigue response in the *CalME* simulations, discussed in Chapter 8, taking into consideration that laboratory test results will generally correspond with field fatigue or reflective cracking performance for overlays thinner than about 75 mm (0.25 ft.) but may not correspond 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.

Fracture Cracking Resistance (SCB)

Fracture cracking resistance was assessed in terms of fracture energy, strength, and the flexibility index determined from the semicircular bending test following AASHTO TP 124 on gyratory-compacted specimens.

Tests were run at 25°C with four replicates. Flexibility index, fracture energy, and strength were determined using Equation 4.7, Equation 4.8, and Equation 4.9, respectively. Potential differences in notch properties in the specimen (i.e., notch ending in the mastic, notch ending in the FAM, notch ending next to a large aggregate, or notch ending within a large aggregate) were taken into consideration when assessing variability between replicate test results (23).

$$G_f = \frac{W_f}{Area_{lig}} \times 10^6 \quad (4.7)$$

$$\sigma = \frac{Lp}{2rt} \quad (4.8)$$

$$FI = A \times \frac{G_f}{|Spp|} \quad (4.9)$$

Where:

G_f : fracture energy (Joule/m²)

W_f : work of fracture (Joule)

$Area_{lig}$: ligament area (mm²)

σ : strength of the SCB specimen

- L_p*: peak load applied during the test
r: radius of the SCB specimen
t: thickness of the SCB specimen
FI: flexibility index
A: correlation parameter, a typical value is 0.01
S_{pp}: post-peak slope

4.3.3. Mix Test Methods for Open-Graded Mixes

Drain Down

A procedure to conduct the drain down test for asphalt binder draining from open-graded mixes is described in AASHTO T305. In the test, the asphalt mix is placed in a wire basket and heated in the oven at the expected mixing temperature for 60 minutes. The wire basket is placed on a plate that collects the drained asphalt. The weight of the plate is determined before and after placing the basket in the oven to determine the amount of drained asphalt binder.

Raveling Resistance

The open-graded mixes were assessed for their raveling resistance, measured using the Cantabro test (ASTM D7064-04). Compacted specimens (4 in. [100 mm] in diameter and 2.5 in. [63.5 mm] in height, compacted by Superpave gyratory compactor with 50 gyrations) are put inside a Los Angeles abrasion machine drum without steel balls, and the drum is turned for 300 revolutions in 10 minutes. The percentage of mass loss during this process was used to evaluate the resistance of asphalt mixtures to raveling. Four gyratory-compacted specimens were prepared for each mix. The compacted specimens were 4 in. (101.6 mm) in diameter and 2.5 in. (63.5 mm) in height and weighed about 1,100 grams each.

4.4. Material Sampling

4.4.1. Plant-Produced Mix

Plant-produced mixes with and without RAP were sampled from the George Reed Inc. asphalt plant in Clements, California, at the time of load-out for transportation to the construction site for the UCPRC HVS test sections in Davis. The trailer and procedure used follow Caltrans test method CT 125. Following that method, the UCPRC staff drove an automated sampling trailer under the storage silo to collect loose mix at load-out under the direction of the asphalt plant

weighmaster. The sampling trailer captures material falling from the silo into a quarter master, splitting the material into four five-gallon buckets, with repeated loading of the trailer until sufficient buckets are filled. The buckets were sealed at the plant and transported to the UCPRC laboratory in Richmond, where they were stored inside in buildings. Material needed for testing in the Davis laboratory was transported from Richmond to Davis as needed.

The crumb rubber modifier (CRM) and PG 64-16 base binder to make the AR binder for the plant-produced mixes were blended and digestion begun at approximately 2 a.m. the morning of construction. Mixing was staged to facilitate required delivery times for paving of the short sections in Davis, while the plant was also producing the virgin 1/2 in. mix (Mix A) for other customers. The virgin 1/2 in. mix was mixed at approximately 5 to 6 a.m. and stored until load-out at approximately 2 to 3 p.m. The other three mixes (Mixes B, C, and D) were mixed in smaller quantities specifically for the HVS test sections between 8 a.m. and 12:00 p.m.. Estimated silo storage times for all four mixes are shown below:

- MixA (1/2", 0% RAP, 64-16 AR), estimated silo storage: 8 to 10 hours
- MixB (3/4", 0% RAP, 64-16 AR), estimated silo storage: 0 to 2 hours
- MixC (1/2", 10% 3/4" RAP, 64-16 AR), estimated silo storage: 0 to 2 hours
- MixD (3/4", 10% 3/4" RAP, 64-16 AR), estimated silo storage: 0 to 2 hours

The maximum allowed silo storage time is 18 hours per Caltrans Material Plant Quality Program Manual section 2-2.11 (32).

4.4.2. Asphalt Binder

The field-blended PG 64-16 AR binder used in the plant mixes was produced by VSSI in West Sacramento. This binder was extracted from field mix sampled at load-out at the plant after the silo time ranges noted in the previous section.

The two field-blended AR binders used in the laboratory-prepared mixes were a PG 64-16 AR sampled at an asphalt mixing plant in Chico, California, that was used on a project on BUT-162 and a PG 70-10 AR sampled at an asphalt mixing plant in Indio, California, that was used on a project on IMP-86. AR binder was sampled in five-gallon steel buckets that were sealed,

transported to the UCPRC laboratories, and stored inside with temperature control until used to prepare laboratory mixes.

4.4.3. Virgin Aggregate

Virgin aggregates (crushed granite) for use in the laboratory-prepared mixes were sampled from stockpiles at the George Reed Inc. mixing plant at Clements, which had been mined near Sonora and transported to the mixing plant. They were sampled following standard quartering procedures.

4.4.4. Reclaimed Asphalt Pavement

RAP was sampled from stockpiles at two asphalt plants: (1) Clements (San Joaquin County, Inland Valley climate region), representing RAP with an expected high degree of aging and (2) the Vulcan (previously Syar) quarry and mixing plant between Benicia and Vallejo (Solano County, North Coast climate region), representing RAP with an expected lower degree of aging. As expected, RAP #1, with its coarse gradation, has a binder content that is approximately half that of RAP #2, which has a much finer gradation.

The two RAP sources were assessed in the laboratory to ensure that RAP with different degrees of aging (exposure to light and exposure to air at high temperatures) were included in the experiment to answer the second question in Section 4.1 regarding differences in performance-related properties when using different RAP sources. The aggregate gradations of the two RAP sources from extracted samples are shown in Table 4.5 and are plotted in Figure 4.4. It can be seen in the figure that RAP #1 has a much coarser gradation than RAP #2 and that RAP #2 has a fine gradation similar to that of another RAP source that is considered “typical” of the fine RAP used in the central valley. Fine RAP typically has higher binder contents than coarse RAP, allowing greater virgin binder replacement with a smaller amount of RAP by mass of total mix.

The binder contents from extraction and high-temperature PG grades of the two RAP sources are shown in Table 4.6 and Table 4.7. Table 4.7 includes results for RAP #1 from extractions done by the testing laboratory for the RAP #1 asphalt plant following AASHTO T 164 (Abson method) and done by the UCPRC laboratory following ASTM D8159-19 (Standard Test Method for Automated

Extraction of Asphalt Binder from Asphalt Mixtures). The results are different, with the AASHTO T 164 results showing a lower PG high temperature than the ASTM D8159-19 results. This difference in results between the two extraction methods is consistent with differences seen in the fall 2022 AASHTO proficiency sample program (PSP) results. Among the 23 laboratories that participated using AASHTO T 164, the DSR $G^*/\sin\delta$ results were 2.357 kPa with a standard deviation of 1.013. Among the 42 laboratories that participated using ASTM D8159-19, the DSR $G^*/\sin\delta$ results were 3.239 kPa with a standard deviation of 1.222.

Table 4.5: Aggregate Gradations of Two RAP Sources Compared with Typical 3/8 in. RAP

Grading (% passing sieve)	RAP #1 (Inland Valley)	RAP #2 (N. Bay Area)	Typical 3/8" RAP (Inland Valley)
2" (50 mm)	100.00	100.0	100.0
1" (25 mm)	100.0	100.0	100.0
3/4" (19 mm)	100.0	99.0	100.0
1/2" (12.5 mm)	94.7	94.5	100.0
3/8" (9.5 mm)	68.9	87.6	98.6
#4 (4.75 mm)	30.1	67.8	66.4
#8 (2.36 mm)	21.8	54.4	48.6
#16 (1.18 mm)	17.5	42.0	36.3
#30 (.6 mm)	14.5	28.0	27.5
#50 (.3 mm)	11.5	18.4	19.8
#100 (.15mm)	8.8	12.2	13.5
#200 (75 μ m)	6.4	9.2	9.6

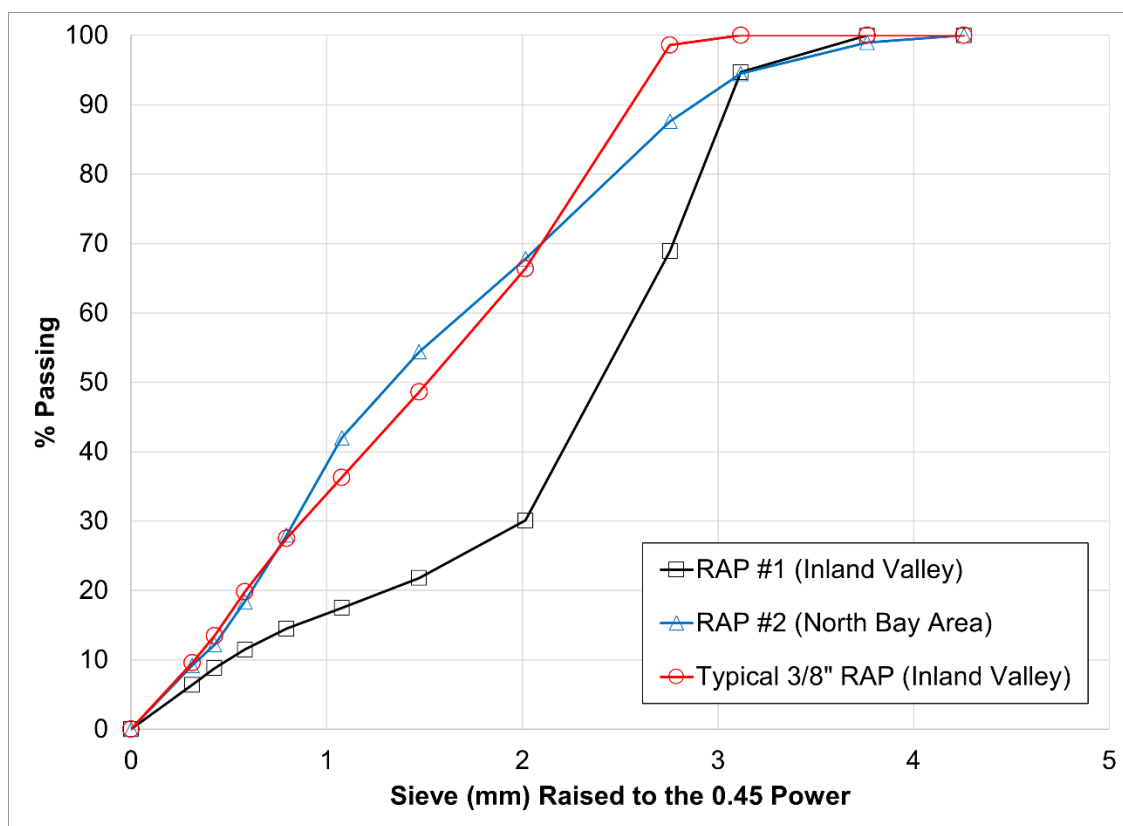


Figure 4.4: Plot of aggregate gradations of two RAP sources compared with typical 3/8 in. RAP.

Table 4.6: Extracted Binder Contents for Two RAP Sources

Binder Content (% by mass of mix)	RAP #1		RAP #2	
	Inland Valley		N. Bay Area	
	Average	Std. Dev.	Average	Std. Dev.
From UCPRC extraction ^a	2.6	0.20	5.2	0.1
From plant data sheet	2.4	—	—	—

^a From three samples.

Table 4.7: Extracted Continuous High-Temperature PG for Two RAP Sources

Aging Condition	RAP #1 (°C)		RAP #2 (°C)	
	Inland Valley		N. Bay Area	
	High Temp. PG ¹	Std. Dev.	High Temp. PG ¹	Std. Dev.
Producer Plant RTFO	96.8	—	—	—
UCPRC Plant Unaged	104.7	0.1	111.8	0.1
UCPRC Plant RTFO	103.9	0.1	108.3	0.5

Notes: The producer plant results are taken from AASHTO T 164 (Abson method). The UCPRC results are taken from ASTM D8159-19 (Standard Test Method for Automated Extraction of Asphalt Binder from Asphalt Mixtures). The unaged PG temperature is evaluated at 1.0 kPa and the RTFO PG temperature is evaluated at 2.2 kPa.

4.5. Mix Designs

4.5.1. Plant-Produced RHMA-G Mix Designs

The plant-produced RHMA-G mixes used in this study were designed and produced at an asphalt plant in Clements, California, for the construction of the HVS test track at the UCPRC. Key material design parameters from the job mix formulas for the four mixes are summarized in Table 4.8. The extracted aggregate gradations are shown in Figure 4.5. The figure shows that the aggregate gradations for the control and RAP mixes with the same NMAS are the same. Although Caltrans currently does not allow the use of any RAP materials in RHMA-G mixes, all the mixes did meet all other Caltrans standard specification requirements for 1/2 in. and 3/4 in. nominal maximum aggregate size (NMAS) RHMA-G mixes.

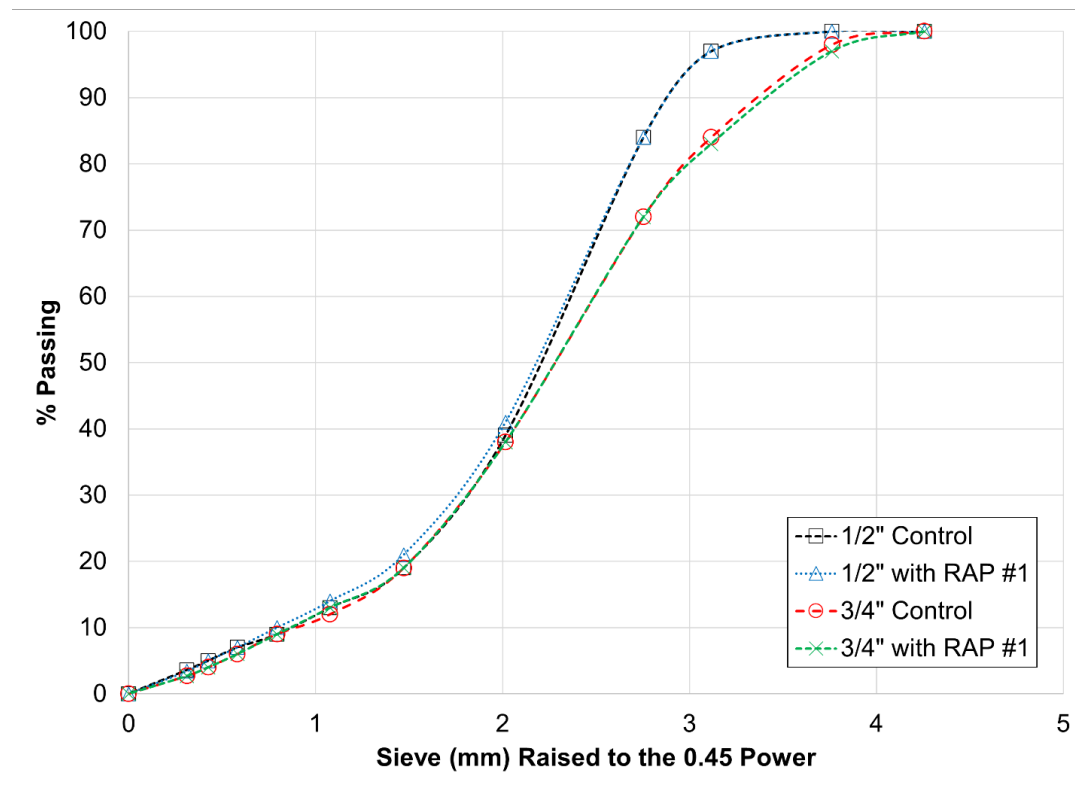


Figure 4.5: Plant-produced mix gradations from extractions.

4.5.2. Laboratory-Produced RHMA-G Mix Designs

The mix designs for the laboratory-produced RHMA-G mixes used in this study were based on the plant-produced 1/2 in. RHMA-G mixes shown in Table 4.8, with adjustments made by the UCPRC to produce the same gradations. The mix designs used the same aggregate and 1/2 in.

gap-graded maximum size aggregate gradation as the plant mixes, with minor adjustments for the two RAP sources, and AR binders sampled on two Caltrans projects, BUT-162 with a PG 64-16 base binder and IMP-86 with a PG 70-10 base binder. Key material design parameters for the six mixes are summarized in Table 4.9. The extracted aggregate gradations are shown in Figure 4.6. The figure shows that the aggregate gradations for the control mix without RAP and the mixes with RAP are the same, including for both RAP #1 (coarse) and RAP #2 (fine). Although Caltrans currently does not allow the use of any RAP materials in RHMA-G mixes, all the mixes did meet all other Caltrans standard specification requirements for 1/2 in. nominal maximum aggregate size (NMAS) RHMA-G mixes.

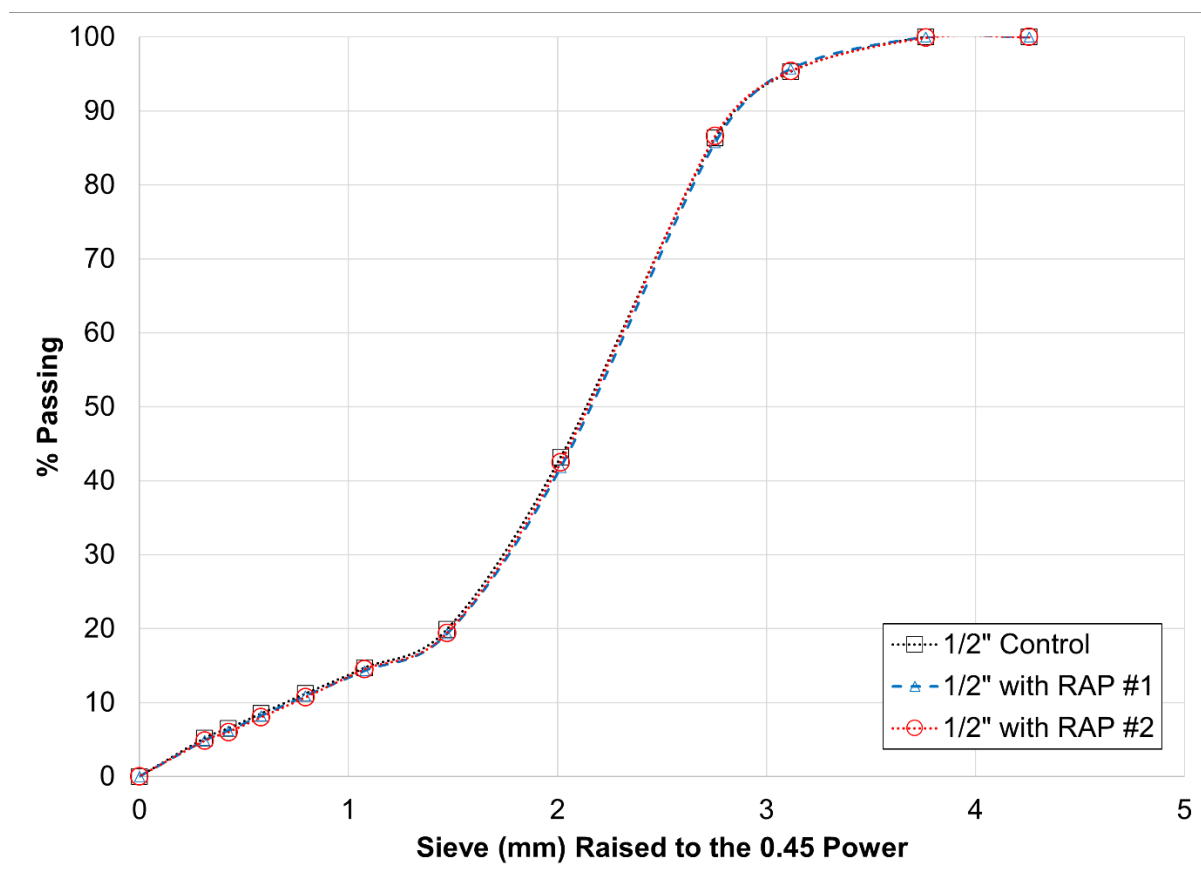


Figure 4.6. Laboratory-produced mix aggregate gradations.

Table 4.8: Mix Design Parameters for Plant-Produced RHMA-G Mixes (Used on HVS Test Track) Designed by Mix Producer

Parameter		Control Mixes (No RAP)				Mixes with RAP			
		1/2 in. NMAS		3/4 in. NMAS		1/2 in. NMAS		3/4 in. NMAS	
		Actual	Compliance	Actual	Compliance	Actual	Compliance	Actual	Compliance
Grading (% passing sieve)	1	100	100	100	100	100	100	100	100
	3/4	100	100	98	95–98	100	100	97	95–98
	1/2	97	90–98	84	83–87	97	90–98	83	83–87
	3/8	84	83–87	72	65–70	84	83–87	72	65–70
	#4	39	28–42	36	28–42	41	28–42	36	28–42
	#8	19	14–22	19	14–22	21	14–22	19	14–22
	#200	3.6	0.0–6.0	2.7	0.0–6.0	3.4	0.0–6.0	2.7	0.0–6.0
RAP content (% by weight of aggregate)		0	N/A	0	N/A	10	N/A	10	N/A
Base asphalt binder performance grade		64-16	N/A	64-16	N/A	64-16	N/A	64-16	N/A
Rubber content (% by weight of binder)		18	N/A	18	18–22	18	18–22	18	18–22
AR binder cone penetration (mm)		3.6	2.5–7.0	3.6	2.5–7.0	3.6	2.5–7.0	3.6	2.5–7.0
AR binder resilience (% rebound)		48	>18	48	>18	48	>18	48	>18
AR binder softening point (°C)		62	52–74	62	52–74	62	52–74	62	52–74
AR binder viscosity (centipoise)		1,600	1,500–4,000	1,600	1,500–4,000	1,600	1,500–4,000	1,600	1,500–4,000
Binder content (% by weight of mix)		7.8	7.4–8.3	7.6	7.1–8.0	7.8	7.4–8.3	7.75	7.1–8.0
Number of gyrations		150	50–150	135	50–150	150	50–150	135	50–150
Air-void content (%)		3.8	4.0	4.0	4.0	4.0	4.0	4.0	4.0
Voids in mineral aggregate (%)		19.8	18–23	19.5	18–23	20	18–23	19.5	18–23
Dust proportion		0.52	N/A	0.44	N/A	0.5	N/A	0.43	N/A
Hamburg (rut depth [mm] at 20k passes)		2.2	<12.5	2.5	<12.5	Not tested	<12.5	Not tested	<12.5
Moisture susceptibility, dry strength (psi)		169	>100	155	>100	Not tested	>100	Not tested	>100
Moisture susceptibility, wet strength (psi)		120	>70	124	>70	Not tested	>70	Not tested	>70

Table 4.9: Mix Design Parameters for RHMA-G Mixes (Laboratory-Produced Mixes) Developed by UCPRC from Plant-Produced Mixes

Parameter		1/2 in. NMAS					
		PG 64-16AR (BUT-162)			PG 70-10 AR (IMP-86)		
		Control	RAP #1 (Inland Valley)	RAP #2 (N. Bay Area)	Control	RAP #1 (Inland Valley)	RAP #2 (N. Bay Area)
		0% RAP	10% RAP	10% RAP	0% RAP	10% RAP	10% RAP
		Mix 10B	Mix 2B	Mix 4	Mix 11	Mix 3	Mix 5
Grading (% passing sieve)	2" (50mm)	100.0	100.0	100.0	100.0	100.0	100.0
	1" (25mm)	100.0	100.0	100.0	100.0	100.0	100.0
	3/4" (19mm)	100.0	100.0	99.9	100.0	100.0	99.9
	1/2" (12.5mm)	95.3	95.7	95.4	95.3	95.7	95.4
	3/8" (9.5mm)	86.3	85.7	86.6	86.3	85.7	86.6
	#4 (4.75mm)	43.2	41.8	42.5	43.2	41.8	42.5
	#8 (2.36mm)	19.9	19.3	19.4	19.9	19.3	19.4
	#16 (1.18mm)	14.7	14.3	14.5	14.7	14.3	14.5
	#30 (.6mm)	11.2	10.9	10.7	11.2	10.9	10.7
	#50 (.3mm)	8.5	8.2	8.0	8.5	8.2	8.0
	#100 (.15mm)	6.5	6.2	6.0	6.5	6.2	6.0
	#200 (75µm)	5.18	4.87	4.83	5.18	4.87	4.83
	Pan	0.00	0.00	0.00	0.00	0.00	0.00
RAP content (% by weight of aggregate)		0	10	10	0	10	10
Base asphalt binder performance grade		64-16	64-16	64-16	70-10	70-10	70-10
Total binder content (% by weight of mix)		7.80	7.80	7.80	7.80	7.80	7.80
Virgin binder content (% by weight of mix)		7.80	7.58	7.22	7.80	7.58	7.22
Recycled binder content (% binder in mix)		0.00	0.22	0.58	0.00	0.22	0.58
Estimated binder replacement (% of total binder)		0.0%	2.9%	7.3%	0.0%	2.9%	7.3%
Number of gyrations		150	150	150	150	150	150
Air-void content (%)		2.5–5.5	2.5–5.5	2.5–5.5	2.5–5.5	2.5–5.5	2.5–5.5

4.6. Laboratory-Produced RHMA-O Mix Designs

The gradation and binder content for the mix designs for the laboratory-produced RHMA-O mixes used in this study were based on an RHMA-O mix that was approved by Caltrans. The Caltrans open-graded mix design procedure uses California Test 368 (CT 368) to determine the optimum binder content of open-graded mixes based on a maximum allowable amount of drained asphalt using neat asphalt binder. The optimum binder content is adjusted based on the type of asphalt binder. For rubberized binders, the optimum binder content from the procedure is multiplied by 1.4.

The same aggregate source was used for the RHMA-O mixes as was used for the RHMA-G mixes. As shown in Table 4.2, the same two field-sampled binders were used for the RHMA-O mixes as were used for the laboratory-produced RHMA-G mixes, one with a PG 64-16 base binder from BUT-162 and the other with a PG 70-10 base binder from IMP-86. The same coarse RAP (RAP #1) was used in the mixes with RAP.

The binder content of the sample of RAP #1 used in the RHMA-O mixes was determined using ASTM D 2172 to be 2.5% by mass of aggregate. For the mixes with 10% RAP, the binder content considering virgin and RAP binder was 8.9% by total mass of mix, resulting in a RAP binder replacement of 2.8%. The aggregate gradation and binder content were kept constant for all four mixes, with adjustments to the virgin aggregate gradation to account for the RAP aggregate for the mixes with RAP. The aggregate gradations for the control and RAP RHMA-O mixes are shown in Figure 4.7. The AASHTO T 305 drain down test was used to check the adequacy of the total binder content, explained in Chapter 6.

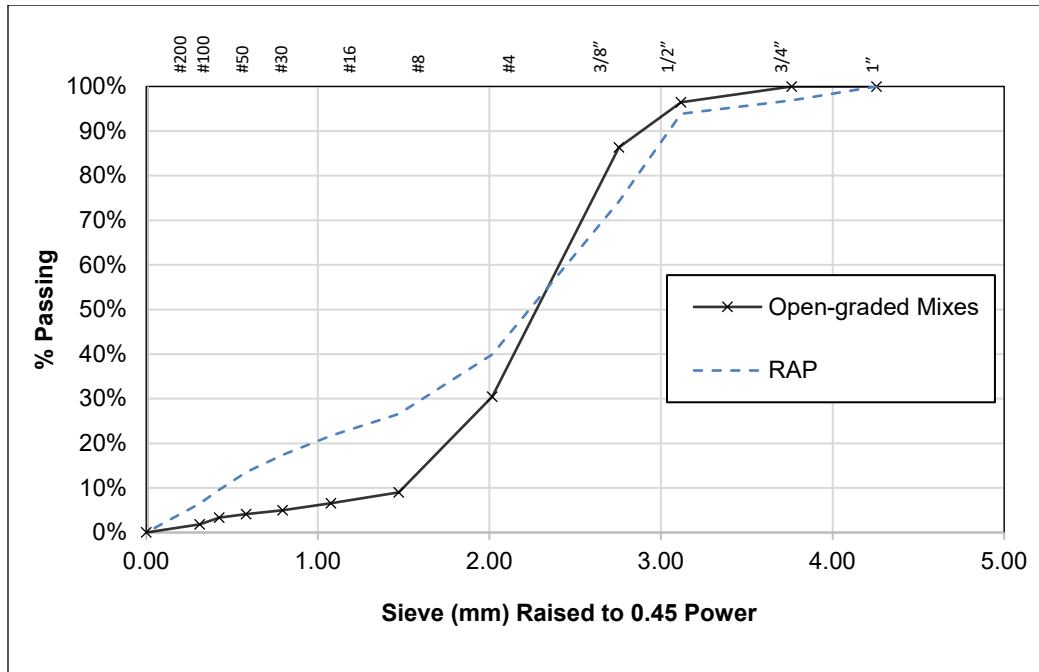


Figure 4.7: Aggregate gradations of RHMA-O mixes and RAP #1 aggregate gradation.

5 BINDER TESTING RESULTS

5.1. Introduction

This chapter discusses binder testing results for the control rubberized asphalt (AR), RAP, and blended AR and RAP binders used in the plant mixes placed on the HVS test track (Table 4.1). The control binder from the test track mixes that was sampled at the mixing plant during construction (AR prepared by VSSI, shown in Table 4.1) was blended with RAP #1 in the laboratory, and the properties of the control and blended binders were tested. The binder properties of the other two control AR binders used in the study that were sampled from the BUT-162 and IMP-86 projects (see Table 4.1) and the RAP binders extracted from RAP #1 and RAP #2 were tested individually, and the results were used to estimate blended binder properties using blending charts. The results of the laboratory binder testing and the blending chart estimates are presented in this chapter, and detailed tabulated results are included in Appendix A.

Two RAP binder contents were used for preparing blended binders with the three control AR binders. Based on industry feedback prior to this study, it was estimated that the additional binder mobilized and blended from coarse RAP in plant-produced mixes is between 0.2% and 0.5% additional binder content by total mass of mix. Using those numbers and the plant data sheet binder content for the coarse RAP (RAP #1), which was 2.4% by mass of mix (Table 4.6), it was calculated that 10% RAP by total mass of mix would result in a blended binder with 2.91% RAP binder in the blend by total mass of binder. Similarly, it was calculated that 25% RAP by total mass of mix would result in 7.28% RAP binder in the blended binder by total mass of binder. It was also calculated that these percentages of RAP binder in the blended binder correspond to 0.23% and 0.57% RAP binder by total mass of mix, approximately corresponding to the industry feedback. As noted in the literature survey in Chapter 2, the use of more than 10% coarse RAP by mass of mix can result in problems with low total binder contents, and mixes with 25% RAP by mass of mix were not included in the mix test factorial and results, shown in Chapter 6.

The following sections of this chapter present and discuss the binder testing results for the VSSI control AR binder and after blending with the two percentages of RAP #1 extracted binder. The

last section presents and discusses the binder blending chart results for the other two control AR binders blended with the two percentages of RAP #1 and with RAP #2.

5.2. High-Temperature Grading

High-temperature grading results for the VSSI control AR binder and the two percentages of RAP #1 are included in Table A.1 (unaged) and Table A.2 (RTFO aged) in Appendix A. Those results indicate that the unaged control VSSI AR binder and blended binders with both RAP #1 percentages met the PG high temperature specification for PG 70 of 1 kPa for $G^*/\sin(\delta)$ per the PG specification (AASHTO M 320) but did not meet the PG 76 specification. Those results also show that the RTFO-aged control VSSI AR binder met the PG 70 high-temperature specification but did not meet the PG 76 specification, while the blended binders with both RAP #1 percentages met the PG high temperature specification for PG 76 of 2.2 kPa for $G^*/\sin(\delta)$. Figure 5.1 and Figure 5.2 plot the average high temperature grade testing results for the unaged and RTFO-aged binders at 76°C. Dashed lines on the plots indicate the 1.00 kPa and 2.20 kPa test thresholds for unaged binders and RTFO-aged binders, respectively. Figure 5.3 plots the phase angles for the unaged and RTFO-aged binders. The high temperature PGs for extracted RAP binders are shown in Table 5.1.

Table 5.1: Continuous Performance Grades for Extracted RAP Binders

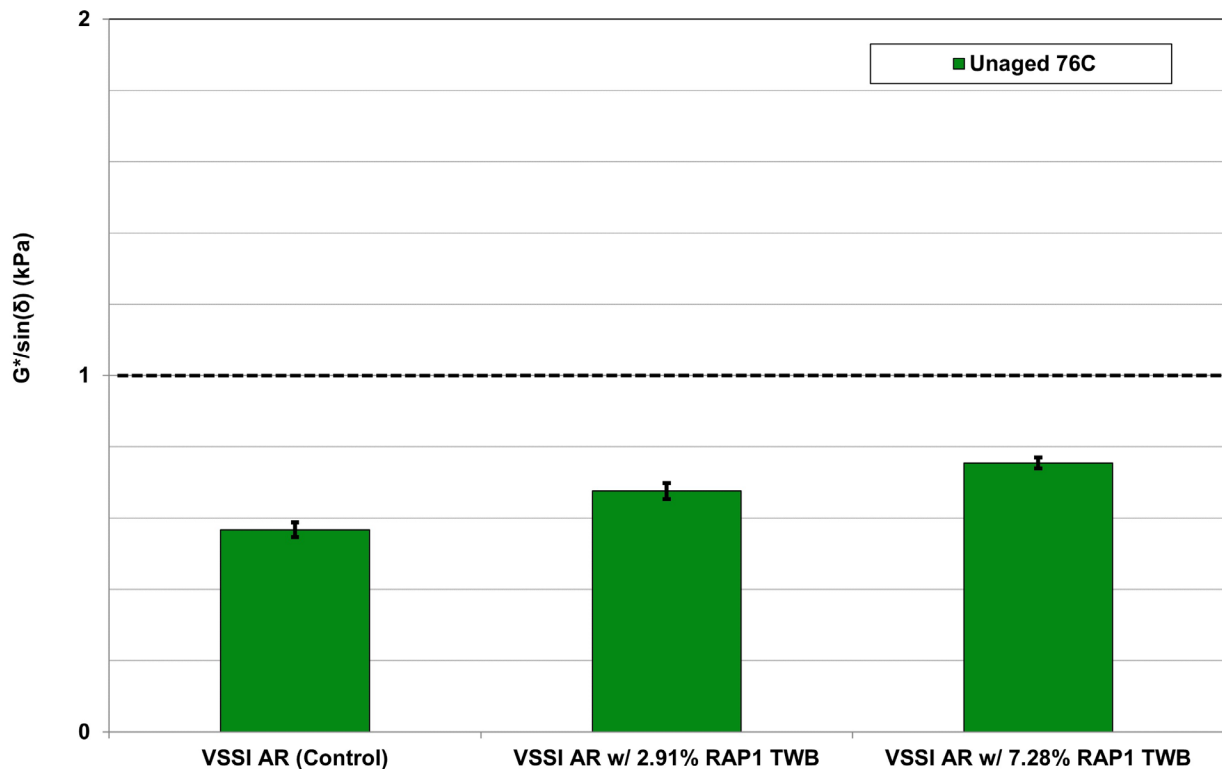
Aging Condition	RAP #1 (°C)		RAP #2 (°C)	
	High Temp. PG	Std. Dev.	High Temp. PG	Std. Dev.
Unaged	104.7	0.1	111.8	0.1
RTFO	103.9	0.1	108.3	0.5

The results show that:

- The value of $G^*/\sin(\delta)$ was found to increase with an increase in RAP content for unaged binder blends. The average $G^*/\sin(\delta)$ value observed for unaged VSSI AR binder at 76°C was 0.57 kPa with a standard deviation of 0.02 kPa. The average $G^*/\sin(\delta)$ values for the VSSI AR binder blended with 2.91% and 7.28% of RAP #1 were 0.68 kPa and 0.75 kPa, respectively, at 76°C, which are increases of 19% and 32%, respectively. The standard deviation observed for both blends with RAP was 0.02 kPa. The observed increases in stiffness match expectations for the inclusion of these percentages of RAP. As shown in

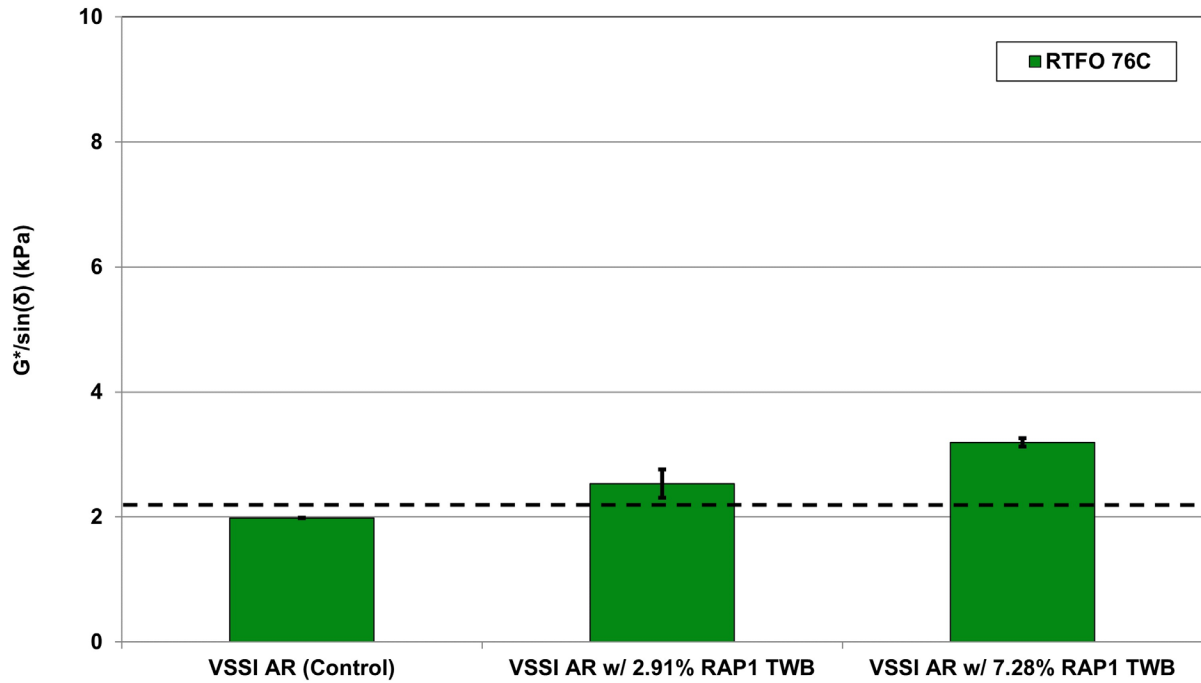
Figure 5.1, none of the binders met the unaged binder specification for PG 76, but, as was shown in Table A.1, they all meet the unaged requirement for PG 70.

- A similar increasing trend of $G^*/\sin(\delta)$ value with the addition of RAP was also observed for RTFO-aged binders, shown in Figure 5.2. Both binder blends with RAP #1 met the RTFO requirement of 2.2 kPa at the 76°C temperature grade. However, the control VSSI AR met the RTFO requirement at a grading temperature of 70°C but not at 76°C.
- As shown in Figure 5.3, the phase angles of the RTFO-aged binders were lower than those of the unaged binders, as expected, indicating that RTFO aging increased the elastic behavior and decreased the viscous behavior of the binder. The results show that the trend was consistent for the two RAP contents, with the addition of increasing amounts of RAP resulting in increasingly elastic behavior.
- Based on these results, the addition of stiffer binder from RAP is expected to increase the rutting resistance of the VSSI AR binder at high temperatures. A similar observation was also reported by other researchers (24,25,26).



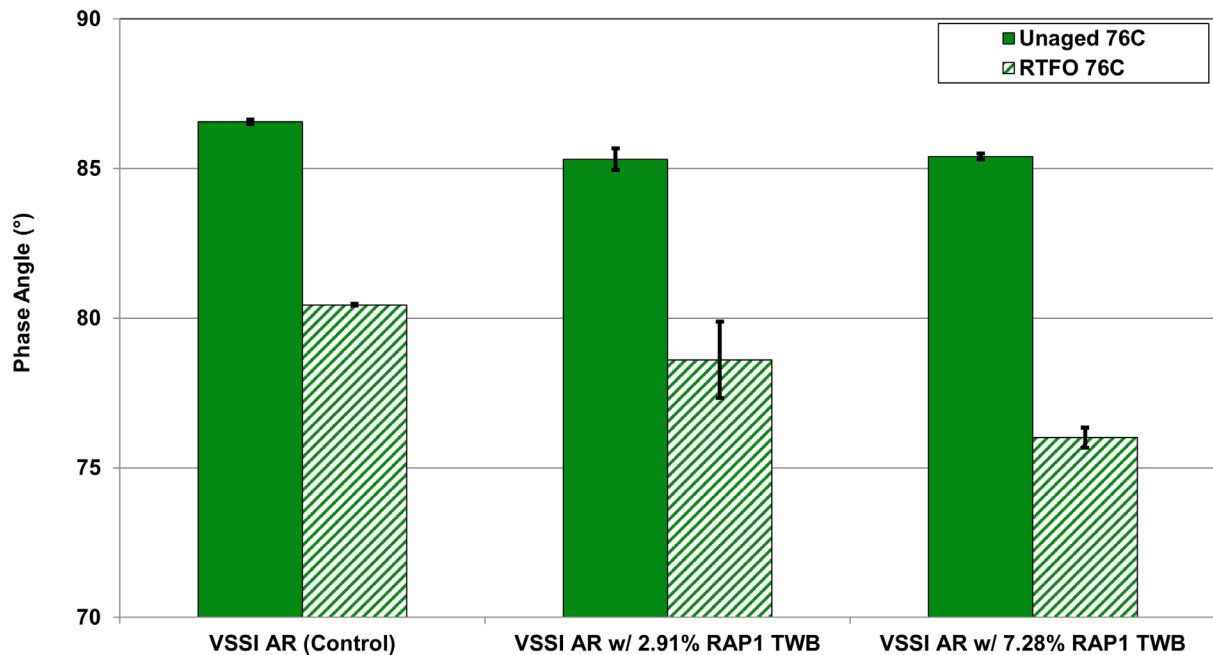
Notes: Specification limit shown as dashed line; error bars indicate one standard deviation of results; TWB = total weight of binder.

Figure 5.1: $G^*/\sin(\delta)$ of unaged binders at 76°C.



Notes: Specification limit shown as dashed line; error bars indicate one standard deviation of results; TWB = total weight of binder.

Figure 5.2: $G^*/\sin(\delta)$ of RTFO-aged binders at 76°C.



Notes: Specification limit shown as dashed line; error bars indicate one standard deviation of results; TWB = total weight of binder.

Figure 5.3: Phase angles of unaged binders at 76°C.

Table 5.2 summarizes the high temperature continuous grades of the binders. The continuous grade is defined as the temperature where the unaged binder's $G^*/\sin(\delta)$ value equals 1.00 kPa and the RTFO-aged binder's $G^*/\sin(\delta)$ value equals 2.20 kPa. The result show the following:

- The RTFO-aged binders showed a higher continuous grade compared to their unaged counterparts, which indicates that the virgin binder in the control AR and the blended binders is more aging-susceptible than binders where the unaged part of the specification would control the high temperature PG.
- An increase in RAP content increases the binder blends' continuous grade. The increase in continuous grade due to the addition of 2.91% and 7.28% of RAP #1 binder was found to be 1.8°C and 2.8°C, respectively, and was controlled by the unaged properties.
- The hardening ratio of the control AR binder was less than that of the blended binders. This could be attributed to a lower aging rate of the rubberized asphalt binder compared with the RAP binder because of the amount of rubber in the control binder. It has been shown that rubber used in AR binders does not age in binder aging tests (27). The RAP binder in the blended binders should have a lower aging rate than the virgin base binder in the control AR. However, there is a higher percentage of rubber in the control AR than in the blended binders because of the dilution of rubber with RAP binder in the blended binders. Because the $G^*/\sin(\delta)$ for RTFO-aged binder is 2.2 kPa and for unaged binder is 1.0 kPa, hardening ratios greater than 2.2 can be considered a benchmark for more aging-susceptible binders.

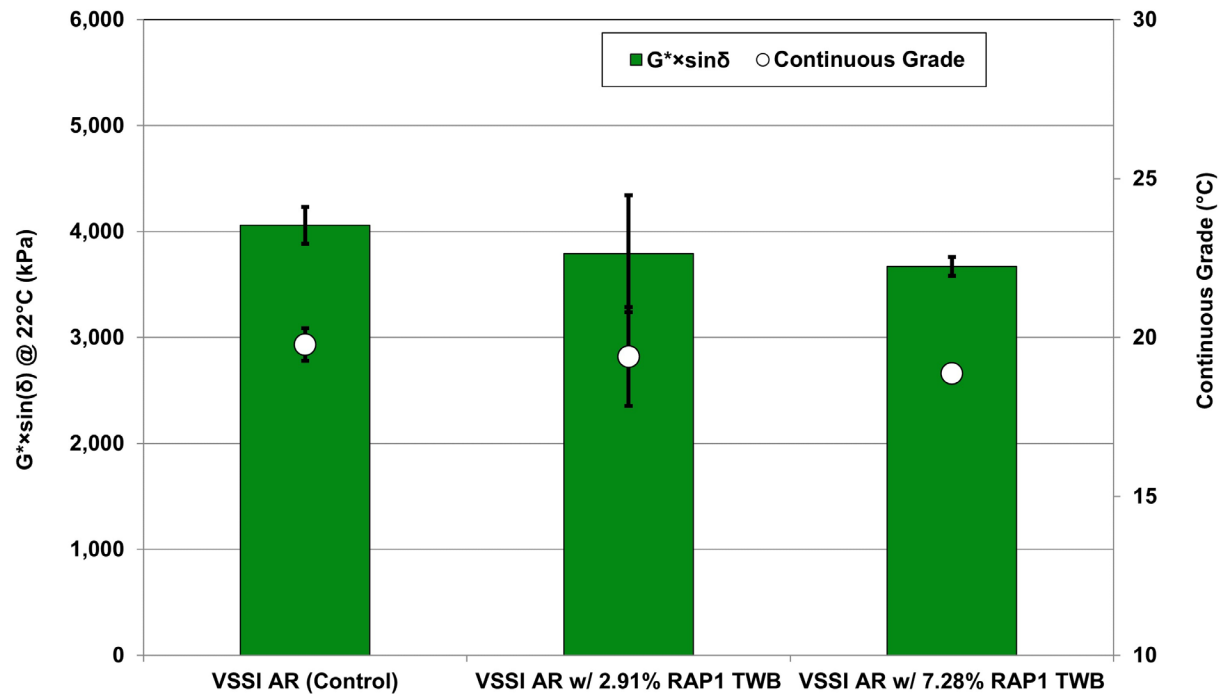
Table 5.2: Continuous High Temperature Performance Grades for Control and Blended Binders

Source	Binder ID	Unaged Binder (°C)			RTFO-Aged Binder (°C)			Hardening Ratio
		$G^*/\sin(\delta) = 1.00 \text{ kPa}$	Std. Dev.	Grade Change	$G^*/\sin(\delta) = 2.20 \text{ kPa}$	Std. Dev.	Grade Change	$G^*/\sin(\delta) \text{ (RTFO)} / G^*/\sin(\delta) \text{ (Unaged) at } 76^\circ\text{C}$
Test Track	VSSI AR (Control)	71.2	0.4	N/A	75.4	0.0	N/A	3.5
	VSSI AR binder w/ 2.91% RAP #1 TWB	73.0	0.3	1.8	77.6	0.9	2.2	3.7
	VSSI AR binder w/ 7.28% RAP #1 TWB	74.0	0.2	2.8	79.8	0.2	4.5	4.2

Note: TWB = total weight of binder.

5.3. Intermediate Temperature Grading

Intermediate temperature grading results are listed in Table A.3 in Appendix A. Figure 5.4 shows the plot of the average intermediate temperature test results for the PAV-aged binders. The figure shows the $G^*\sin(\delta)$ values at 22°C, and the dot points show the continuous grades at the temperature where the binder $G^*\sin(\delta)$ values equal 5,000 kPa, following the PG specification.



Notes: Error bars indicate one standard deviation of results; TWB = total weight of binder.

Figure 5.4: $G^*\sin(\delta)$ of PAV-aged binders at 22°C.

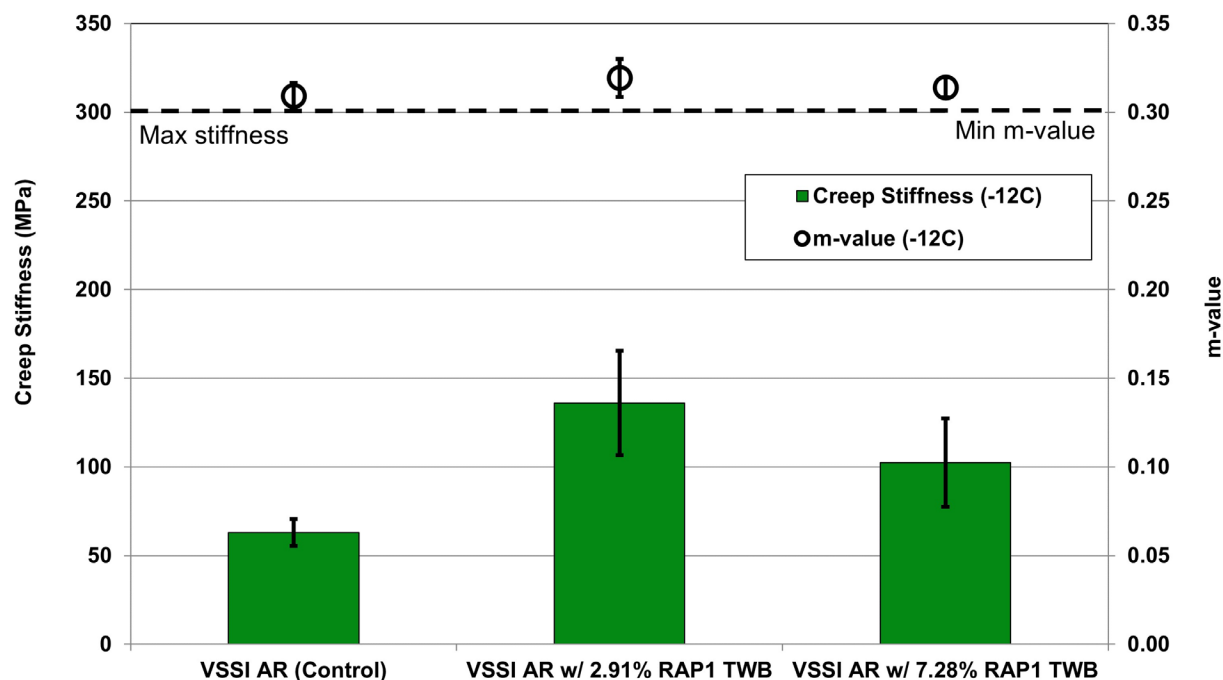
The results show the following:

- The addition of RAP #1 binder to the VSSI AR control binder did not have a significant effect on the intermediate PGs. The intermediate temperatures ranged between 18.9°C and 19.8°C for all binders. The standard deviation of the intermediate temperatures varied between 0.2°C and 1.6°C. The trend of decreasing stiffness after PAV aging, slight though it may be, is unexpected. It may be a coincidence of random ordering within the variability of the test itself. The results indicate that the addition of the RAP should not have much effect on the binder performance for fatigue cracking for both amounts of RAP added.

5.4. Low Temperature Grading

BBR test results are listed in Table A.4 in Appendix A. Figure 5.5 shows the plot of the average results for the PAV-aged binders at one test temperature (-12°C) for each binder. The maximum allowable creep stiffness (300 MPa) and minimum allowable m-value (0.300) limits at the selected measuring temperature are shown as dashed lines on the plots. The results show the following:

- At -12°C, similar m-values were observed for the control VSSI AR binder and for the blends with both amounts of RAP #1. This indicates that the three binders have approximately the same ability to relax stresses.
- Although both RAP quantities increase the creep stiffness at -12°C compared to the control binder, this trend is not consistent with increasing RAP in the blends going from 2.91% to 7.28% of RAP binder in the blend. This may be due to an unknown cause of the blended binders or may be due to BBR testing difficulties for rubberized binders. There is an inherent difficulty in doing BBR testing with AR mixes that contain undigested rubber particles. These particles may introduce very small voids within the binder beam, which can increase the coefficient of variance between poured beams. The acceptability criteria for the coefficient of variation for neat and polymer-modified binders between BBR replicates following AASHTO T313-19 is 6.6% for the creep stiffness $S(60)$ and 2.6% for the slope m-value. The testing of the blends showed that each beam set exceeds the coefficient of variation from the standard, which may explain the deviation in the expected trend between the two blends.
- As shown in Table A.4 in Appendix A, the difference in the m-value between the control and blended binders with RAP was relatively higher at -36°C compared with -12°C, with the control binder having a much better value than the blended binders at the lower temperature.



Notes: Specification limit shown as dashed line; error bars indicate one standard deviation of results; TWB = total weight of binder.

Figure 5.5: Low temperature creep stiffness and m-value at -12°C.

The additional BBR tests run at -36°C were also used to calculate the critical temperatures for these binders (i.e., where stiffness equals 300 MPa or m-value equals 0.300). The results are summarized in Table 5.3. The difference between the critical temperatures calculated by stiffness and m-value (ΔT_c) is an indicator of the binder's stress relaxation at low temperatures (28).

Table 5.3: Low Temperature True Grade Test Results

Binder ID	$T_{C-stiffness}$ (°C)	$T_{C-m\ value}$ (°C)	ΔT_c (°C)
VSSI AR binder (Control)	-28.6	-14.1	-14.5
VSSI AR binder w/ 2.91% RAP #1 TWB	-20.6	-14.5	-6.2
VSSI AR binder w/ 7.28% RAP #1 TWB	-22.5	-13.8	-8.6

Note: TWB = total weight of binder.

The results show the following:

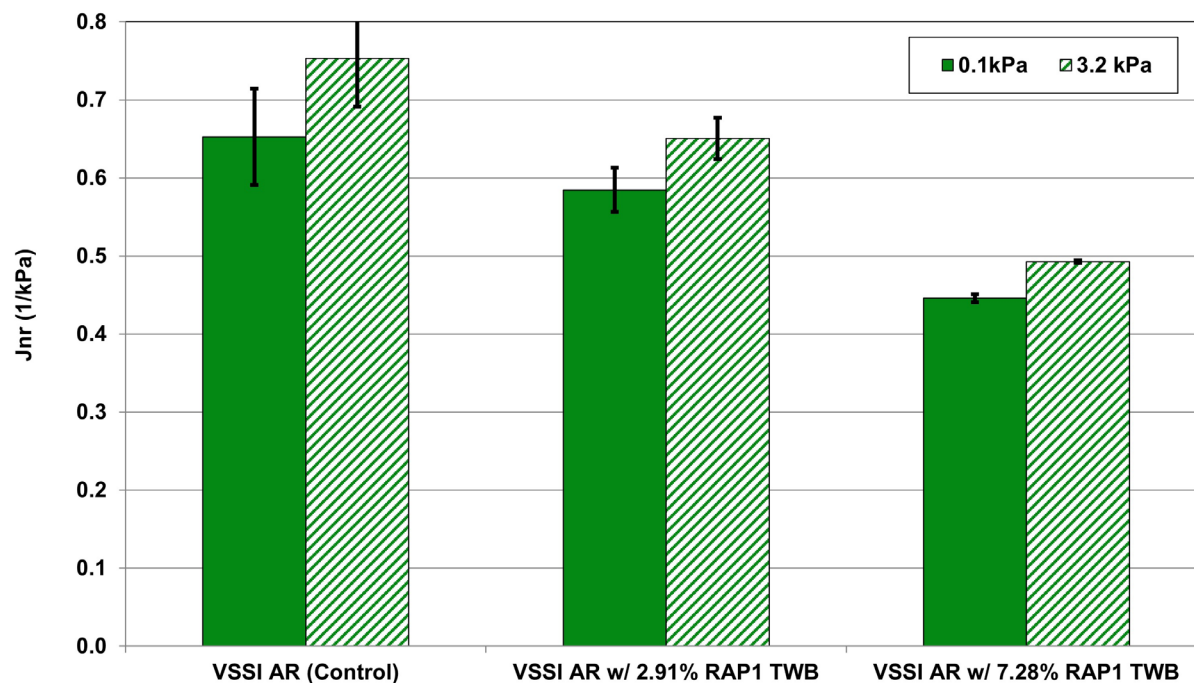
- The critical temperatures for all binders were governed by the m-value. Therefore, a greater loss in creep relaxation was observed compared to an increase in creep stiffness at low temperatures.

- The control VSSI AR binder showed a worse (more negative) ΔT_C value of -14.5°C compared to blends with RAP #1, according to research for conventional binders that recommends that ΔT_C not be below -5°C (29). A value below this parameter is an indicator that there is less viscous relaxation relative to the creep stiffness. However, the same tech brief (29) notes that for elastomeric polymer-modified asphalt binders (such as those modified by tire rubber), a lower ΔT_C may not be an indicator of poor performance. As noted above, the binders with RAP had greater stiffness at both -12°C and -36°C , similar m-values at -12°C , and lower m-values (less relaxation) at -36°C , all of which indicate that overall the control mix would have better low temperature cracking performance. These test results indicate that ΔT_C is not a good indicator of the performance of these AR mixes with the addition of RAP.

5.5. Multiple Stress Creep Recovery

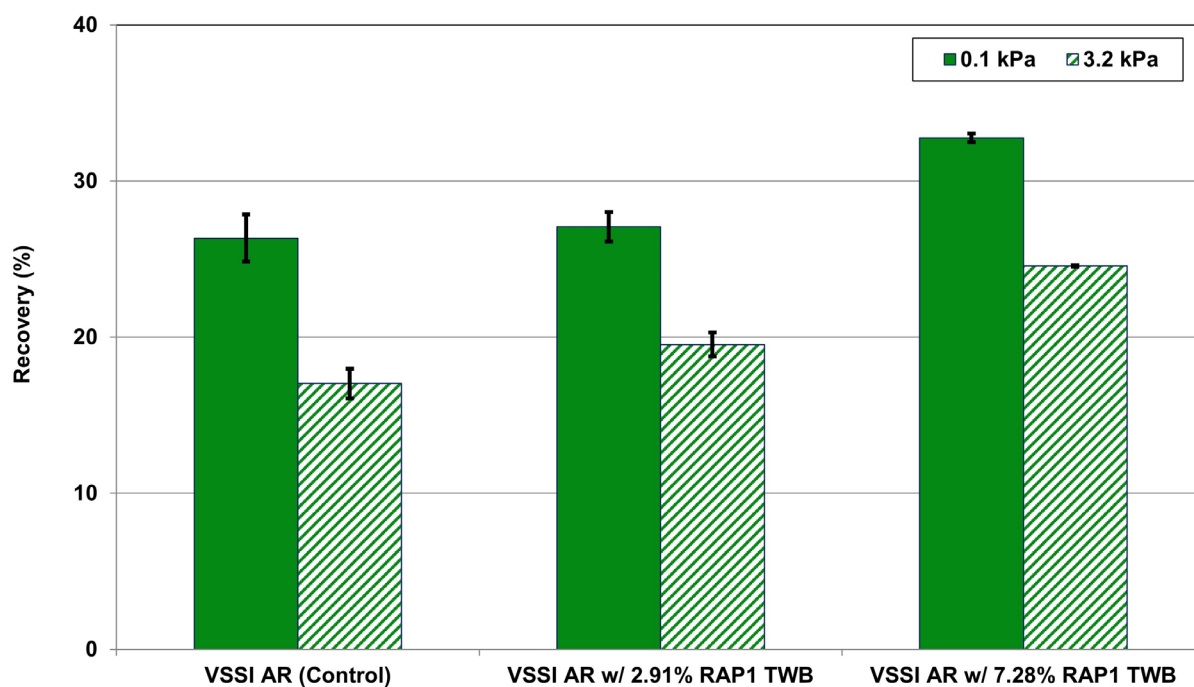
Multiple stress creep recovery test results are listed in Table A.5 in Appendix A. Figure 5.6 and Figure 5.7 plot the non-recoverable creep compliance (J_{nr}) and percentage recovery results at 64°C for the RTFO-aged binders. The results show the following:

- A reduction in non-recoverable creep compliance (J_{nr}) was observed with addition of RAP for both loading conditions (0.1 kPa and 3.2 kPa). A reduction in J_{nr} indicates a material with greater stiffness when measuring only the permanent (non-recoverable) part of the strain, which indicates greater rutting resistance.
- As expected, the percent recovery of the binder was found to increase with an increase in RAP amount. However, the differences in the percent recovery values were much smaller between the control binder and the binder with 2.91% RAP than between the binders with 2.91% and 7.28% RAP binder.
- Increasing the RAP amount is expected to reduce the permanent deformation of asphalt pavement, based primarily on the change in J_{nr} .



Notes: Error bars indicate one standard deviation of results; TWB = total weight of binder.

Figure 5.6: Jnr values of RTFO-aged binders at 64°C.



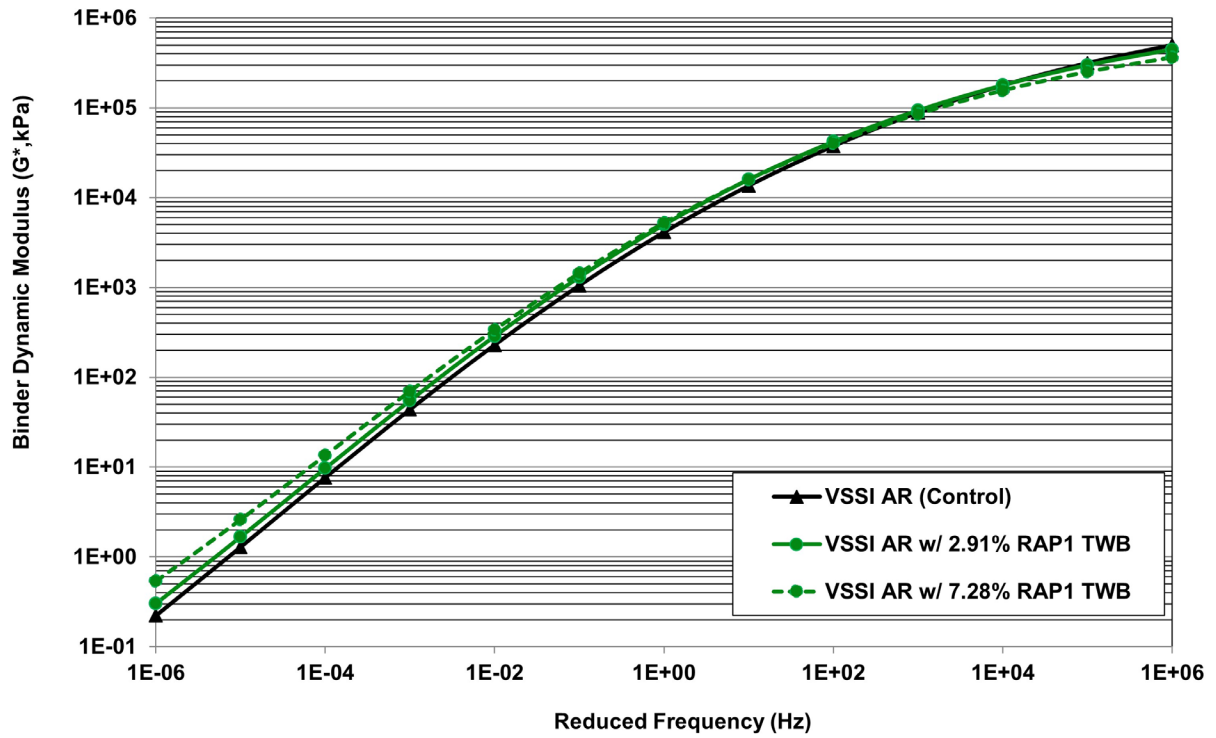
Notes: Error bars indicate one standard deviation of results; TWB = total weight of binder.

Figure 5.7: Percentage recovery of RTFO-aged binders at 64°C.

5.6. Frequency Sweep

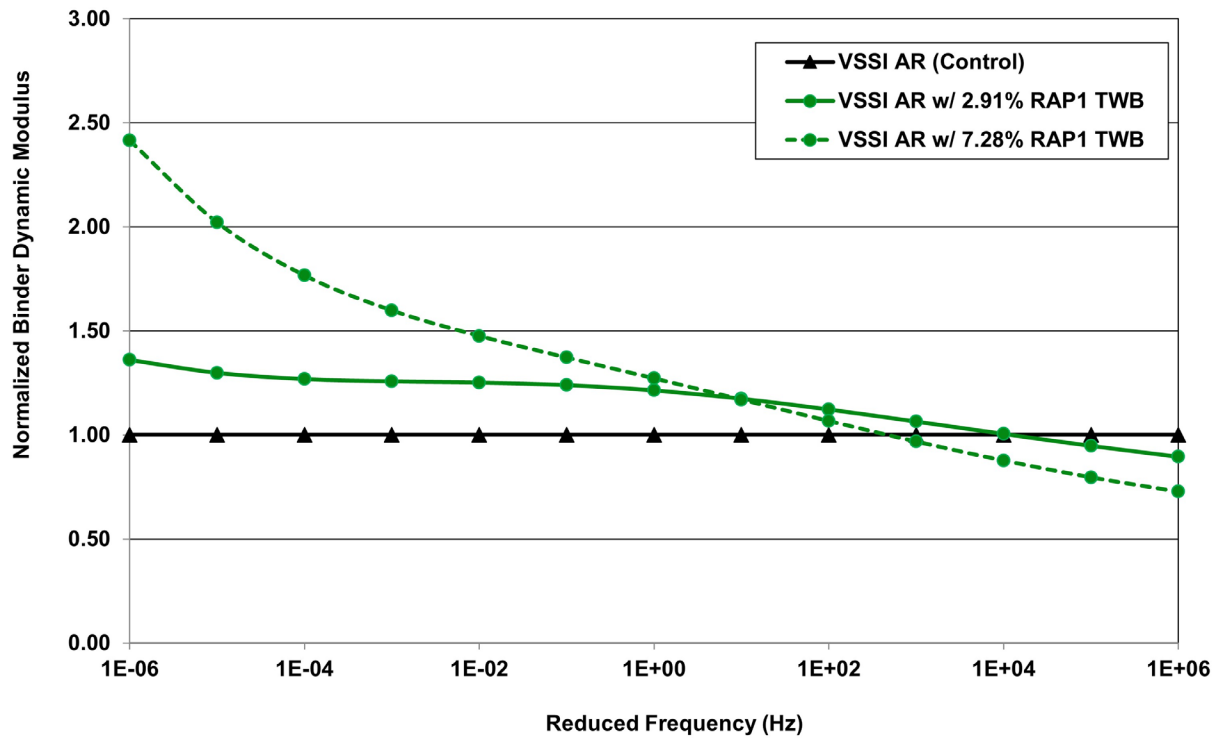
Figure 5.8 shows the master curves for the RTFO-aged binders, and Figure 5.9 shows the plot of the curves normalized to the control binders to facilitate comparison. The master curves were developed at a reference temperature of 20°C using dynamic moduli and phase angles from frequency sweep tests (test temperatures of 20°C, 40°C, and 50°C). The results show the following:

- The addition of RAP was found to increase the stiffness of asphalt binder blends at low frequencies, with a greater increase when more RAP was included. At 20°C and 1E-05 Hz, which corresponds to 64°C and 10 Hz on a trafficked pavement based on the time-temperature superposition principle, the normalized moduli of the blends containing 2.91% and 7.28% RAP were 1.3 and 2.0 times higher than the control binder, respectively. These results indicate greater rutting resistance at higher temperatures and slower speeds.
- At intermediate temperatures, the inclusion of RAP binder also had a stiffening effect, but to a lesser extent than at high temperatures/low frequencies. This can be seen in the figures for the results at 20°C and 1E+00 to 1E+02 Hz. These results would generally indicate somewhat worse fatigue cracking performance in thin overlays and better performance in thicker overlays, with the change from thick to thin occurring between approximately 0.15 and 0.25 ft. (45 to 75 mm), depending on the materials and thicknesses of the other layers in the structure, as well as the axle loads and environmental conditions. This is a general trend, and the results must be evaluated with mix fatigue and stiffness results in ME simulations to determine how well a mix holds to the trend.
- The complex modulus values at higher frequencies (greater than 1E+04 Hz at 20°C) can be considered an indicator of low temperature performance (27). However, the literature indicates that the master curve regression model is often not precise at these higher frequencies (30). Therefore, BBR tests are considered in this study to be more indicative of low temperature performance.



Note: TWB = total weight of binder.

Figure 5.8: RTFO-aged binder master curves at 20°C .



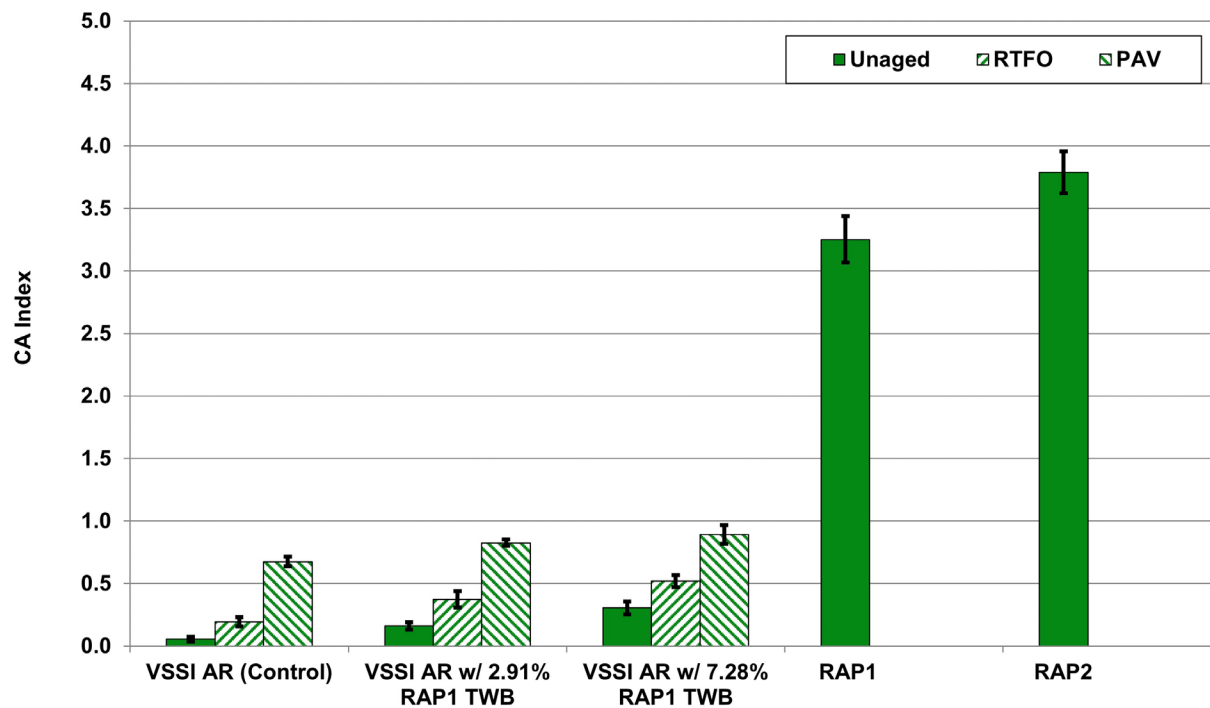
Note: TWB = total weight of binder.

Figure 5.9: Normalized RTFO-aged binder master curves at 20°C .

5.7. FTIR Testing

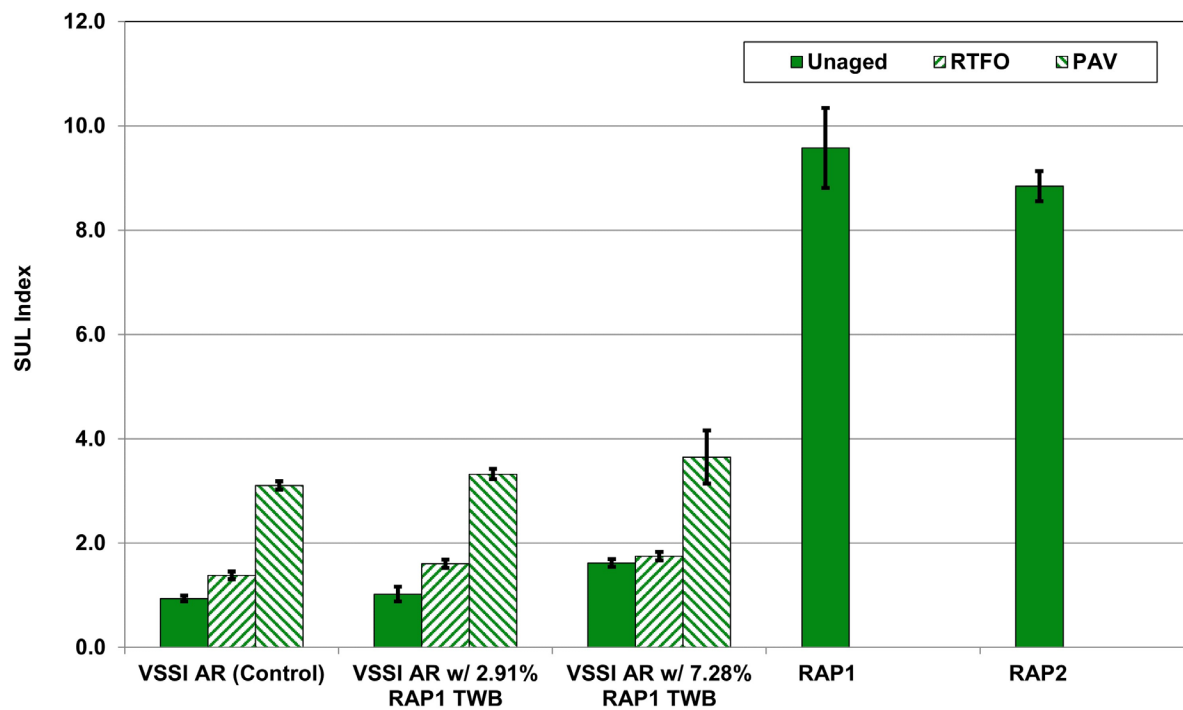
Binders were tested in unaged, RTFO-aged, and PAV-aged conditions for carbonyl (CA) area and sulfoxide (SUL) area, which are indicators of aging-related chemical products in the binder. Figure 5.10 and Figure 5.11 plot the CA and SUL area indices of the binders, with increasing CA and SUL indicating greater aging. The results show the following:

- Both CA and SUL indices increased after RTFO aging and again after PAV aging, indicating that these indices are sensitive to the level of aging in these binders and can be used to track oxidative aging.
- The addition of RAP was found to increase both CA and SUL indices for all aging conditions. The CA index value obtained for unaged control VSSI AR binder was 0.05. For the addition of 2.91% and 7.28% of RAP #1 to VSSI AR binder, the CA indices went up to 0.16 and 0.30, respectively (Table A.6). As noted previously, rubber in asphalt binders does not age, and the binders with RAP have a larger amount of material that can age, even if the RAP binder is already well-aged, and less rubber that does not age.
- The CA indices of unaged RAP sources were much higher compared to PAV-aged blends because of the higher degree of aging in the field for the materials in the RAP. The true high PGs of RAP #1 and RAP #2 were 103.9°C and 108.3°C, respectively. Therefore, higher chemical indices (CA and SUL) are expected for RAP #2 compared to RAP #1. The CA indices for RAP #1 and RAP #2 found were 3.25 and 3.77, respectively. Therefore, CA indices followed the same trend as binder rheological properties ($G^*/\sin(\delta)$). However, SUL indices failed to follow this trend for the two RAP sources, as shown in Figure 5.11. SUL has been found in other binders to increase with initial aging and then decrease with more advanced aging (32).



Notes: Error bars indicate one standard deviation of results; TWB = total weight of binder.

Figure 5.10: Carbonyl area index changes after aging.



Notes: Error bars indicate one standard deviation of results; TWB = total weight of binder.

Figure 5.11: Sulfoxide area index changes after aging.

5.8. Blending Chart

The blending chart results for the high temperature PG for the VSSI control binder and the control binder blended with 2.91% and 7.28% of RAP #1 binder are shown in Table 5.4. The results indicate the following:

- The actual tested temperatures obtained for both unaged and RTFO-aged binders were slightly higher than their corresponding blending chart predicted temperatures. The standard deviation of the RAP blends with RAPs varied between 0.2°C and 0.9°C, whereas the difference between tested and predicted temperatures was between 0.4°C and 2.4°C, indicating similar uncertainty.
- The PG high temperature values were controlled by the unaged properties.

Table 5.4: Blending Chart for Blends with VSSI Base Binder and Two Percentages of RAP #1

Aging Condition	VSSI AR (Control) (°C)		RAP #1 (°C)		VSSI AR w/ 2.91% RAP #1 TWB (°C)				VSSI AR w/ 7.28% RAP #1 TWB (°C)			
	High Temp. PG	Std. Dev.	High PG	Std. Dev.	Predicted PG	Actual	Std. Dev.	Diff, °C	Predicted PG	Actual	Std. Dev.	Diff, °C
Unaged	71.2	0.4	104.7	0.1	72.2	73.0	0.3	0.8	73.6	74.0	0.2	0.4
RTFO	75.4	0.0	103.9	0.1	76.2	77.6	0.9	1.4	77.4	79.8	0.2	2.4

Note: TWB = total weight of binder.

The predicted temperatures for blends with the BUT-162 and IMP-86 AR base binders and RAP #1 (less stiff RAP) and RAP #2 (stiffer RAP) extracted binders at the two binder replacement rates are shown in Table 5.5. The results show the following:

- The blending chart results with the control AR binder from BUT-162 showed lower true grades compared to the IMP-86 control AR binder counterparts, as expected based on the small difference between the control binder PG high temperatures for the respective AR binders.
- The true grade of the RAP #2 binder was 4.4°C higher than that of RAP #1. Therefore, a slightly greater change in performance was found for blends with RAP #2 compared with RAP #1 for the two binder replacement levels, although the differences are very small.

These temperatures were calculated assuming the full blending of RAP and control binders. However, the degree of blending and diffusion of the RAP binder may be different in the mix.

Table 5.5: Blending Chart for Blends with BUT-162 and IMP-86 AR Binders and RAP #1 and RAP #2 Extracted Binders (Predicted)

Blend ID	RAP Source	Unaged				RTFO Aged				Predicted True High Temp. PG (°C)
		RAP High Temp. PG (°C)	Base Binder High PG (°C)	% RAP of TWB	Predicted PG (°C)	RAP High Temp. PG (°C)	Base Binder High PG (°C)	% RAP of TWB	Predicted PG (°C)	
BUT-162 (Control)	N/A	—	85.3	0.00	85.3	—	94.8	0.00	94.8	85.3
BUT-162 AR w/ 2.91% RAP #1 TWB	RAP #1	104.7	85.3	2.91	85.8	103.9	94.8	2.91	95.0	85.8
BUT-162 AR w/ 7.28% RAP #1 TWB	RAP #1	104.7	85.3	7.28	86.7	103.9	94.8	7.28	95.4	86.7
BUT-162 AR w/ 2.91% RAP #2 TWB	RAP2	111.8	85.3	2.91	86.0	108.3	94.8	2.91	95.1	86.0
BUT-162 AR w/ 7.28% RAP #2 TWB	RAP2	111.8	85.3	7.28	87.2	108.3	94.8	7.28	95.7	87.2
IMP-86 AR (Control)	N/A	—	87.4	0.00	87.4	—	90.9	0.00	90.9	87.4
IMP-86 AR w/ 2.91% RAP #1 TWB	RAP #1	104.7	87.4	2.91	87.9	103.9	90.9	2.91	91.2	87.9
IMP-86 AR w/ 7.28% RAP #1 TWB	RAP #1	104.7	87.4	7.28	88.7	103.9	90.9	7.28	91.8	88.7
IMP-86 AR w/ 2.91% RAP #2 TWB	RAP #2	111.8	87.4	2.91	88.1	108.3	90.9	2.91	91.4	88.1
IMP-86 AR w/ 7.28% RAP #2 TWB	RAP #2	111.8	87.4	7.28	89.2	108.3	90.9	7.28	92.1	89.2

Note: TWB = total weight of binder.

6 RHMA-G MIX TESTING RESULTS

6.1. Introduction

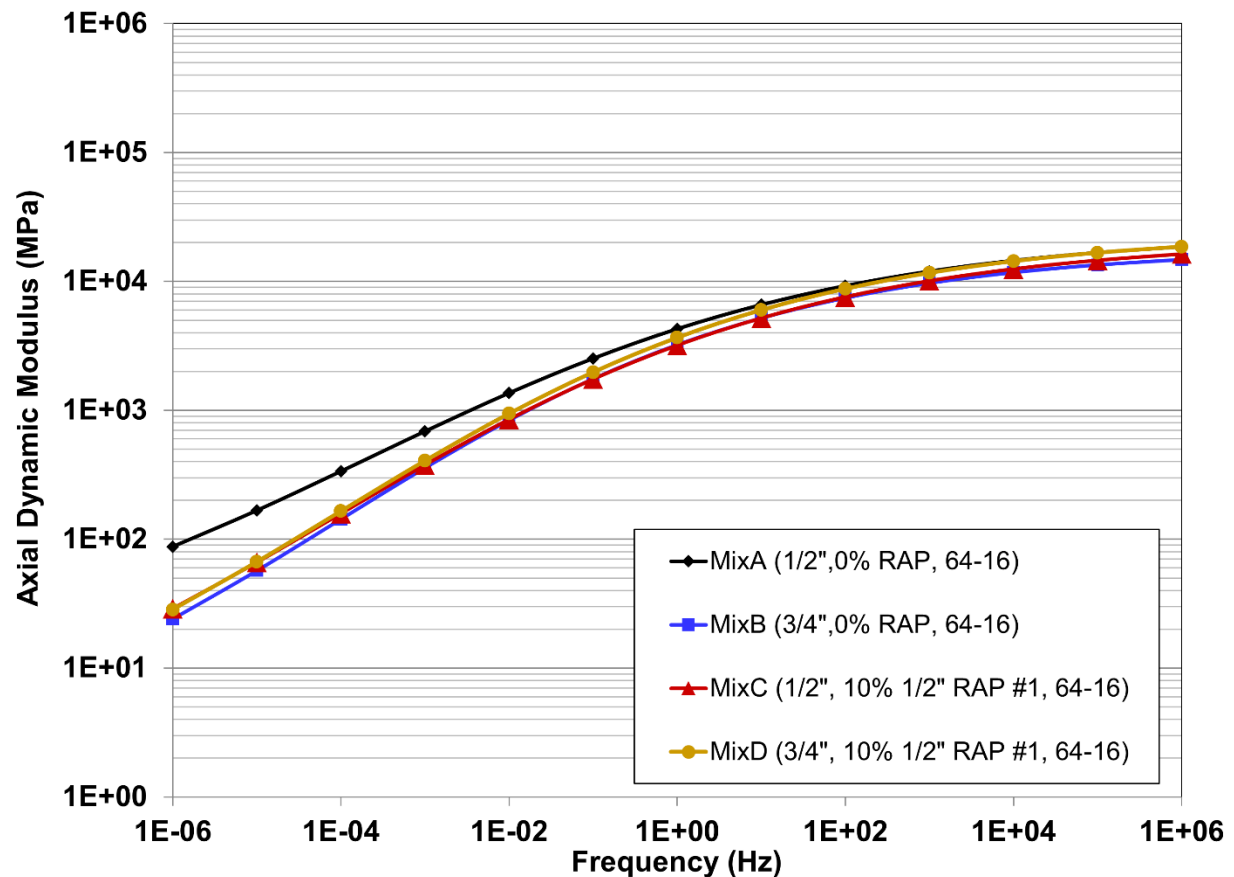
This chapter discusses mix testing results for the plant- and laboratory-produced RHMA-G mixes included in this study. The plant-produced mixes were sampled during test track construction at the UCPRC (referred to as “test track” in this chapter). The laboratory-produced specimens were prepared with the aggregate from the plant-produced test track mixes, RAP from the two RAP sources (RAP #1 and RAP #2), and control AR binders sampled from two Caltrans projects (BUT-162 and IMP-86). Summary plots are presented with the text, while more detailed, tabulated results are provided in Appendix B. Mix designs and test method details are discussed in Chapter 4 and are not repeated in this chapter.

6.2. Mix Stiffness: Dynamic Axial and Flexural Modulus

Dynamic axial and flexural modulus test results are shown in Table B.1 to Table B.20 in Appendix B. Dynamic axial modulus master curves based on a 20°C reference temperature (developed from AMPT frequency sweep tests at 4°C, 21°C, 38°C, and 54°C) for the plant-produced mixes placed on the test track and for the laboratory-produced mixes with the BUT-162 and IMP-86 binders are plotted in Figure 6.1 for the plant-produced mixes and in Figure 6.2 for the laboratory-produced mixes. Master curves normalized to the unmodified base binder for comparison purposes are plotted in Figure 6.3 for the plant-produced track mixes (3/4 in. max), Figure 6.4 for the laboratory-produced mixes normalized to the PG 64 base binder (BUT-162) control mix, and Figure 6.5 for both the PG 64-16 based binder and the PG 70 base binder (IMP-86) control mixes.

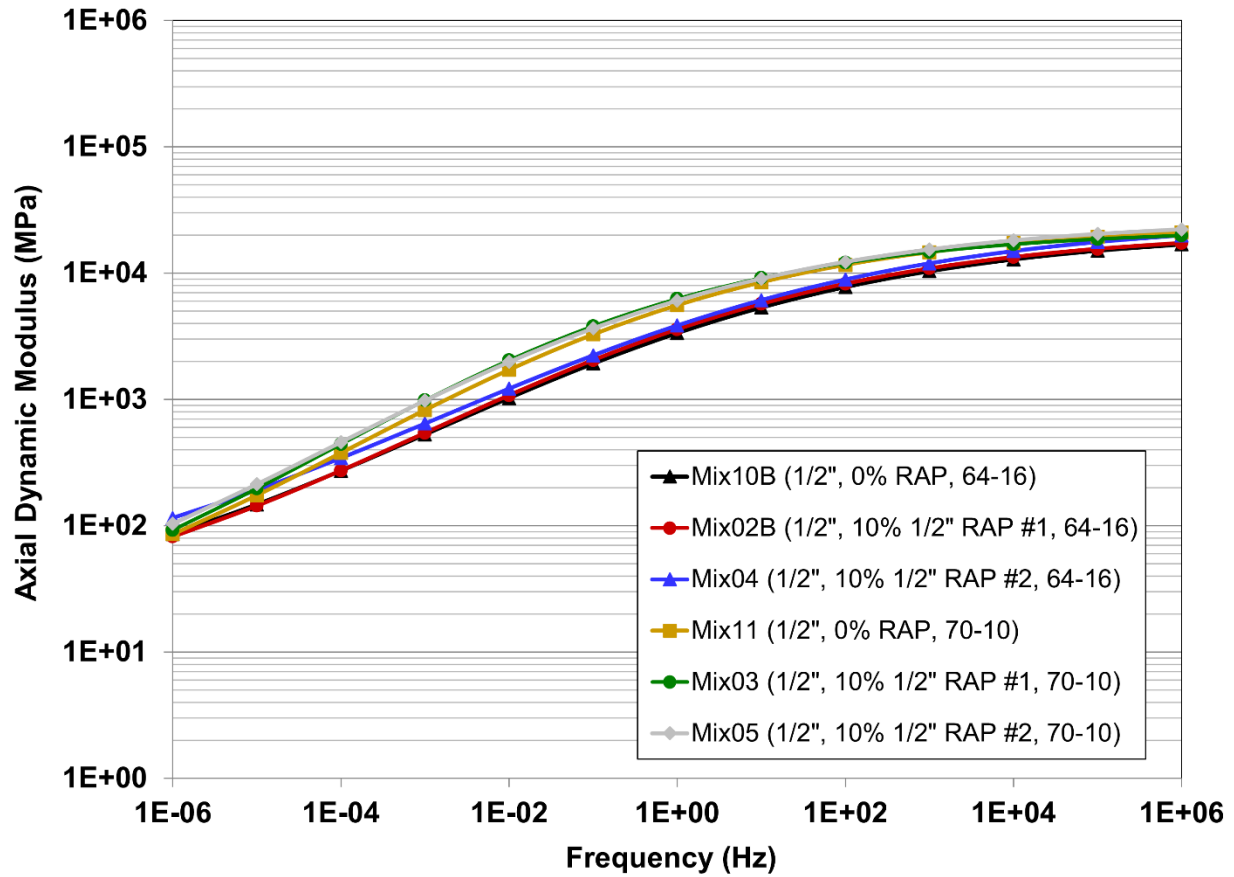
Dynamic flexural modulus master curves representing a 20°C reference temperature are plotted in Figure 6.6 for the plant-produced mixes and Figure 6.7 for the laboratory-produced mixes. Master curves normalized to the unmodified base binder for comparison purposes are plotted in Figure 6.8 for the plant-produced track mixes (3/4 in. max), Figure 6.9 for the laboratory-produced mixes with the PG 64 base binder (BUT-162), and Figure 6.10 for both of the laboratory-produced mixes. These master curves were developed from beam frequency sweep tests at 10°C, 20°C, and 30°C.

Figure 6.11 and Figure 6.12 show Black Space diagrams (complex modulus versus phase angle) derived from the flexural modulus test results from the plant-produced test track mixes and laboratory-produced mixes, respectively.



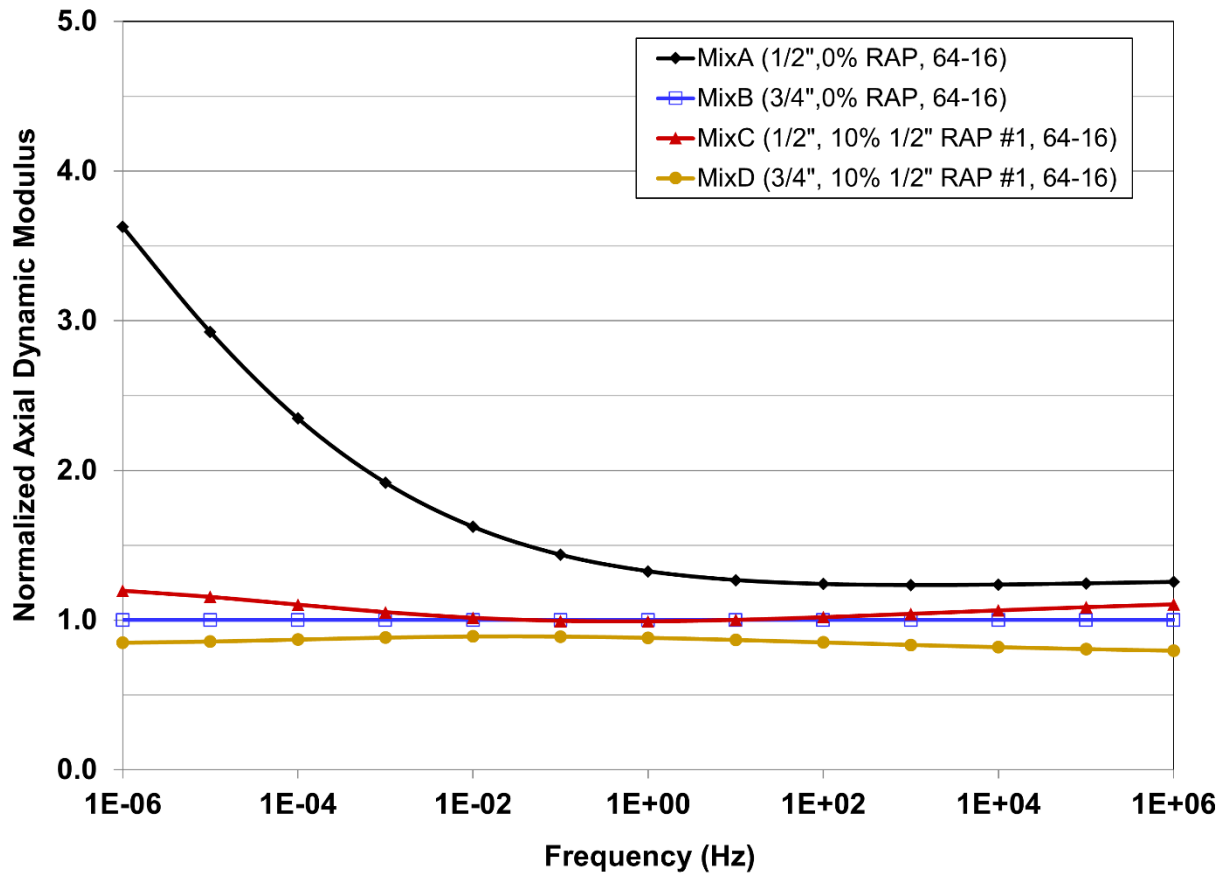
Note: Mix A (1/2", 0% RAP, 64-16) and Mix B (3/4", 0% RAP, 64-16) are the control mixes.

Figure 6.1: Plant-produced mixes: axial dynamic modulus master curves from AASHTO T 378.



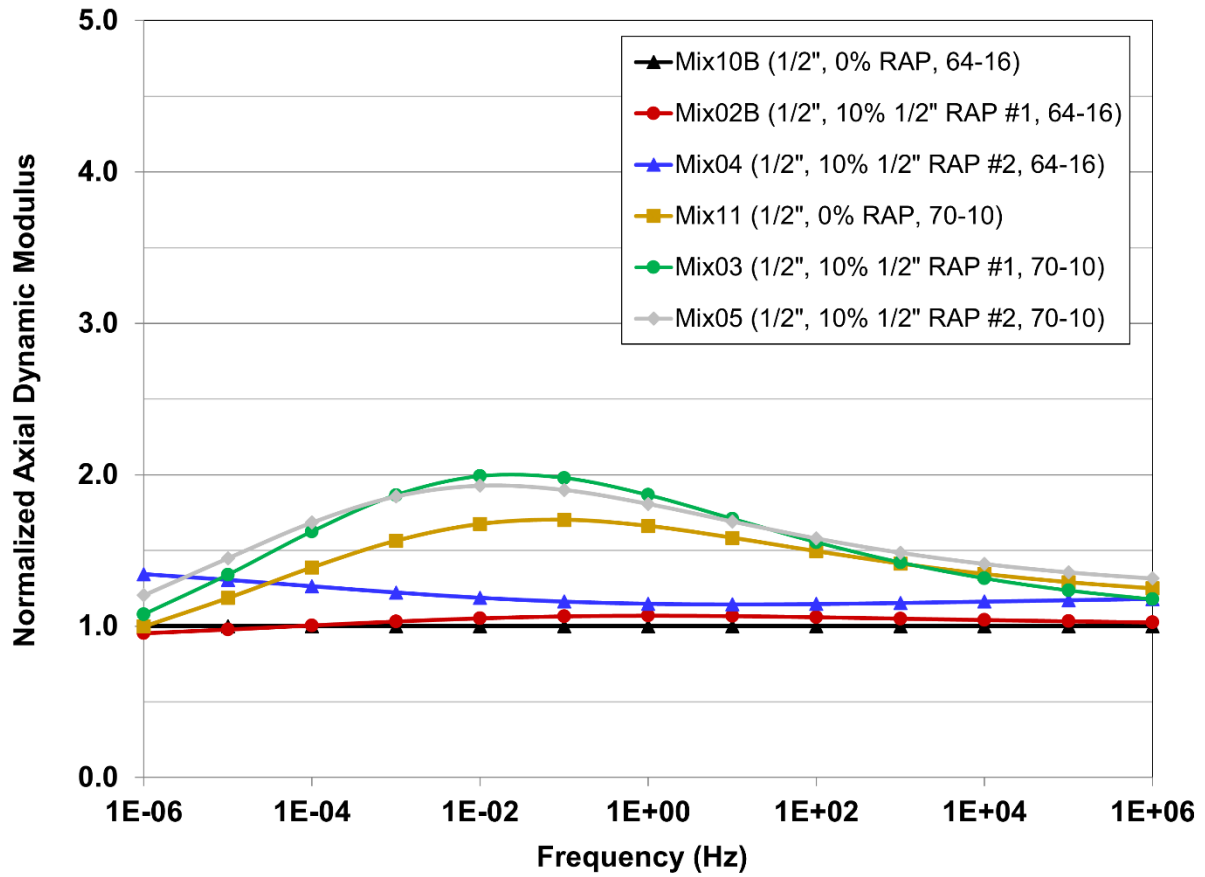
Note: Mix 11 (1/2", 0% RAP, 70-10) and Mix 10B (1/2", 0% RAP, 64-16) are the control mixes.

Figure 6.2: Laboratory-produced BUT-162 (PG 64-16) and IMP-86 (PG 70-10) mixes: axial dynamic modulus master curves from AASHTO T 378.



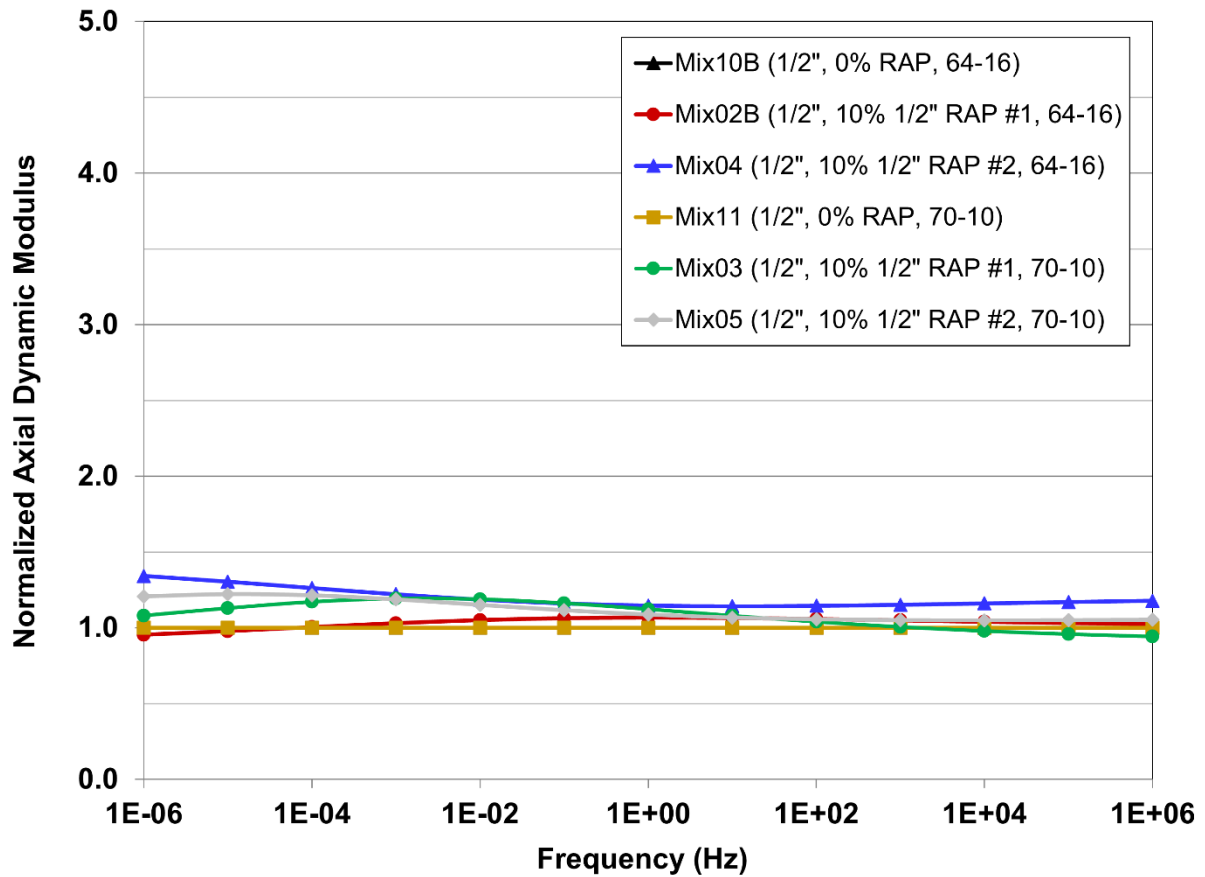
Note: Mix B (3/4", 0% RAP, 64-16) is the control mix.

Figure 6.3: Plant-produced mixes: normalized axial dynamic modulus master curves from AASHTO T 378.



Note: Mix 10B (1/2", 0% RAP, 64-16) is the control mix.

Figure 6.4: Laboratory-produced BUT-162 (PG 64-16) and IMP-86 (PG 70-10): normalized axial dynamic modulus master curves to the PG 64-16 control.



Note: Mix 10B (1/2", 0% RAP, 64-16) and Mix 11 (1/2", 0% RAP, 70-10) are the control mixes for their respective sets of mixes.

Figure 6.5: Laboratory-produced BUT-162 (PG 64-16) and IMP-86 (PG 70-10) mixes: normalized axial dynamic modulus master curves to the PG 64-16 control and the PG 70-10 control from AASHTO T 378.

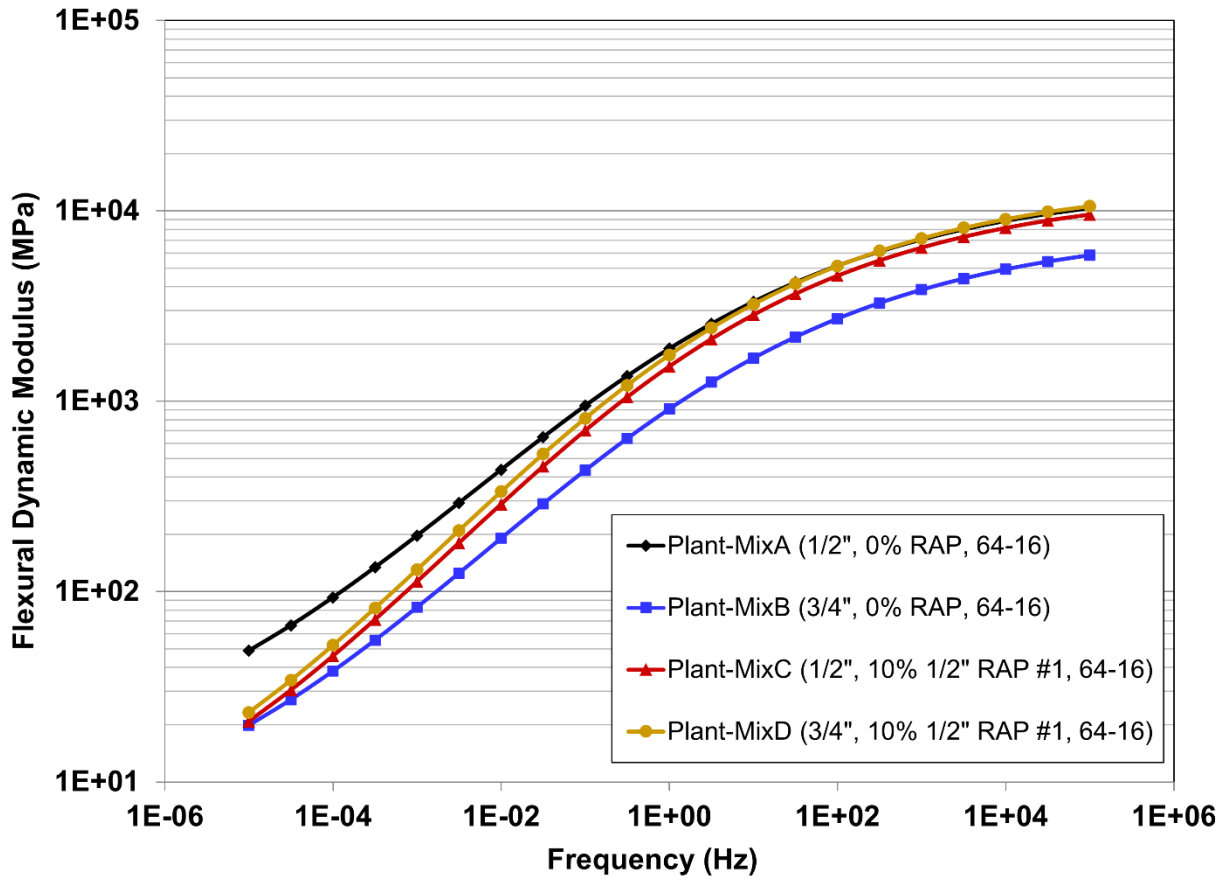


Figure 6.6: Plant-produced mixes: dynamic flexural modulus master curves at 20°C.

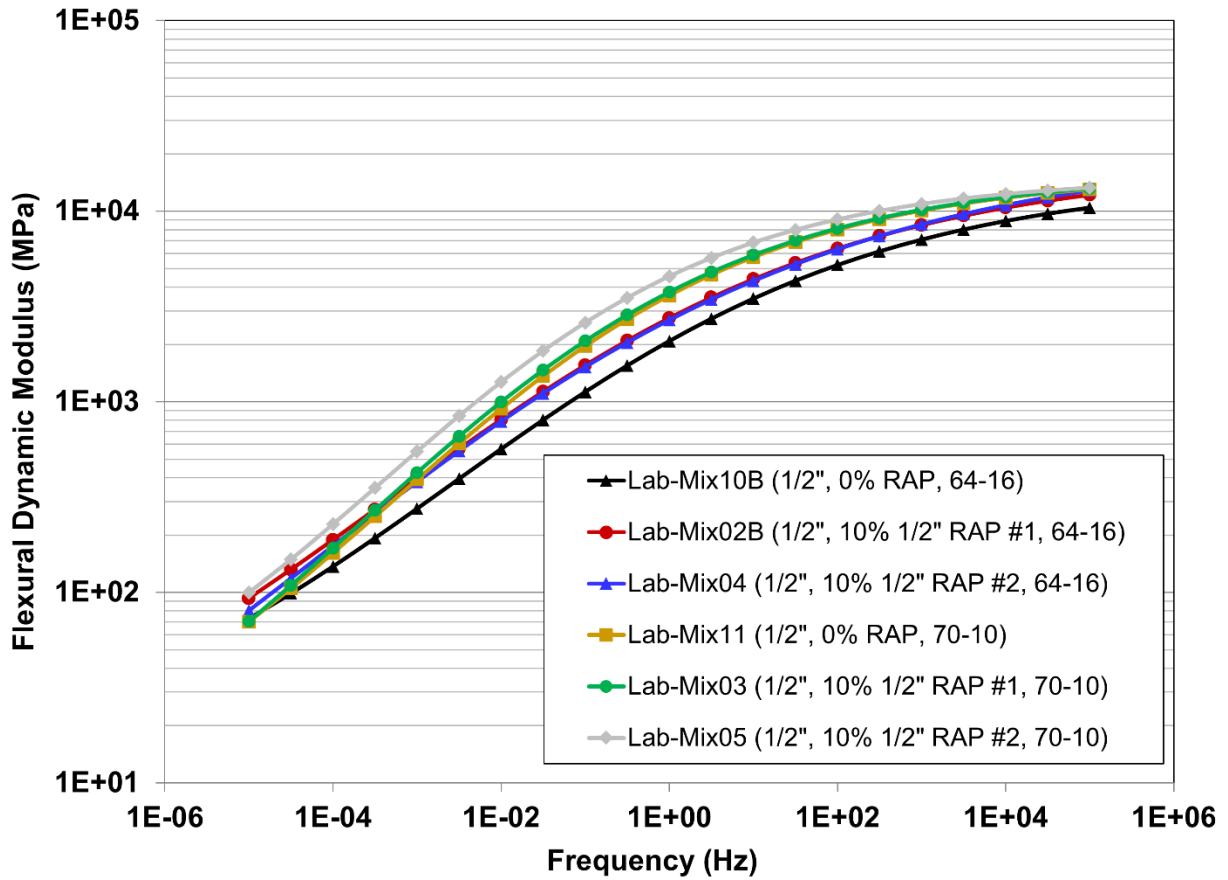
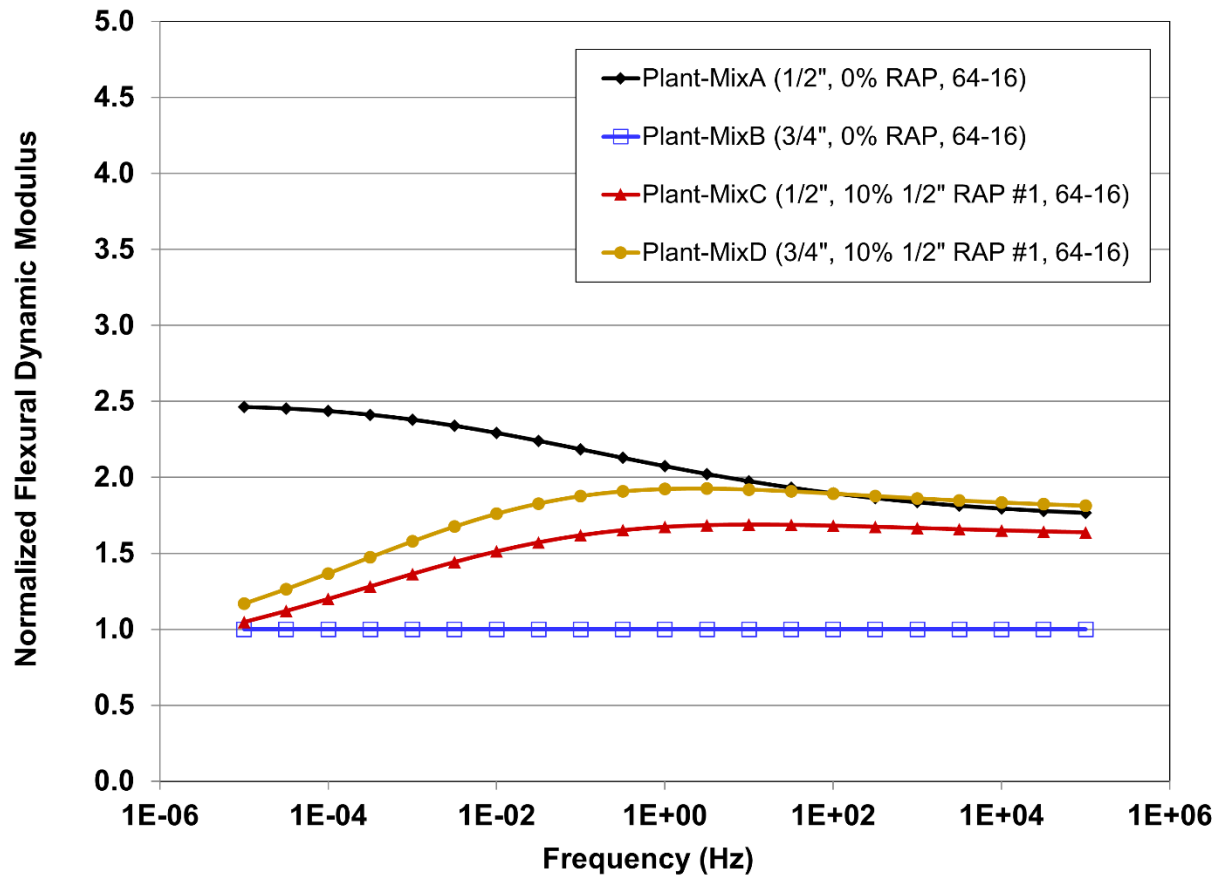
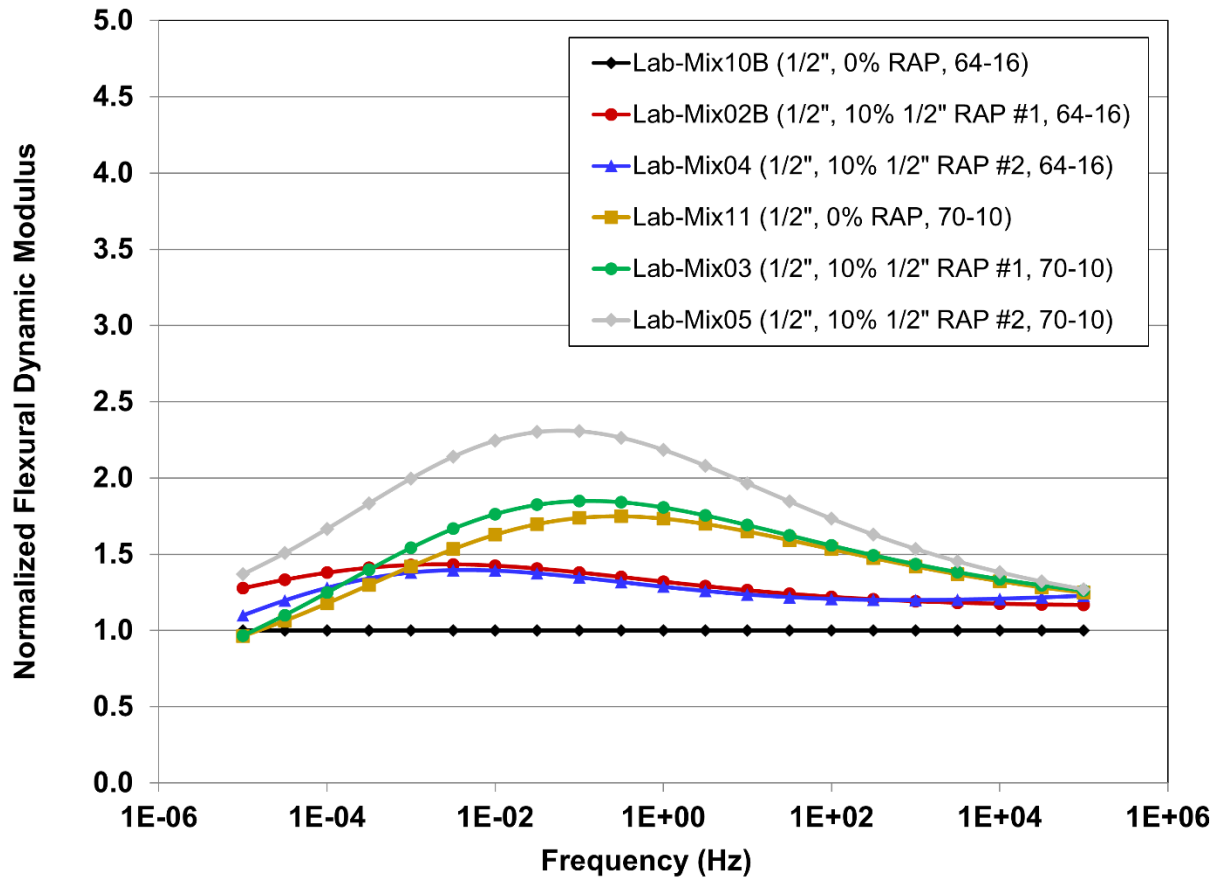


Figure 6.7: BUT-162 (PG 64-16) and IMP-86 (PG 70-10): dynamic flexural modulus master curves at 20°C.



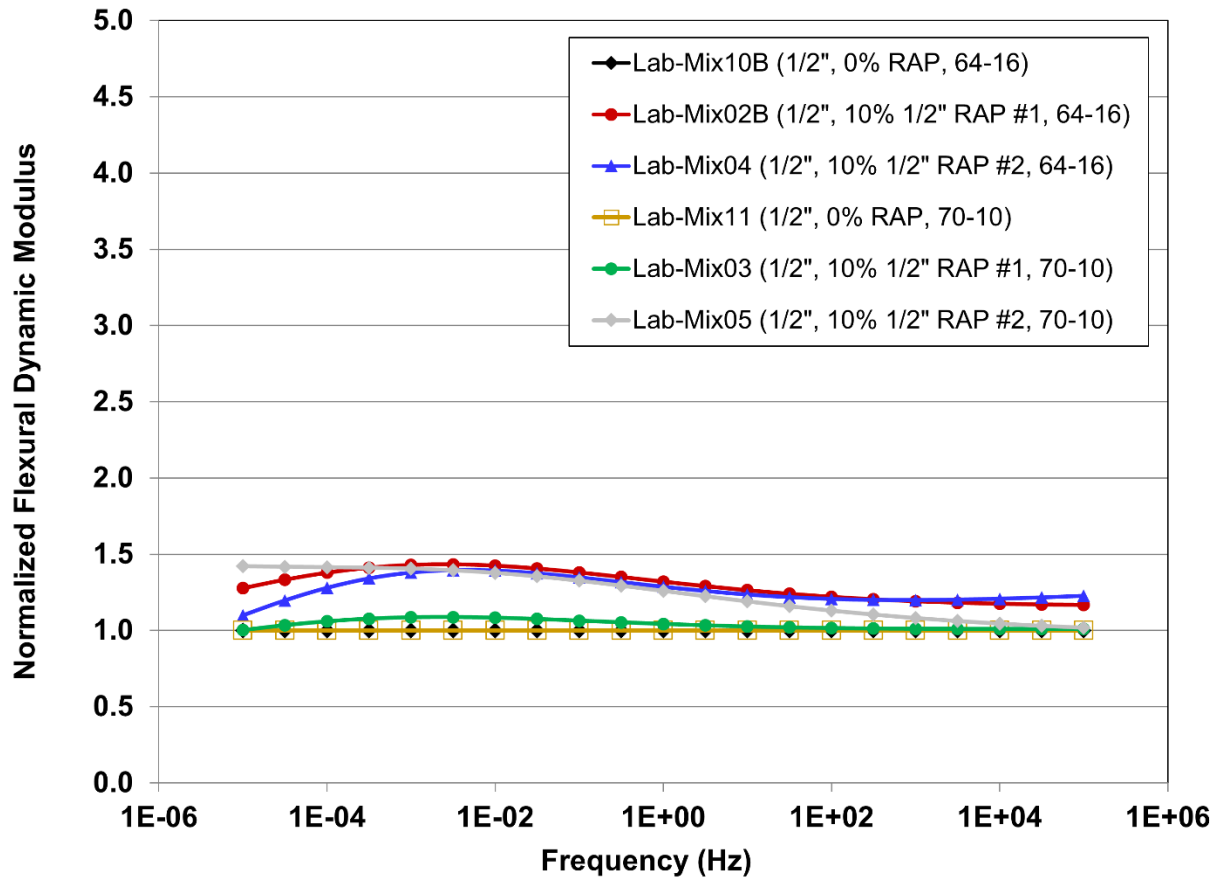
Note: Mix B (3/4", 0% RAP, 64-16) is the control mix.

Figure 6.8: Plant-produced mixes: normalized dynamic flexural modulus master curves from AASHTO T 378.



Note: Mix 10B (1/2", 0% RAP, 64-16) is the control mix.

Figure 6.9: Laboratory-produced BUT-162 (PG 64-16) and IMP-86 (PG 70-10): normalized flexural dynamic modulus master curves to the PG 64-16 control.



Note: Mix 10B (1/2", 0% RAP, 64-16) and Mix 11 (1/2", 0% RAP, 70-10) are the control mixes for their respective sets of mixes.

Figure 6.10: Laboratory-produced BUT-162 (PG 64-16) and IMP-86 (PG 70-10) mixes: normalized flexural dynamic modulus master curves to the control mixes for both base binder sets from AASHTO T 378.

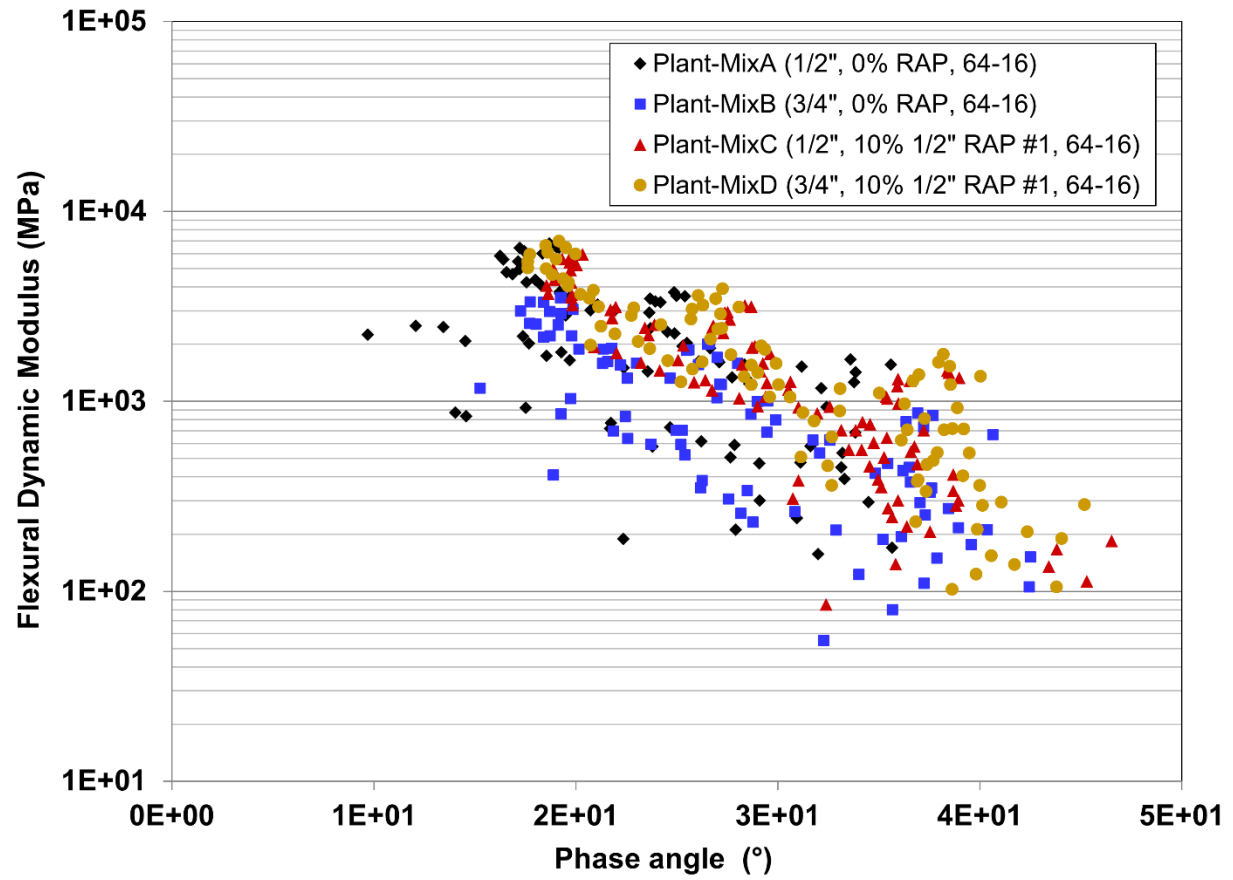


Figure 6.11: Plant-produced mixes: Black Space diagrams of flexural modulus results.

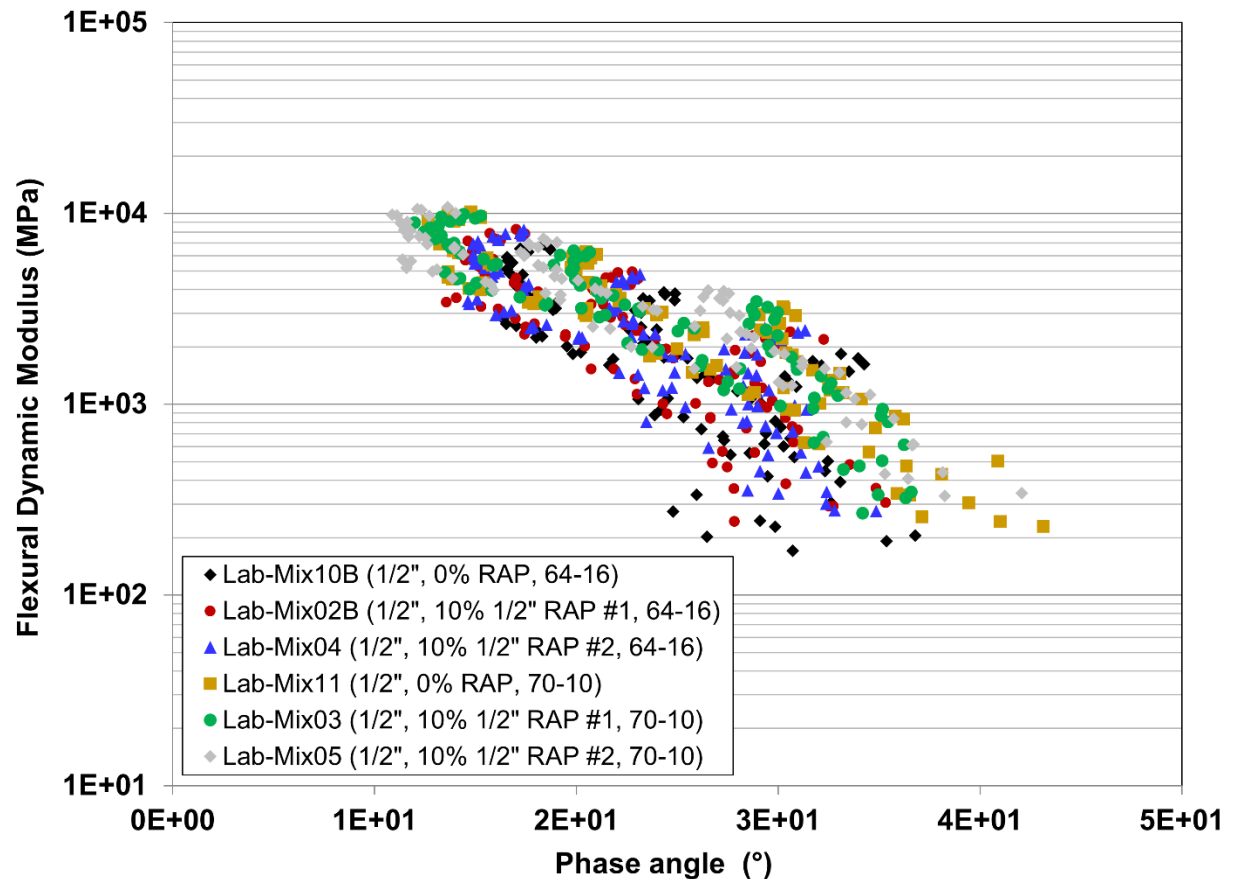


Figure 6.12: BUT-162 (PG 64-16) and IMP-86 (PG 70-10): Black Space diagrams of flexural modulus results.

The results show the following for the plant-produced test track mixes:

- The axial stiffnesses were generally similar with and without RAP, except in the case of the 1/2 in. control mix. The 1/2 in. control mix was up to 3.6 times stiffer than the other mixes at the lowest frequencies, corresponding to slower traffic and higher temperatures, and showed stiffnesses that were closer to those of the other three mixes as the frequency increased, becoming nearly the same at the highest frequencies. This is attributed to the silo time aging of that mix, compared with the other three mixes, which had little or no silo time.
- The effects on the flexural stiffness results of adding RAP and silo time were similar to the effects on the axial stiffnesses, with the 1/2 in. control mix being stiffer at lower frequencies, corresponding to slower traffic and higher temperatures, with the difference decreasing as the frequency of loading increased. The exception was that the flexural stiffnesses of the 3/4 in. control mix were softer than the other mixes at higher frequencies, corresponding to faster traffic and colder temperatures, while the axial stiffnesses of the 3/4 in. control mix were similar to the other two mixes that did not have silo aging at all

frequencies. It is not known why this difference in the trends for the two modes of loading occurred.

The results for the laboratory-produced mixes with the two types of base binders show the following:

- For the laboratory-produced mixes with the PG 64-16 base binder (BUT-162), the axial stiffnesses were generally similar with and without RAP across all frequencies. The mixes with the PG 70-10 base binder (IMP-86) are stiffer, as expected, than those with the PG 64-16 base binder at nearly all frequencies, becoming more similar to the PG 64-16 base binder mixes at the extreme high and low frequencies.
- For the laboratory-produced mixes with the PG 64-16 base binder (BUT-162), the effects of adding RAP can be seen in the flexural stiffness results within each set of base binder mixes, stiffening both control mixes by a factor of up to 1.5. The stiffer RAP #2 affected the PG 70-10 mix more than the softer RAP #1 mix, while the effects of the two RAP sources were similar for the PG 64-16 set of binders. The mixes with the PG 70-10 base binder (IMP-86) also showed the effects of adding RAP from both sources and the additional effects of the stiffer RAP #2 compared to the softer RAP #1. The PG 70-10 mixes are stiffer, as expected, than those with the PG 64-16 base binder at nearly all frequencies, becoming more similar to the PG 64-16 base binder mixes at the extreme high and low frequencies.

The results for the Black Space diagrams show the following:

- The flexural frequency sweep Black Space diagrams, with stiffness and phase angle plotted together, show that for the plant-produced test track mixes, the silo-aged 1/2 in. control mix has lower phase angles at colder temperatures (the values at the extreme left of the plot for each mix) than the other three mixes with or without RAP, which are similar to each other. This indicates that the effect of the silo aging made that mix more elastic and less able to relax stresses at lower temperatures than did the effect of adding the RAP.
- The Black Space diagram for the laboratory-produced mixes indicates that the mixes with PG 70-10 base binder had lower phase angles at colder temperatures than the PG 64-16 binders. The data also plot to a small degree toward lower, more elastic phase angles for the mixes with RAP compared to those without RAP for mixes for both sets of base binders.

Overall, the dynamic modulus test results indicate the following:

- The plant-produced mix results did not always follow expected trends with regard to the addition of RAP. Additional silo aging confounded the results for the 1/2 in. mixes, with the effects of silo aging being much stronger than the effects of adding RAP. The silo aging increased the stiffness, as expected. For the 3/4 in. mix, the effects of adding RAP

depended on the testing mode, axial or flexural, with the flexural results showing a large increase in stiffness, while the axial stiffness results showed little effect. Small decreases in phase angle occurred as expected from additional silo aging, while adding RAP did not have much effect.

- The mix stiffness results for the same base binder and RAP #1 used in the plant-produced mixes showed an increase in stiffness with the inclusion of RAP, particularly at low frequencies. The axial dynamic mix stiffnesses showed mixed results regarding the change in stiffness with the inclusion of RAP, while the flexural stiffness results showed increases like the binder test results, although with differing levels of influence at different frequencies compared with the binder tests. This result is generally expected because the influence of aggregate is more pronounced in the mix at higher temperatures and slow frequencies, while the binder effect is dominant in the mix at lower temperatures and faster frequencies.
- For the laboratory-produced mixes, trends in stiffness generally followed expectations, with the stiffer PG 70-10 base binder set of mixes being stiffer than the PG 64-16 base binder set of mixes, the inclusion of RAP stiffening the mixes, the stiffer RAP source (RAP #2) increasing the stiffness more than the less stiff RAP source (RAP #1), and the inclusion of RAP slightly decreasing phase angles. For both axial and flexural stiffness, the maximum increase from the inclusion of RAP relative to the control mixes for both sets of mixes across all frequencies was always less than 50% and less than 25% at most reduced frequencies.

6.3. Flexural Fatigue Resistance and Initial Stiffness

Flexural initial stiffness and fatigue test results are shown in Table B.23 to Table B.25 in Appendix B. For the plant-produced test track mixes, the initial flexural stiffnesses at the 10 Hz and 20°C fatigue test conditions are shown in Figure 6.13, plots of fatigue life versus tensile strain level (Wöhler curves) in Figure 6.14, and normalized fatigue life in Figure 6.15. For the laboratory-produced mixes using the two base binders and the two sources of RAP, the initial stiffnesses are shown in Figure 6.16, the Wöhler curves are shown in Figure 6.17 for the mixes with the BUT-162 PG 64-16 base binder and in Figure 6.18 for the mixes with the IMP-86 PG 70-10 base binder, and for both sets of laboratory-produced mixes in Figure 6.19.

The results for both sets of laboratory-produced mixes are summarized at three strain levels in Figure 6.20. Normalized fatigue lives are shown for the PG 64-16 set in Figure 6.21, for the PG 70-10 set in Figure 6.22, and together in Figure 6.23. The plots of normalized fatigue life include extrapolation to smaller strains than those at which the mixes were tested for fatigue. In general, the linear relationship between the log of the fatigue life and the log of the tensile strain shown on the Wöhler curve holds down to tensile strains in the 100 to 200 microstrain range, provided the materials are not polymer or rubber modified. In the case of polymer- and rubber-modified materials, very long fatigue lives occur at strains in that range. The fatigue results were extrapolated to 300 microstrain in the figures with normalized fatigue life.

It should be noted that all the laboratory tests were run in controlled deformation mode, and the laboratory fatigue life is applicable to thin asphalt layers for pavement fatigue life and pavement reflective cracking life for thin overlays of cracked pavements. In general, but not always, softer mixes will need less energy to deform and tend to have longer fatigue lives if the air-void contents are the same. For thicker asphalt layers used in new or reconstructed pavements or overlays, the pavement fatigue life will depend on the interaction of asphalt mix stiffness, which influences the tensile strains causing fatigue or reflective cracking, and the fatigue life at a given tensile strain.

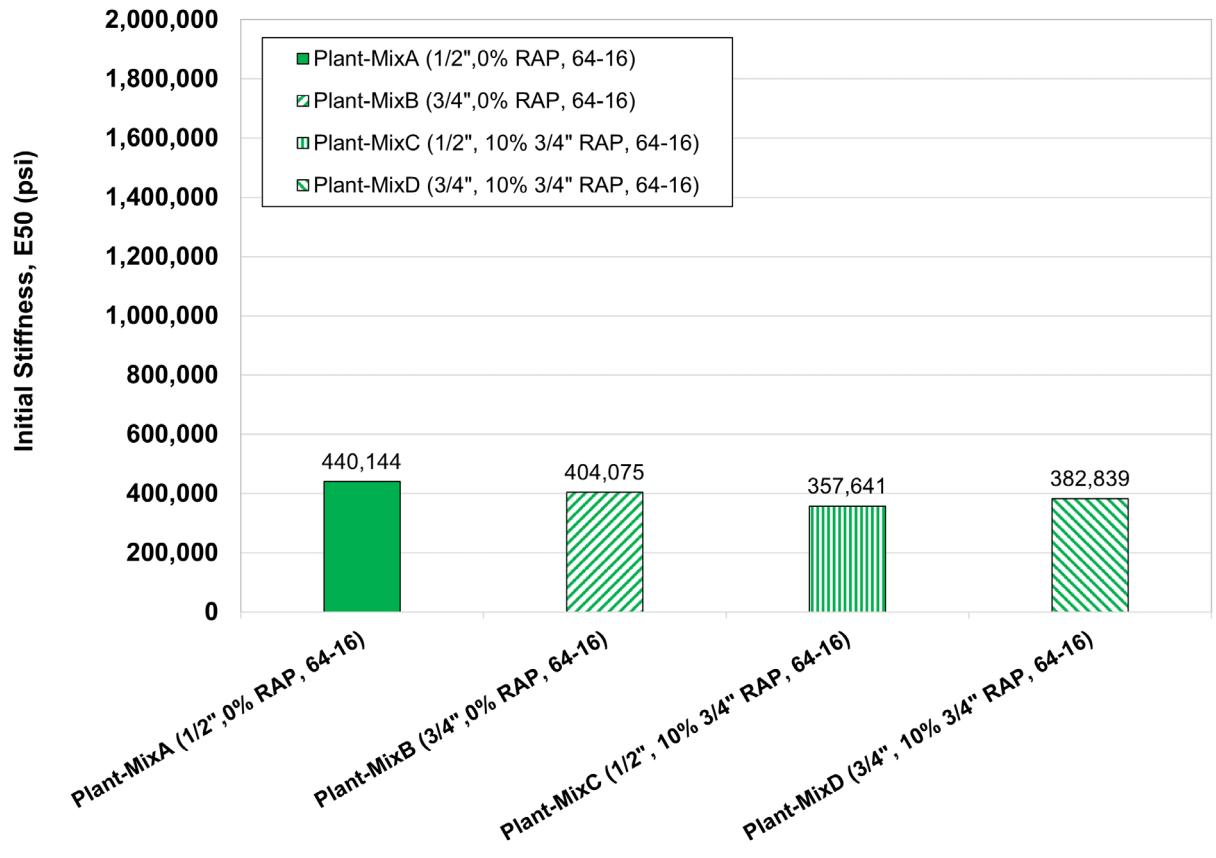


Figure 6.13: Plant-produced (PG 64-16) initial stiffness, E50.

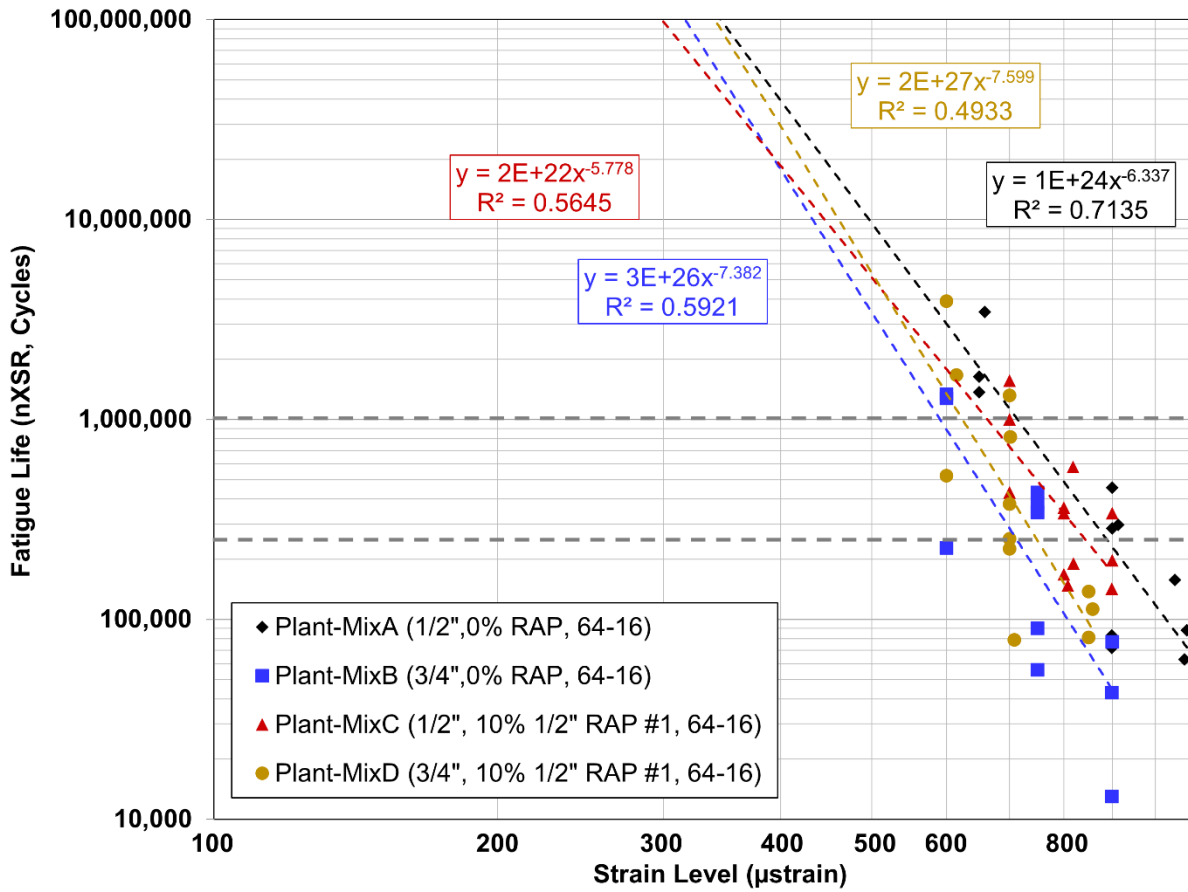
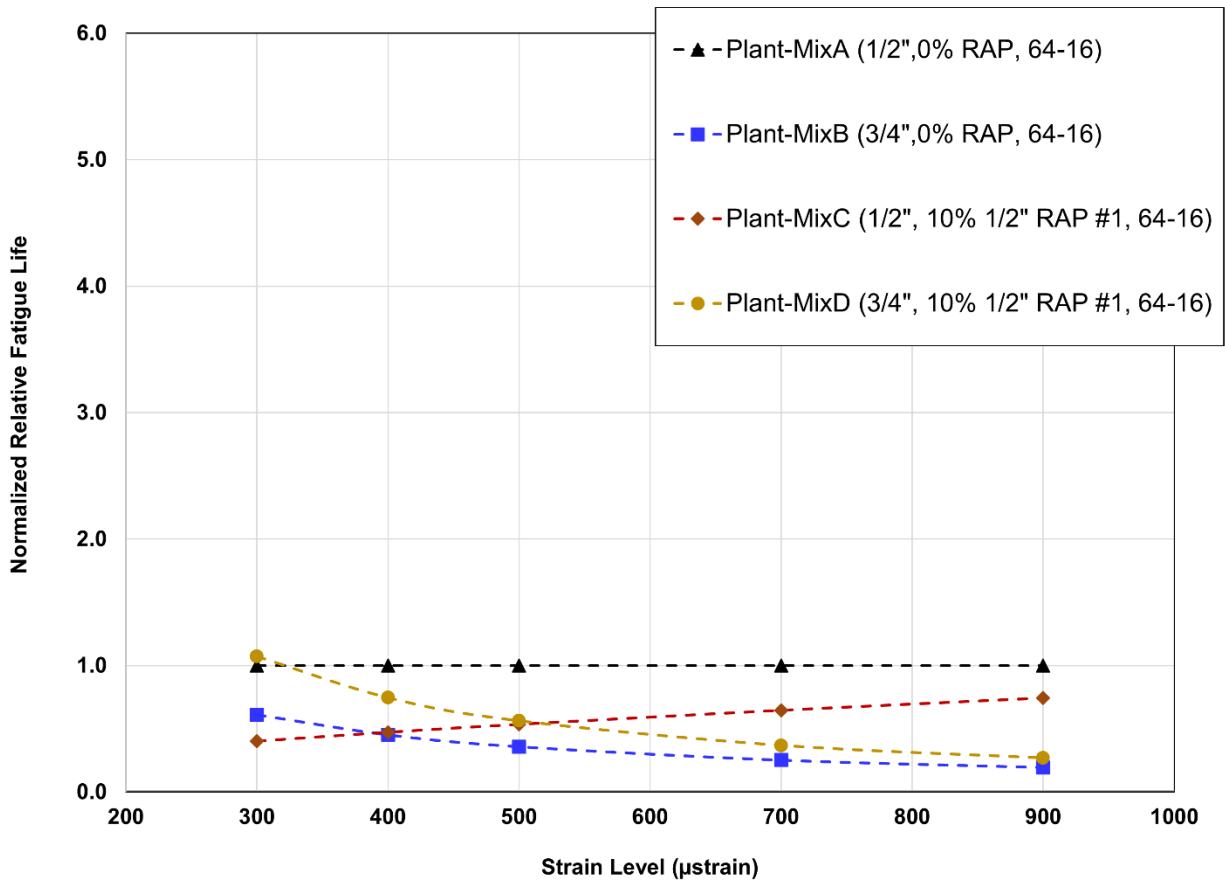


Figure 6.14: Plant-produced (PG 64-16) fatigue life.



Notes: The 1/2 in. mix with no RAP is the basis for normalization in the figure. These results include extrapolation to smaller strains than were used in testing.

Figure 6.15: Plant-produced (PG 64-16) normalized fatigue life.

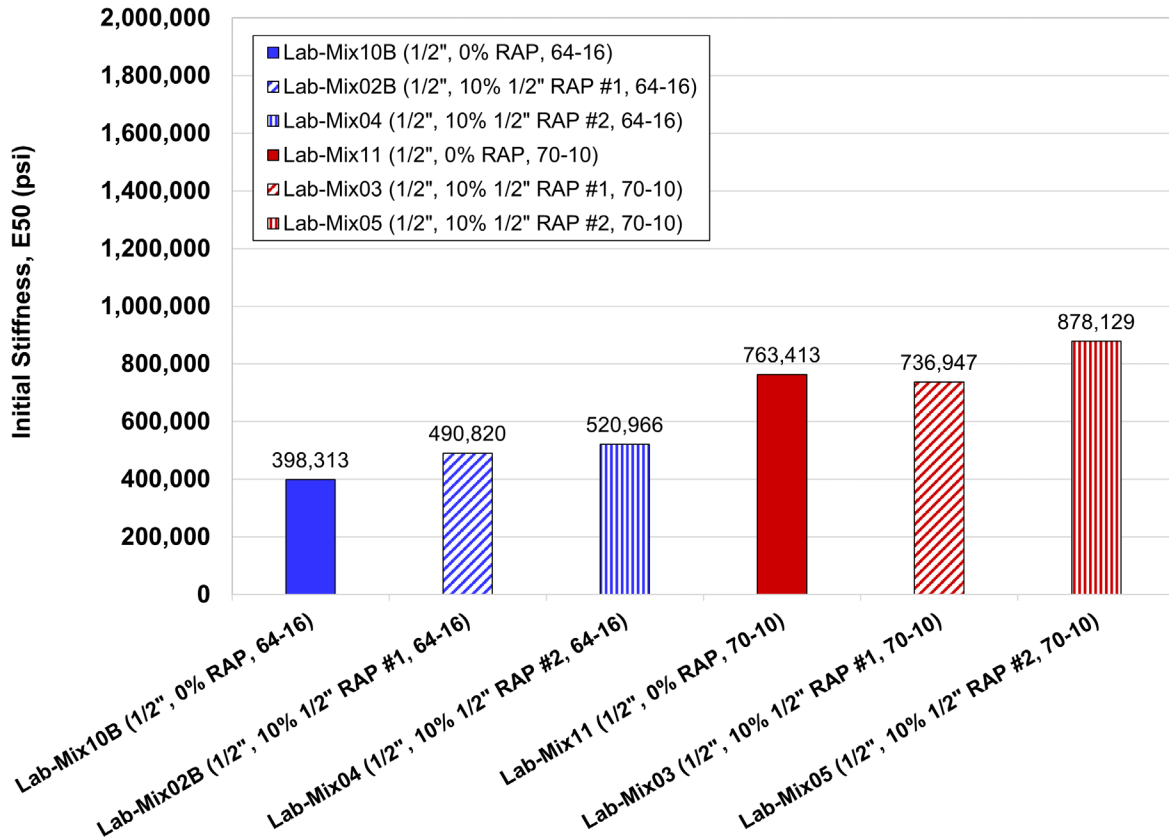


Figure 6.16: Laboratory-produced BUT-162 (PG 64-16) and IMP-86 (PG 70-10) initial stiffness, E50.

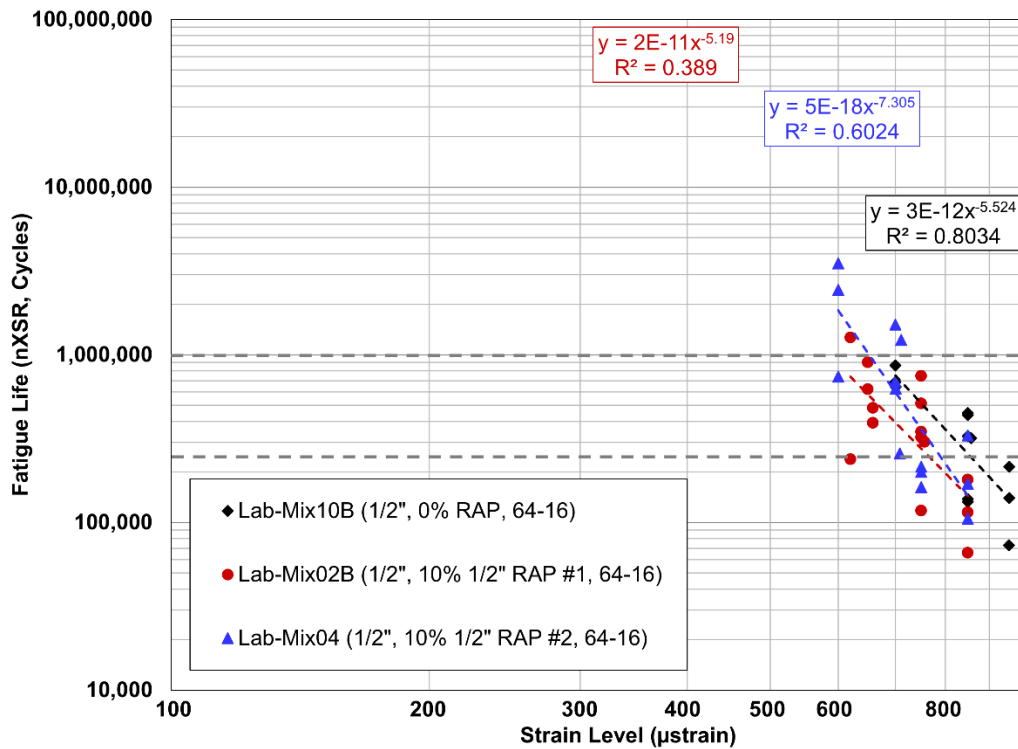


Figure 6.17: Laboratory-produced BUT-162 (PG 64-16) flexural fatigue life versus tensile strain.

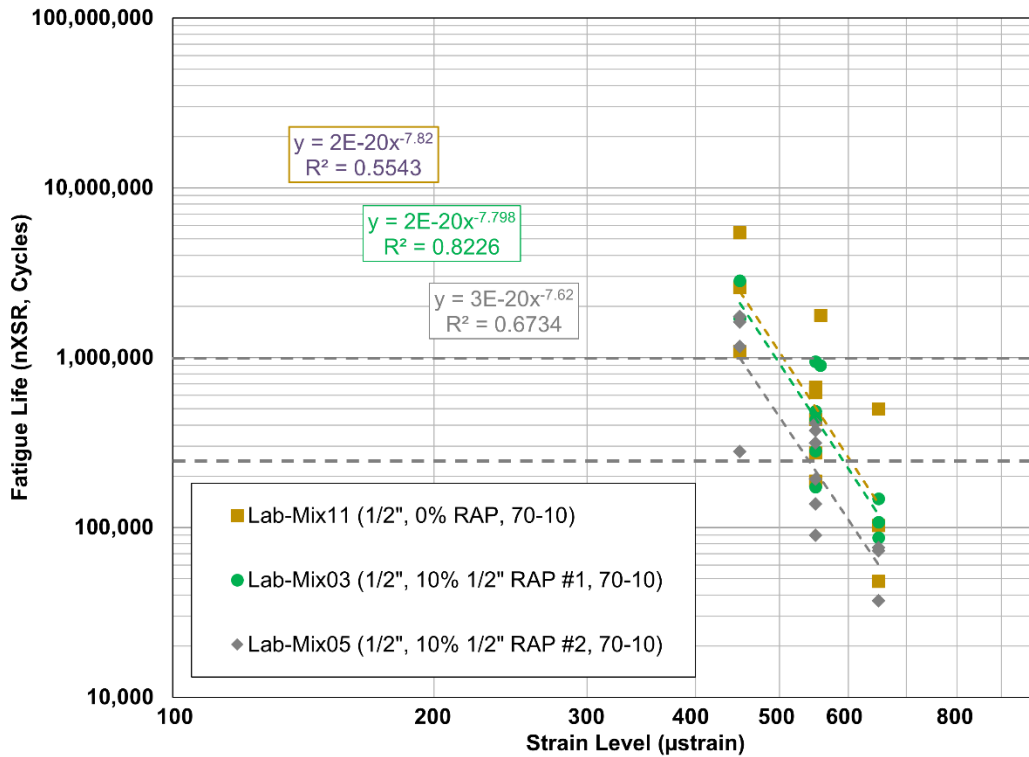


Figure 6.18: Laboratory-produced IMP-86 (PG 70-10) flexural fatigue life versus tensile strain.

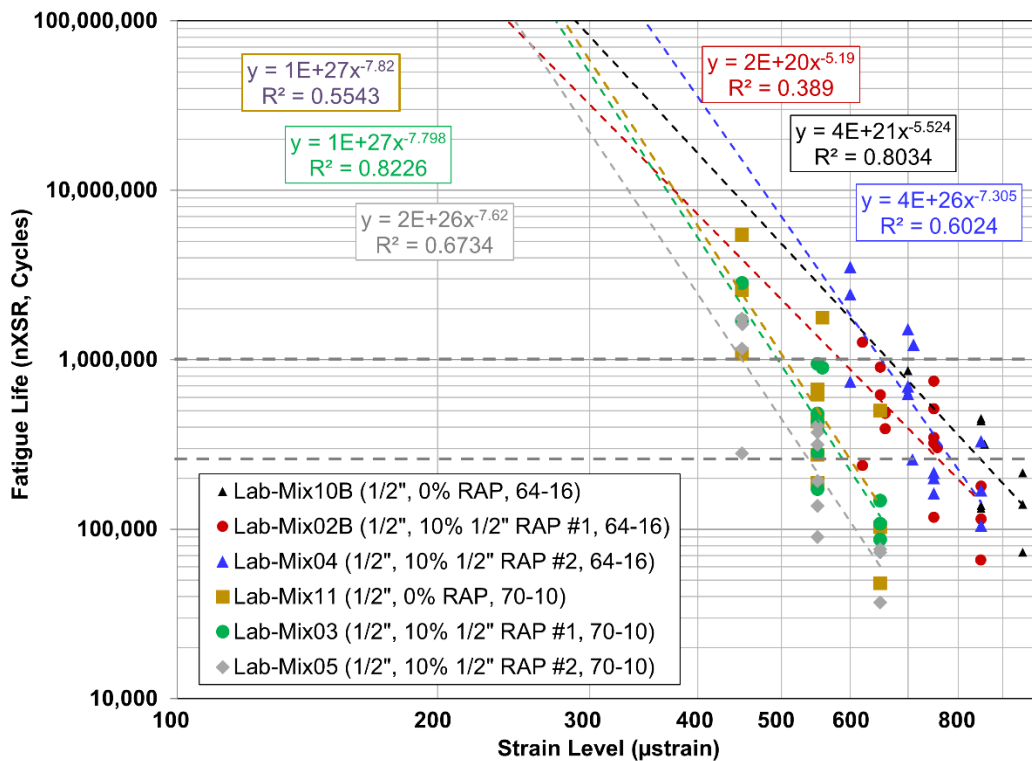


Figure 6.19: Laboratory-produced BUT-162 (PG 64-16) and IMP-86 (PG 70-10) flexural fatigue life versus tensile strain.

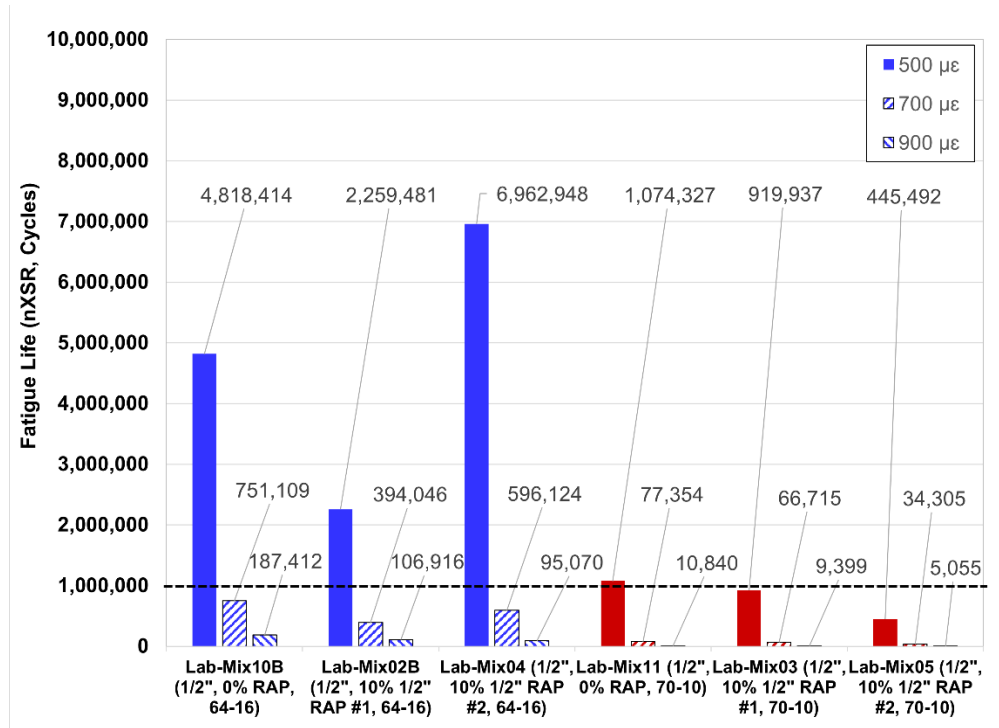


Figure 6.20: Laboratory-produced BUT-162 (PG 64-16) and IMP-86 (PG 70-10) summary of flexural fatigue life for three strain levels.

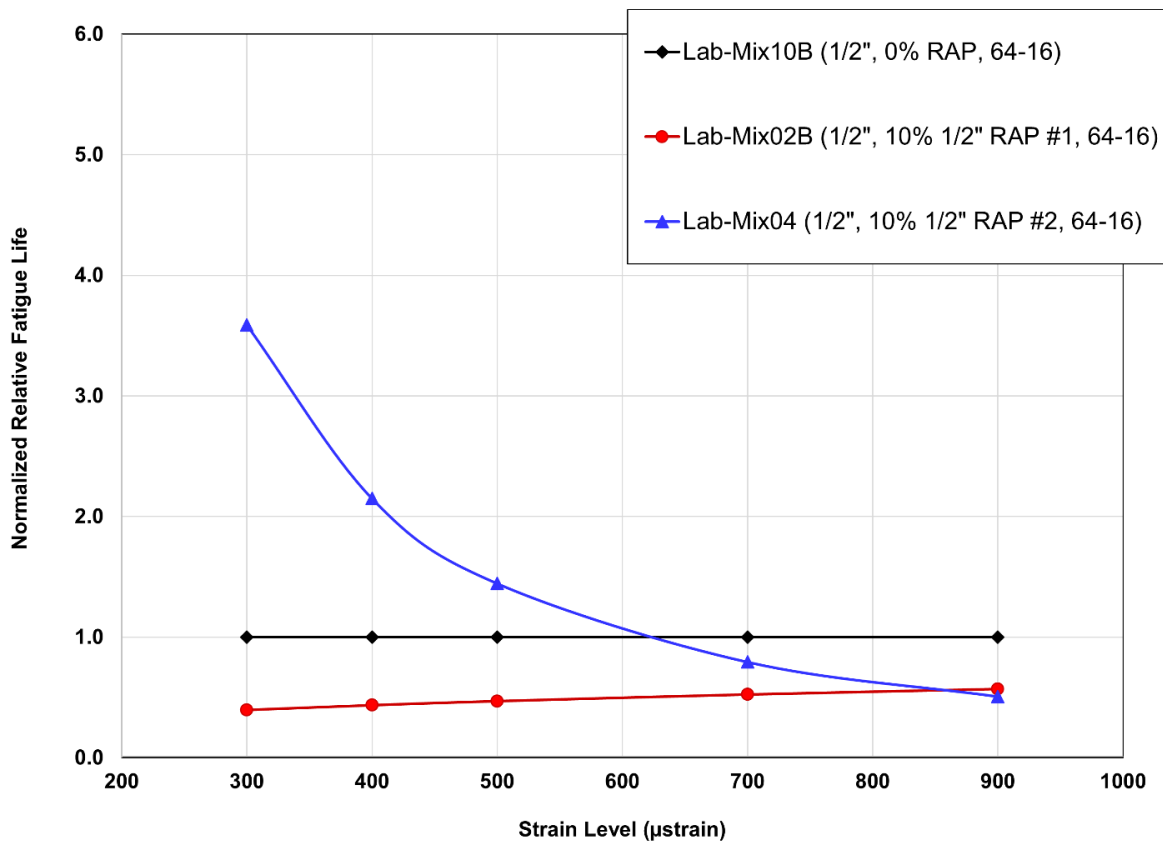


Figure 6.21: Laboratory-produced BUT-162 (PG 64-16) normalized fatigue life.

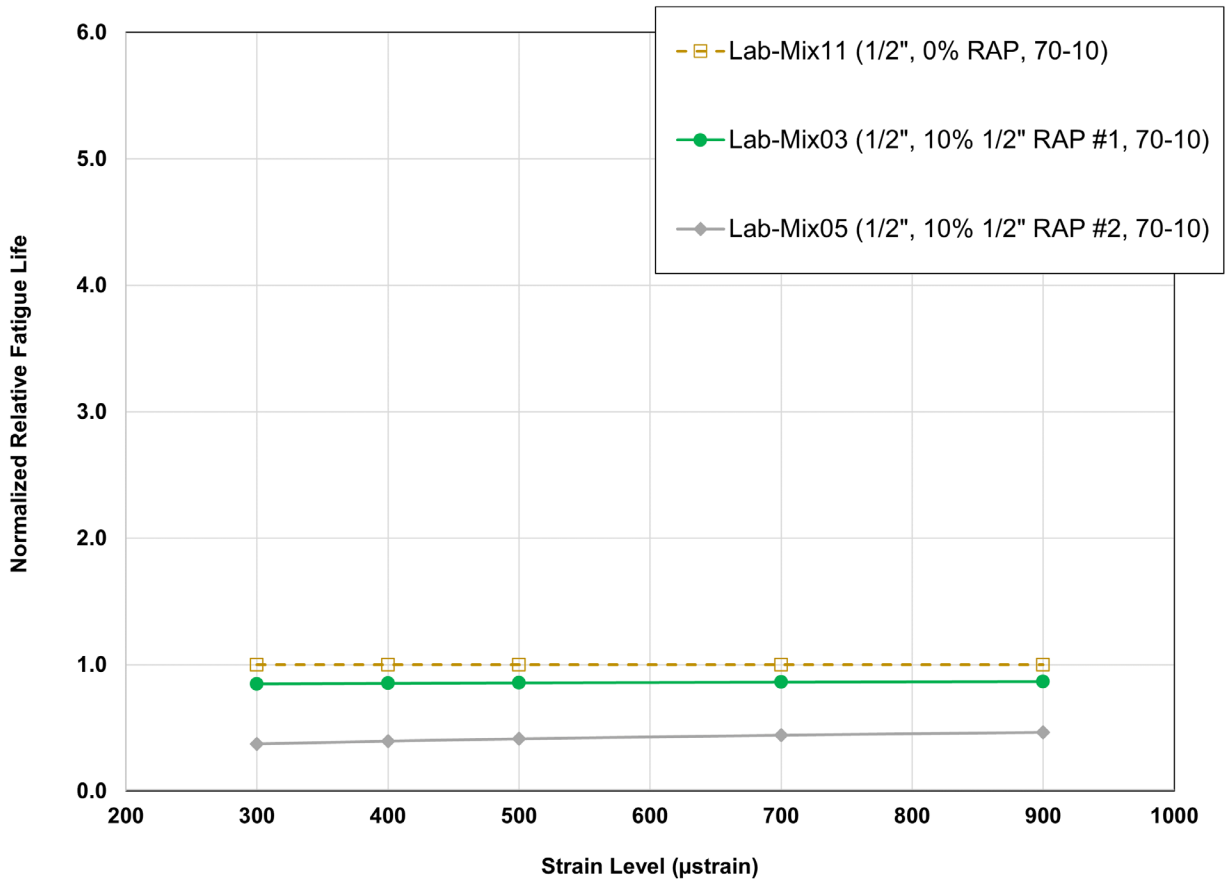


Figure 6.22: Laboratory-produced IMP-86 (PG 70-10) normalized fatigue life.

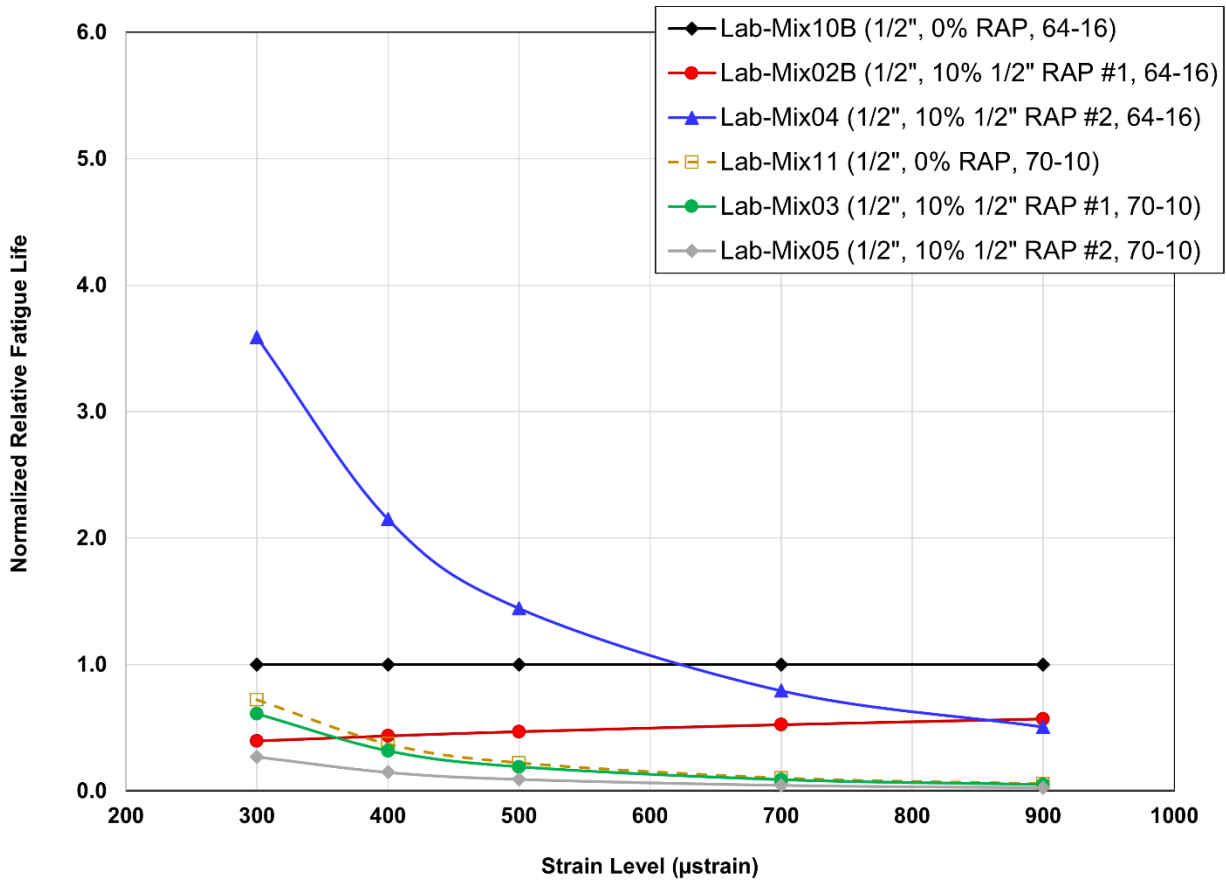


Figure 6.23: Laboratory-produced BUT-162 (PG 64-16) and IMP-86 (PG 70-10) normalized fatigue life relative to the BUT-162 (PG 64-16) control.

The results for the plant-produced test track mixes show the following:

- The control 1/2 in. mix with no RAP had the highest initial stiffness. The control 1/2 in. mix is approximately 23% stiffer than the 1/2 in. mix with RAP, which can be attributed to the greater time kept at high temperatures in the silo compared to the other three mixes and the likelihood of more blending of the RAP and virgin binders. The greater silo time would be expected to age the virgin base binder and also increase the amount of blending between the RAP and virgin binders. Comparing the 3/4 in. control mix and the 3/4 in. mix with RAP, the control mix is approximately 5% stiffer than the mix with RAP for the average values shown in the plot, which is insignificant. These trends match those from the frequency sweep results at the same temperature and frequency; however, differences are larger in the frequency sweep results. This may be attributable to some strain sensitivity of flexural stiffness, with smaller strains (100 microstrain) used in the frequency sweep test and much larger strains used in the flexural fatigue test.
- For the 1/2 in. mixes, the fatigue lives of the mix with no RAP were greater than those of all the other mixes for the range of 300 to 900 microstrain. As noted previously, the mix

with no RAP was somewhat stiffer than the other three plant-produced mixes, whether they had RAP or not, because of greater aging in the silo. For the 3/4 in. mixes, the mix with 10% RAP had slightly longer lives than the mix with no RAP. As noted, the 1/2 in. mix without RAP was stiffer than the control mix with no RAP, while for the 3/4 in. mixes the mix with RAP was slightly stiffer than the control. This would generally indicate, all other variables being the same, that the mixes with no RAP should have shorter fatigue lives (1/2 in. mixes), which is the opposite of what occurred in the results as can be seen in Figure 6.15, or similar fatigue lives (3/4 in. mixes) which did occur, as apparent in the same figure. It is not known why the more aged 1/2 in. control mix had the longest life, although for both sets of mixes the virgin binder contents were fixed and the RAP binder would be expected to provide a very small increase in the total binder content. It is unlikely that the binder content increase is sufficient to explain the results of the 1/2 in. mix testing.

The results for the laboratory-produced mixes show that:

- The initial stiffnesses for the mixes from the two sets of base binders follow the expected trends of increases with the inclusion of RAP and a greater increase with the inclusion of the stiffer RAP, except for the PG 70-10 base binder mix with RAP #1, which was about 4% softer than the control mix. The PG 64-16 mix with 10% of the stiffer RAP #2 was 31% stiffer than the control mix, and the PG 70-10 with RAP #2 was 15% stiffer than the control mix. The stiffness differences between the mixes with and without RAP at 20°C and 10 Hz from the flexural fatigue tests are similar to those found for the same frequency and temperature but for smaller strains with the frequency sweep test.
- The Wöhler curve plots show expected results between the two sets of mixes with different base binders and mixed results within each set. All of the mixes with the stiffer PG 70-10 base binder have shorter fatigue lives than those with the softer PG 64-16 base binder. However, the slopes (fatigue life versus tensile strain) of the mixes in each set are different, and as strains become smaller, the fatigue lives of the two sets start to converge. At strains smaller than 300 microstrain, the stiffer mixes would be expected to have increasingly similar fatigue lives to those of the softer mixes.
- Within the PG 64-16 base binder set of mixes, the mix with 10% of the softer RAP #1 had shorter fatigue lives than the control mix, as expected based on its higher initial stiffness. However, the mix with 10% of the stiffer RAP #2 had better fatigue life than the control at low strains and worse fatigue life at higher strains. This behavior, with a steeper slope for stiffer mixes, has been seen before, and it can be seen in the differences between all of the PG 64-16 mixes and the stiffer PG 70-10 mixes.

- Within the PG 70-10 base binder set of mixes, the mixes with 10% RAP had worse fatigue lives than the control mix, and the mix with the stiffer RAP #2 had worse fatigue life than the mix with RAP #1.

Overall, the results indicate that:

- The addition of 10% RAP typically increased stiffnesses, in the range of no change to a 50% increase as measured in various modes of loading and at different strains, and differed depending on the frequency of loading and temperature. The ability to relax stresses, as evidenced by the change in phase angles, was slightly decreased.
- The effect of 6 to 8 more hours of time at a high temperature in a silo at the plant had a greater effect on the stiffness of one of the plant-produced mixes than did the addition of 10% coarse RAP.
- The inclusion of 10% RAP generally reduced fatigue lives in the controlled deformation flexural fatigue test, but not always, and whether there was an increase or decrease sometimes depended on the strain level. Stiffer mixes tended to have steeper slopes between fatigue life and tensile strain, which would lead them to trend toward better fatigue lives as strains became smaller than would softer mixes.
- As noted previously, greater stiffness will result in smaller strains, with the effect increasing as the RHMA-G layer becomes thicker. Greater stiffness also generally decreases fatigue life at a given strain. Considering the results of generally higher stiffnesses and lower fatigue lives at a given strain found in these test results, the net effect on expected pavement fatigue or reflective cracking life of adding RAP to RHMA-G should be further investigated using ME simulation. The results of those simulations are presented in Chapter 7.

To determine whether these trends are statistically significant, statistical tests were conducted on initial stiffness and fatigue life determined from fatigue tests of both the plant mixes and the lab mixes (see Appendix C for details). It should be noted that the initial stiffnesses from the fatigue tests are at 20°C and 10 Hz, shown at 10 Hz on the x-axis of the frequency sweep figures, and at much larger strains than the strain level in the frequency sweep data shown in this chapter. In summary, when adding 10% RAP to RHMA-G mix:

- The effects on stiffness are not statistically significant for both plant mixes and laboratory mixes. The only exception is at higher strain levels 400, 600, and 700 microstrain for the mixes with PG 70-10 base binder and at 700 microstrain for the mixes with PG 64-16 binder.
- The effects on fatigue life are not statistically significant for both plant mixes and lab mixes.

6.4. Rutting Resistance: Unconfined Repeated Load Triaxial Test

RLT test results are included in Table B.21 and Table B.22 in Appendix B. Figure 6.24, Figure 6.25, and Figure 6.26 show the flow number, unconfined RLT, and confined RLT results for the plant-produced test track mixes, respectively. Figure 6.27, Figure 6.28, and Figure 6.29 show the same plots for the laboratory-produced mixes made with the BUT-162 and IMP-86 binders. Whiskers on the data indicate the lowest and highest flow numbers of the five replicates in each mix.

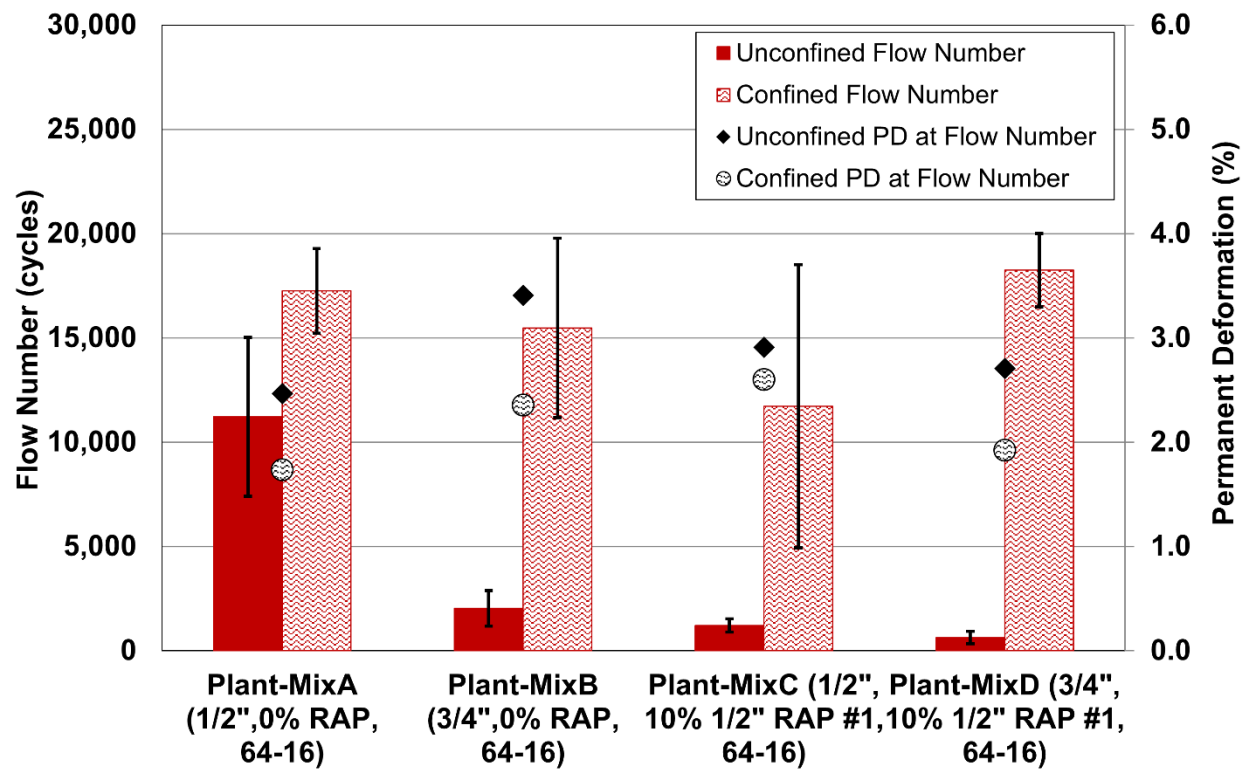


Figure 6.24: Plant-produced mixes used on test track: Flow number and permanent deformation strain at flow number at 50°C.

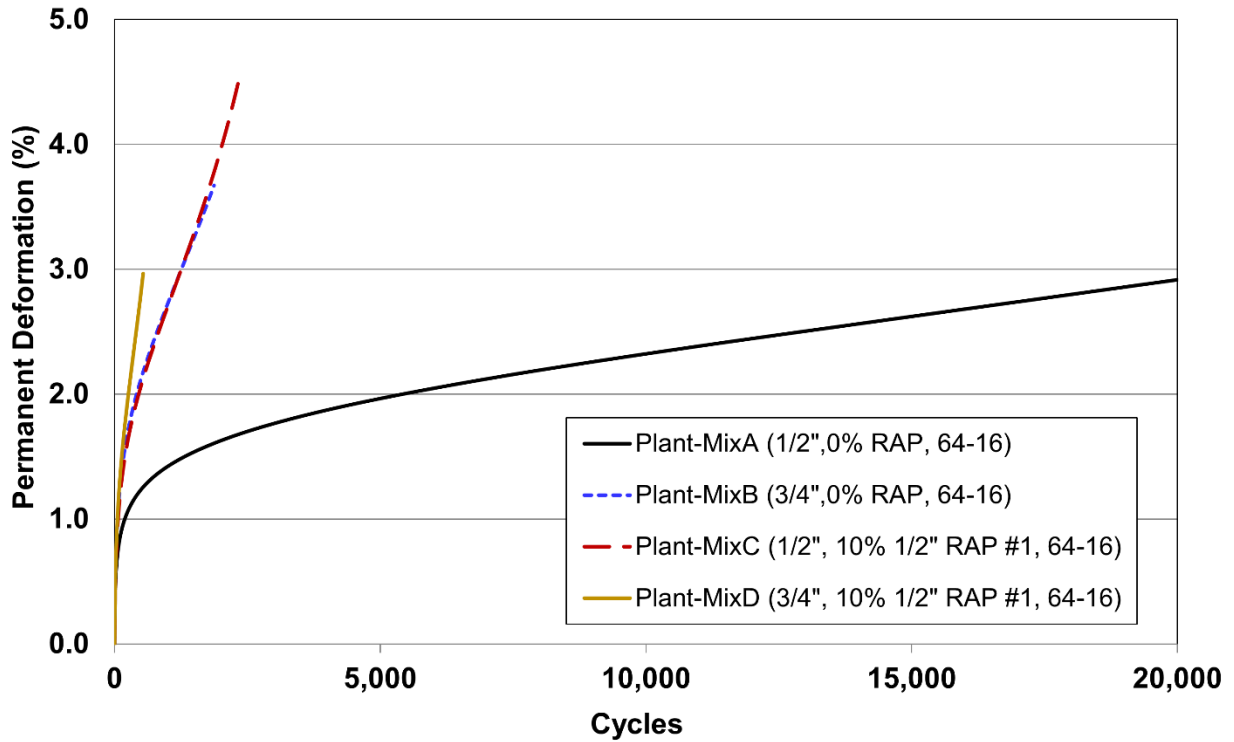


Figure 6.25: Plant-produced mixes: Average permanent strain versus load cycle at 50°C, unconfined.

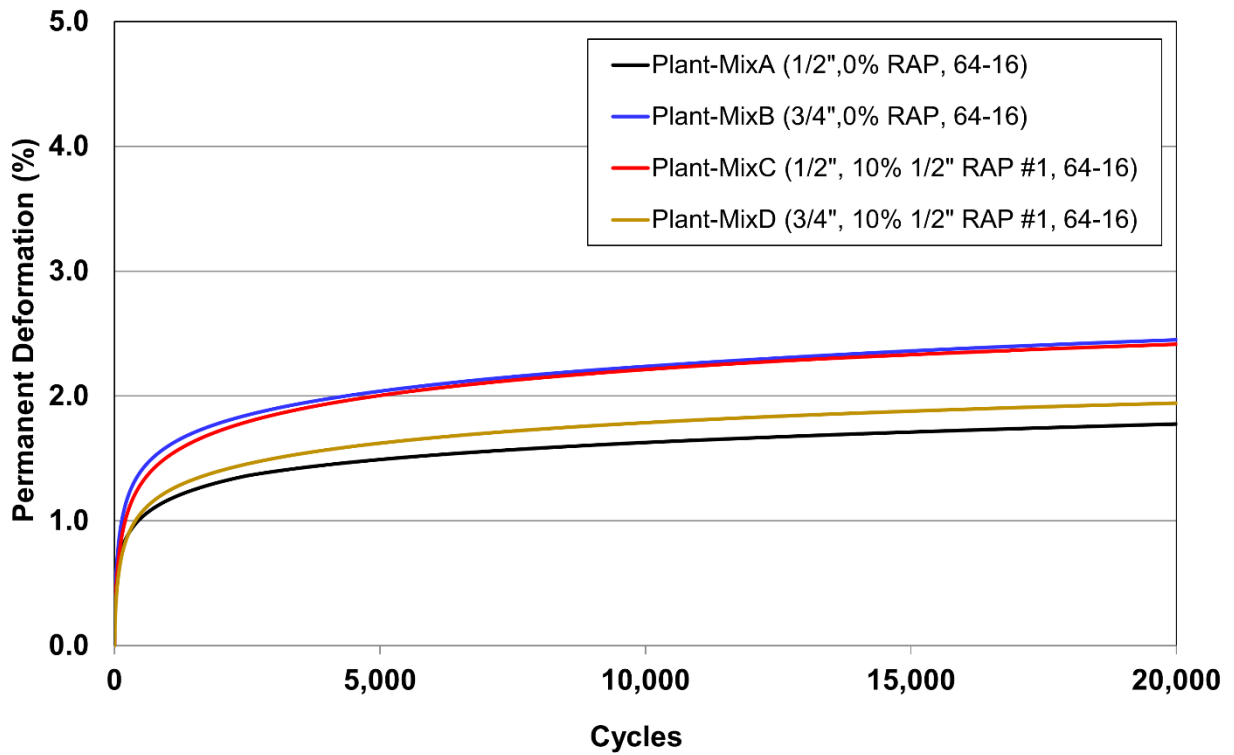


Figure 6.26: Plant-produced mixes: Average permanent strain versus load cycle at 50°C, confined.

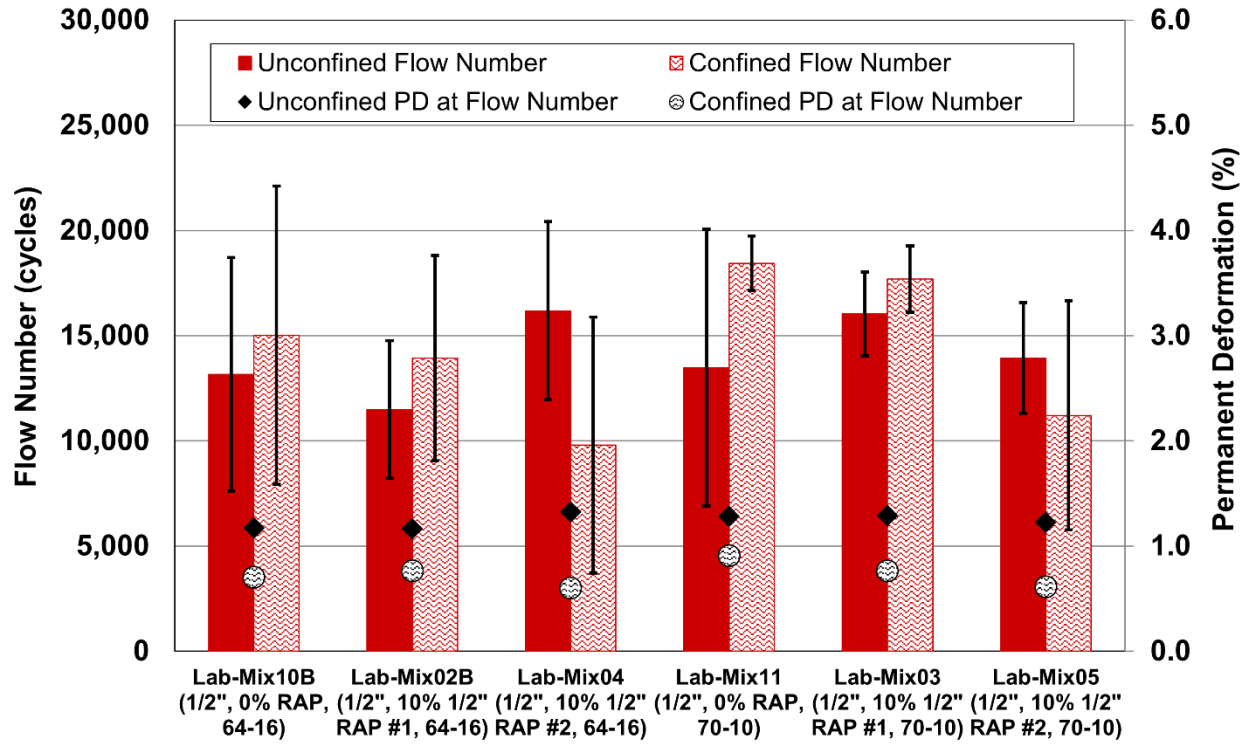


Figure 6.27: Laboratory-produced BUT-162 and IMP-86: Flow number and permanent deformation strain at flow number at 50°C.

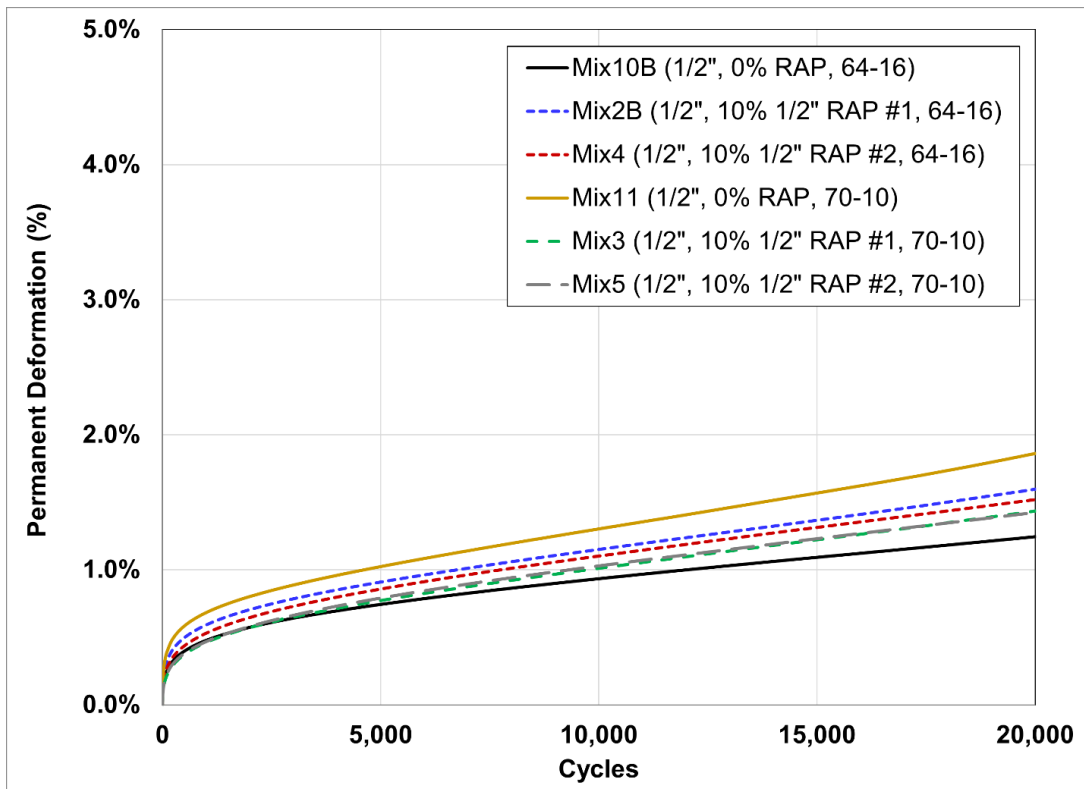


Figure 6.28: Laboratory-produced PG 64-16 (BUT-162) and PG 70-10 (IMP-186): Average permanent strain versus load cycle at 50°C, unconfined.

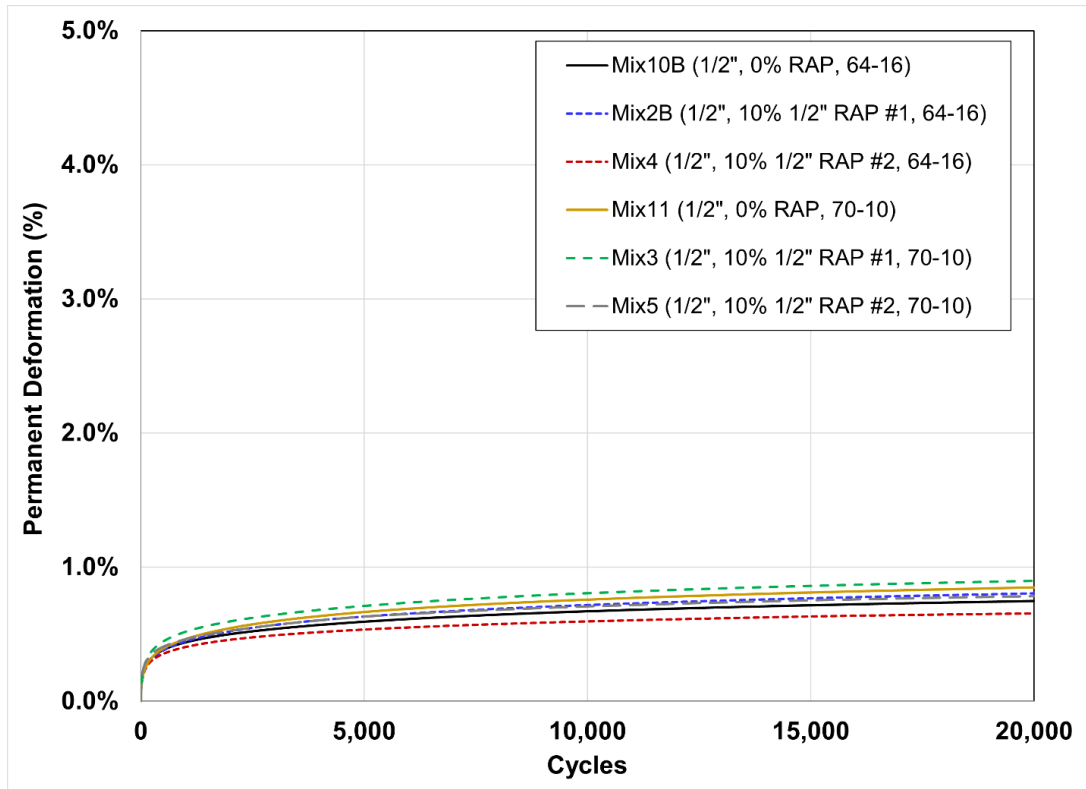


Figure 6.29: Laboratory-produced BUT-162 and IMP-86: Average permanent strain versus load cycle at 50°C, confined.

For the plant-produced mixes, the results show the following:

- The flow number of the silo-aged control 1/2 in. mix with no RAP has the highest unconfined flow number of all four mixes, and it is much greater than any of the other flow numbers. The unconfined flow number of the control 3/4 in. mix with no RAP is somewhat larger than that of the same mix with RAP. The confined flow number for the control 1/2 in. mix is also high. The confined flow number for the control 3/4 in. mix with RAP is somewhat greater than that of the same mix without RAP.
- For the plots of average permanent strain versus load cycles, a clearly defined flow number (change in slope) is difficult to identify for the unconfined and confined RLT results. Those plots also show that for the unconfined RLT, the control 1/2 in. mix that was aged in the silo had very different performance than the other three mixes. Those three mixes had similar performance, with the 3/4 in. mix with RAP having slightly worse performance than the 1/2 in. mix with RAP and the 3/4 in. mix without RAP. For the confined RLT plot, the silo-aged control 1/2 in. mix had the best permanent deformation performance, followed by the 3/4 in. mix with RAP, while the control 3/4 in. mix and the 1/2 in. mix with RAP had similar performance. The confined permanent deformation versus load cycles and the flow number results between the 3/4 in. mixes with and without RAP are, as expected, with the

RAP increasing the rutting resistance. The unconfined flow number results are essentially the same.

For the laboratory-produced mixes, the results show the following:

- The flow numbers from the unconfined RLT tests do not show any clear trend. Inclusion of RAP increased or decreased the unconfined flow number depending on the base binder and the RAP source. The confined RLT results show a clearer trend that is the opposite of what is expected: the flow number decreased as RAP was added, decreasing slightly when 10% of the stiffer RAP #1 was added, and more when the softer RAP #2 was added. As with most mixes produced in California, it is difficult to identify a clear change in the slope of the permanent deformation versus load cycles plot for all of the mixes.
- The plots of permanent deformation versus load cycles for the unconfined and confined RLT show that all of the mixes are similar, for the two base binders and no RAP and when 10% of RAP #1 and RAP #2 are added to both base binders.
- + This is not unsurprising considering that the base binder blending chart data shown in Table 5.5 showed nearly identical high temperature PG true grade temperatures for the control AR binders made with PG 70-10 and PG 64-16 base binders. The best mix (most cycles to reach a given permanent strain) in the unconfined RLT was the PG 64-16 with no RAP; the worst mix was the PG 70-10 with no RAP, and the mixes with the two base binders and two RAP sources fall in between with similar performance. The plots for the confined RLT show similar performance for all of the mixes and generally similar rankings as the unconfined results, with some changes, with the PG 64-16 mixes overall doing slightly better than the PG 70-10 mixes.
- + The difference in the base binder high temperature PG grade (PG 64 for BUT-162 and PG 70 for IMP-186) resulted in only a 1.9°C difference in the high temperature PG true grade temperatures for the two extracted AR binders, as shown in Table 5.5. The addition of 10% RAP from the two sources similarly only resulted in a maximum difference in the high temperature PG true grades of 2.1°C. Considering that binders did not have much difference in stiffness at high temperatures, the small differences in permanent deformation performance of the laboratory-produced mixes in both the confined and unconfined RLT results are not surprising. This indicates that the high temperature PG grade alone did not do a good job of predicting the permanent deformation resistance, and other differences between how those AR binders were produced resulted in similar performance. Samples of the base binders were not obtained prior to the production of the AR binders from them, so it is not known if the

PG 64 base binder high temperature true grade was close to a PG 70 or if the PG 70 base binder high temperature true grade was close to a PG 64.

Overall, the results indicate the following:

- For the test track mixes, the effects of silo aging in the plant-produced test track mixes were more important for rutting resistance than was the inclusion of RAP, which was clear from every test. The effects of adding RAP were highly variable depending on the test.
- For the laboratory-produced mixes, the key takeaways are, first, that the base binder high temperature PG grade's influence on the mix properties is not necessarily sufficient to produce significantly different permanent deformation resistance, and second, that the addition of 10% RAP from either of the two sources did not produce large differences in the permanent deformation resistance. A third takeaway is that the flow number does not necessarily provide a good reflection of the permanent deformation resistance in the RLT.

6.5. Fracture Cracking Resistance: Semicircular Bending Test

Semicircular bending (SCB) test results are included in Table B.26 and Table B.27 in Appendix B. Figure 6.30 and Figure 6.31 show the flexibility index and strength results from the test for the plant-produced test track mixes, respectively, while Figure 6.32 and Figure 6.33 show the same type of results for the laboratory-produced mixes made with the BUT-162 and IMP-86 binders. Whiskers on the data show the lowest and highest fracture energies and flexibility indices, respectively, for the four replicates tested for each mix.

The SCB flexibility and strength results tested at 25°C have been found to have good correlations with mix stiffness from flexural beams tested at 20°C and 10 Hz (33), with the flexibility index negatively correlated with stiffness and strength positively correlated.

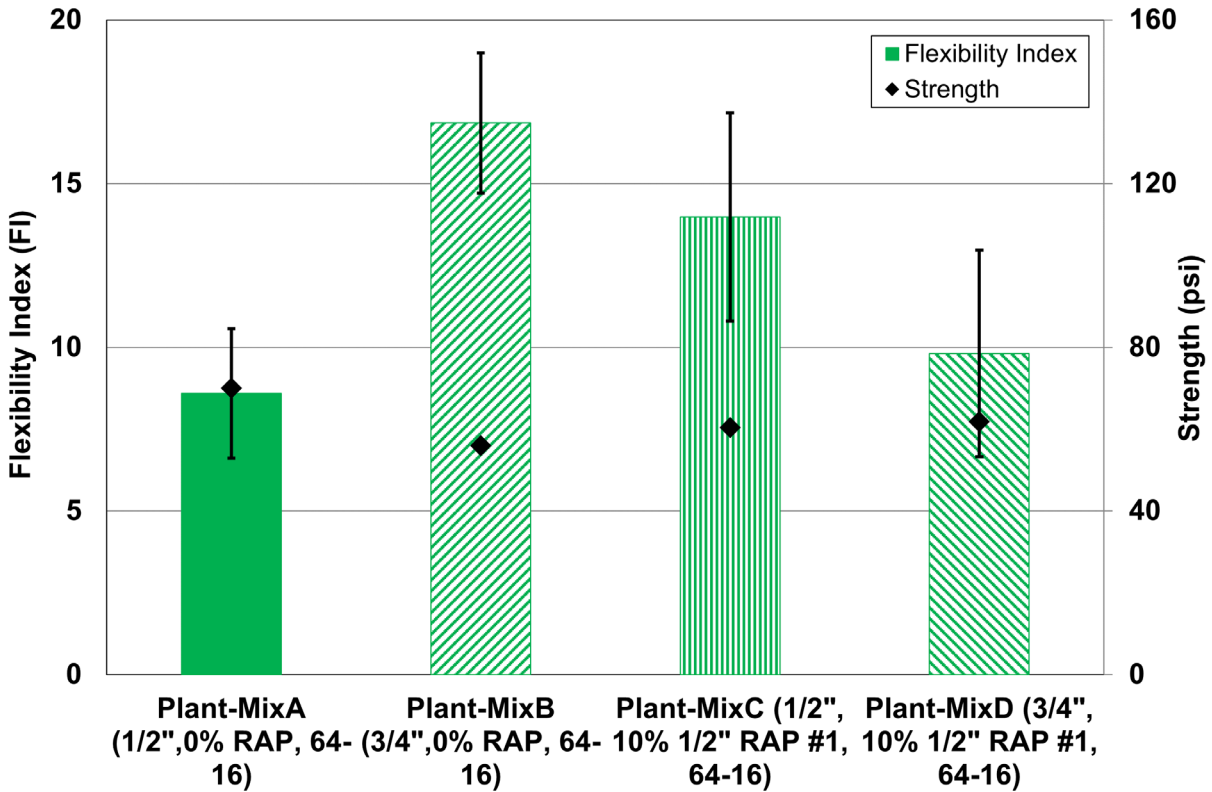


Figure 6.30: Plant-produced mixes: SCB flexibility index and strength at 25°C.

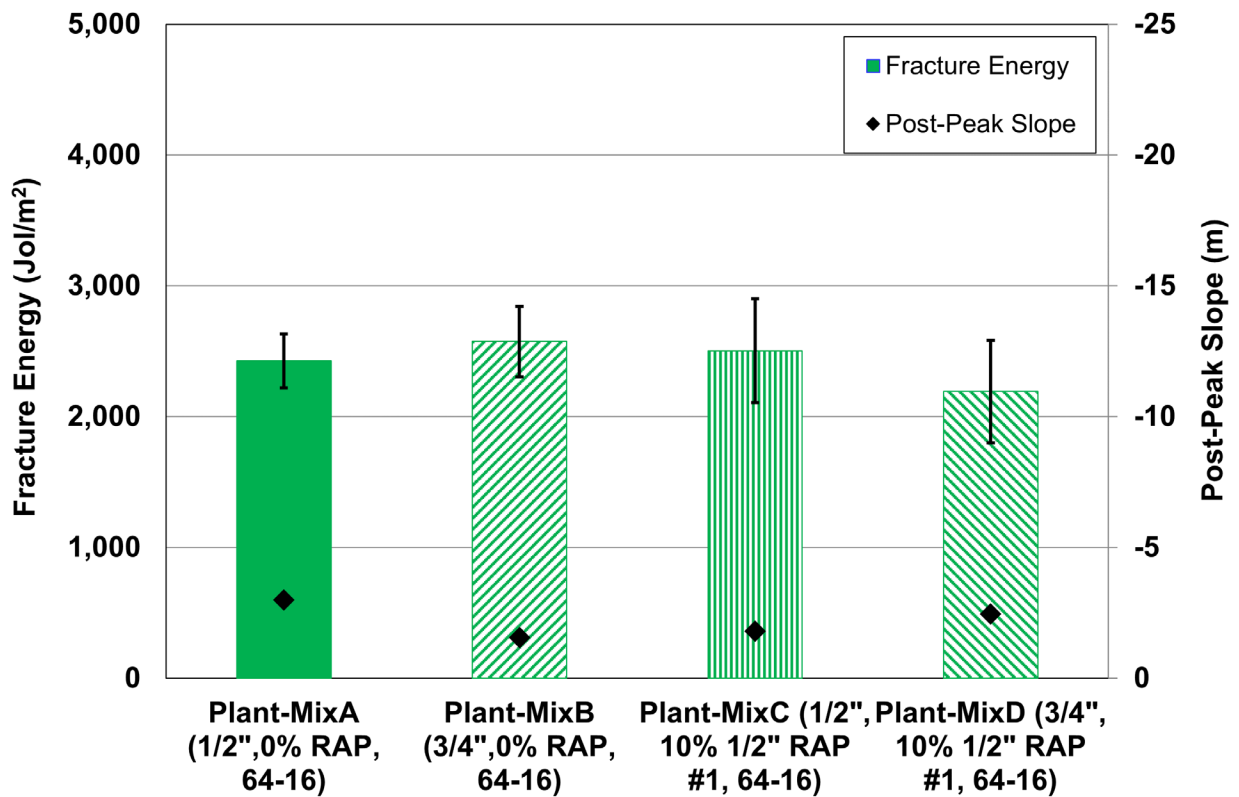


Figure 6.31: Plant-produced mixes: SCB fracture energy and post-peak slope at 25°C.

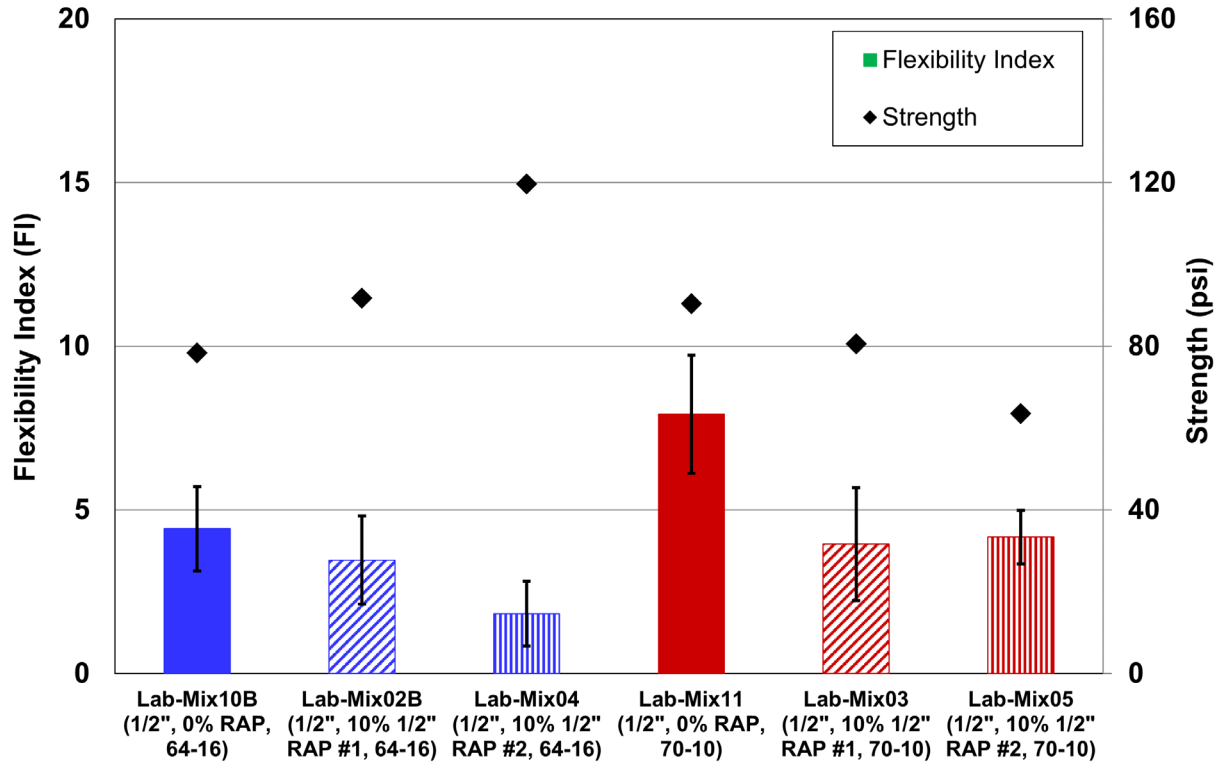


Figure 6.32: Laboratory-produced mixes: BUT-162 and IMP-86: SCB flexibility index and strength at 25°C.

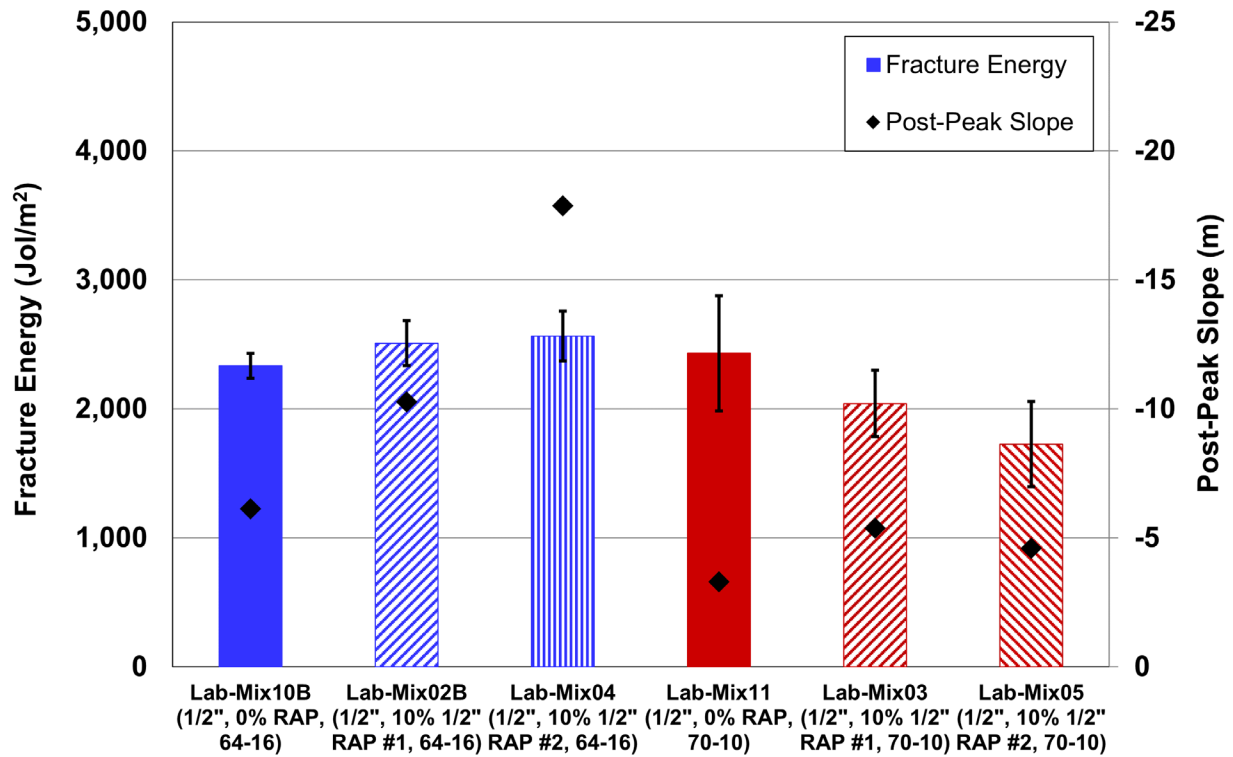


Figure 6.33: Laboratory-produced mixes: BUT-162 and IMP-86: SCB fracture energy and post-peak slope at 25°C.

The results show the following:

- For the plant-produced test track mixes, the silo-aged 1/2 in. control mix and the 3/4 in. mix with RAP have the highest strengths and lowest flexibility indices, as expected based on all previous results for stiffness. The strength values correspond very well with the initial flexural stiffnesses from the fatigue tests, as were shown in Figure 6.16.
- The fracture energies are similar for all the mixes. The post-peak slopes of the silo-aged control 1/2 in. mix and the 3/4 in. mix with RAP are steeper, indicating more brittle fracture, as expected.

For the laboratory-produced mixes, the trends of the flexibility index and strength results match those of the flexural fatigue initial stiffnesses shown in Figure 6.16 for the PG 64-16 base binder mixes, with the flexibility index decreasing and the strength increasing with the inclusion of RAP, and also showing the effects of the stiffer RAP. For the PG 70-10 mixes, the results do not match expectations for the strengths compared with the flexural initial stiffnesses, with strength decreasing as RAP is added. The fracture energies and post-peak slopes of the PG 70-10 base binder mixes also show an opposite trend compared to expectations.

7 RHMA-O MIX TESTING RESULTS

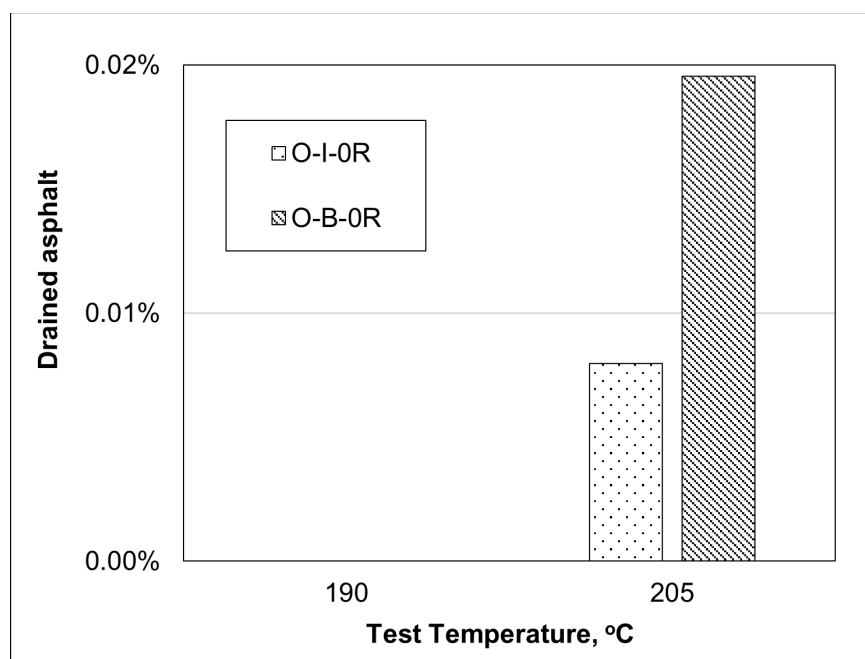
7.1. Introduction

This chapter discusses mix testing results for the laboratory-produced RHMA-O mixes included in this study. These open-graded mixes were produced using aggregates from the same quarry used for the plant-produced and laboratory-produced RHMA-G mixes discussed in Chapter 6, as well as the same two RAP sources (RAP #1 and RAP #2) and the same two control AR binders sampled from two Caltrans projects (BUT-162 and IMP-86) used in the laboratory-produced RHMA-G mixes. Summary plots are presented with the text, while more detailed, tabulated results are provided in Appendix B. Mix designs and test method details are discussed in Chapter 4 and are not repeated in this chapter.

7.2. Drain Down Test

The binder content of the mixes was verified using the procedure outlined in AASHTO T305. For the drain down test, the binder content was verified based on the two mixes containing no RAP, mixes O-I-OR and O-B-OR (I indicates the IMP-86 binder and B indicates the BUT-162 binder; OR indicates zero RAP), since these mixes are expected to be less stiff than the mixes with RAP. The addition of RAP is expected to increase the binder stiffness and result in less drain down. Hence, the mixes with no RAP were considered more critical as far as the drain down test.

The mixes with no RAP showed 0% of drained asphalt at 190°C as shown in Figure 7.1. Drained asphalt was measurable at the test temperature of 205°C where the IMP-86 mix and BUT-162 mixes showed an average of 0.01% and 0.02% binder that drained, respectively. As expected, the stiffer IMP-86 binder showed a lower drained asphalt percentage. According to the design guide provided by the National Asphalt Pavement Association (NAPA), the maximum allowable percentage of drained asphalt for open-graded mixes should be 0.3% (34). The drain down percentages obtained at 205°C were much lower than the maximum specified by the NAPA design guide. Hence, the binder content selected for the mix designs was deemed acceptable to be used for Cantabro testing.



Notes: O-I indicates mixes with IMP-86 PG 70-10 base binder, O-B indicates mixes with BUT-162 PG 64-16 base binder, OR indicates no RAP.

Figure 7.1: Percentage drained asphalt at different test temperatures for the rubberized mixes with no RAP.

7.3. Cantabro Test

Figure 7.2 shows one of the IMP-86 specimens without RAP before and after conducting the Cantabro test. The percentage loss in mass of all specimens is shown in Figure 7.3. The mixes prepared with the stiffer IMP-86 binder showed a higher average percentage loss than those prepared with the BUT-162 binder. The error bars shown represent one standard deviation on both sides of the mean. Overall, the results showed high variability. A t-test was conducted to compare the mixes with and without RAP. The p-values determined using the t-test are shown in Table 7.1. For both the IMP-86 and BUT-162 mixes, using a 5% significance level, the addition of the RAP did not have a statistically significant effect on the abrasion resistance.

According to the NAPA guidelines, the recommendation is that the average percentage mass loss not exceed 20% to 25% (34). Figure 7.3 shows that all mixes were within that maximum allowable limit except for the IMP-86 mix with no RAP, which showed an average percentage mass loss of 38%. A previous study conducted in 2012 by the UCPRC showed that the average Cantabro loss for AR mixes and polymer-modified PG 64-28 mixes was 39.5% and 22.1%, respectively (35). The

Cantabro test specimens in the 2012 UCPRC study were prepared using a fixed number of 50 gyrations rather than being compacted to a specified height, as in this study.

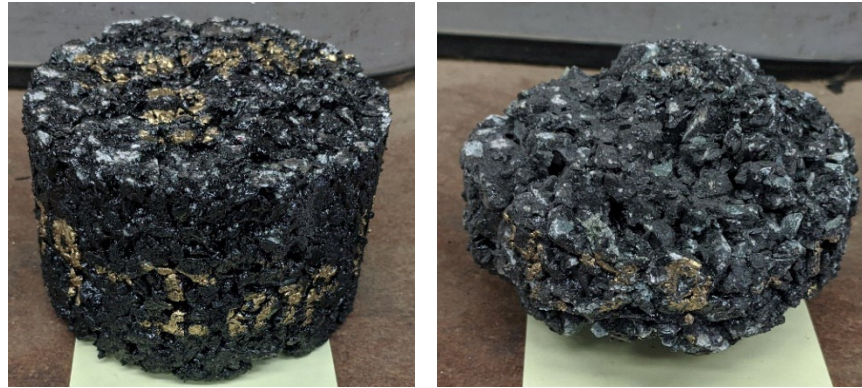
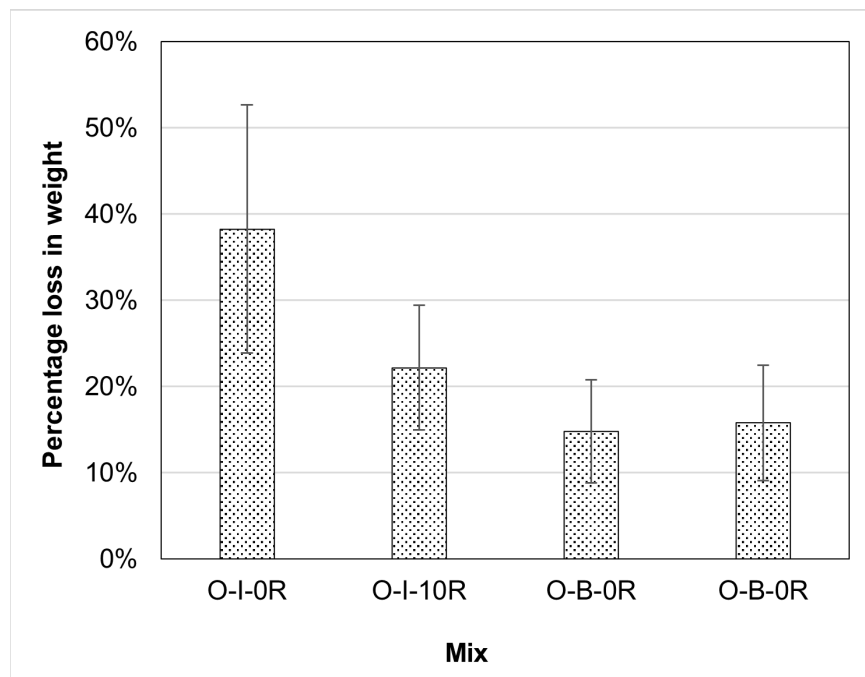


Figure 7.2: An IMP-86 specimen without RAP before (left) and after (right) the Cantabro testing.



Notes: O-I indicates mixes with IMP-86 PG 70-10 base binder, O-B indicates mixes with BUT-162 PG 64-16 base binder, 0R indicates no RAP, 10R indicates 10% RAP.

Figure 7.3: Percentage loss in weight of all mixes from the Cantabro test.

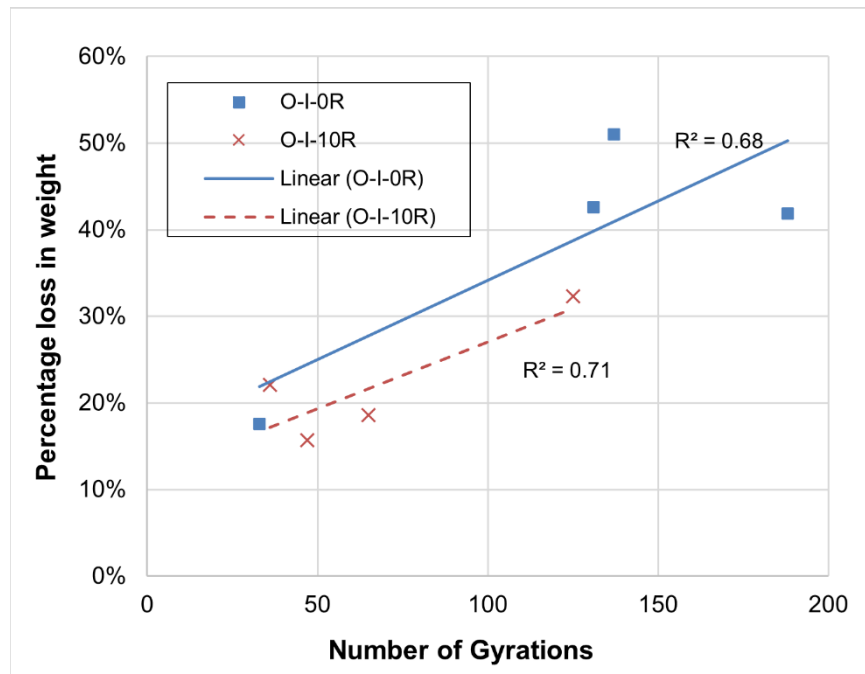
Table 7.1: P-values from T-test Between RHMA Mixes with and without RAP

Mix	RHMA Without RAP	RHMA With RAP	p-value
IMP-86	O-I-0R	O-I-10R	9%
BUT-162	O-B-0R	O-B-10R	81%

Notes: O-I indicates mixes with IMP-86 PG 70-10 base binder, O-B indicates mixes with BUT-162 PG 64-16 base binder, 0R indicates no RAP, 10R indicates 10% RAP.

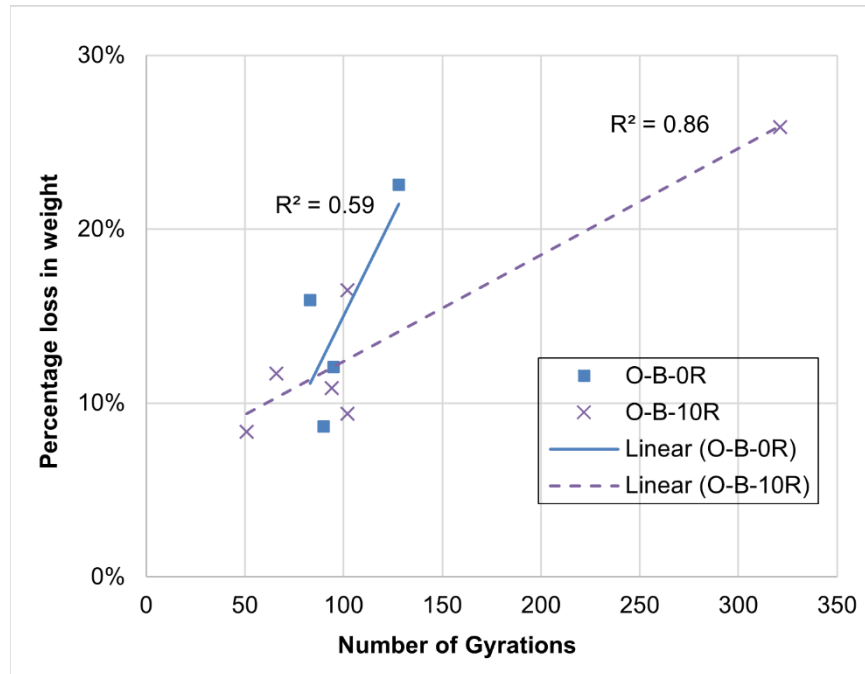
7.4. Effect of Gyration Levels on Cantabro Test Results

As indicated previously, the specimens were all compacted to the same height, and the number of compactions required was noted. To further investigate the high variability in the results, the effect of the gyration levels on the percentage of mass loss in the Cantabro test was studied, as shown in Figure 7.4 and Figure 7.5 for the IMP-86 and BUT-162 mixes, respectively. The number of gyrations for a given mix was highly variable, and it was noted that the percentage of mass loss was correlated with the number of gyrations. As the gyration level increases, the percentage of mass loss tends to increase. High gyration levels indicate that a high compaction energy is required to reorient the aggregate particles to achieve the specified height. A possible explanation for the increase in percentage mass loss with gyration levels is that the high compaction energy is causing breakage of the aggregate, resulting in increased abrasion.



Notes: O-I indicates mixes with IMP-86 PG 70-10 base binder, O-B indicates mixes with BUT-162 PG 64-16 base binder, 0R indicates no RAP, 10R indicates 10% RAP.

Figure 7.4: Relationship between gyration levels and Cantabro loss for IMP-86 open-graded mixes.



Notes: O-I indicates mixes with IMP-86 PG 70-10 base binder, O-B indicates mixes with BUT-162 PG 64-16 base binder, OR indicates no RAP, 10R indicates 10% RAP.

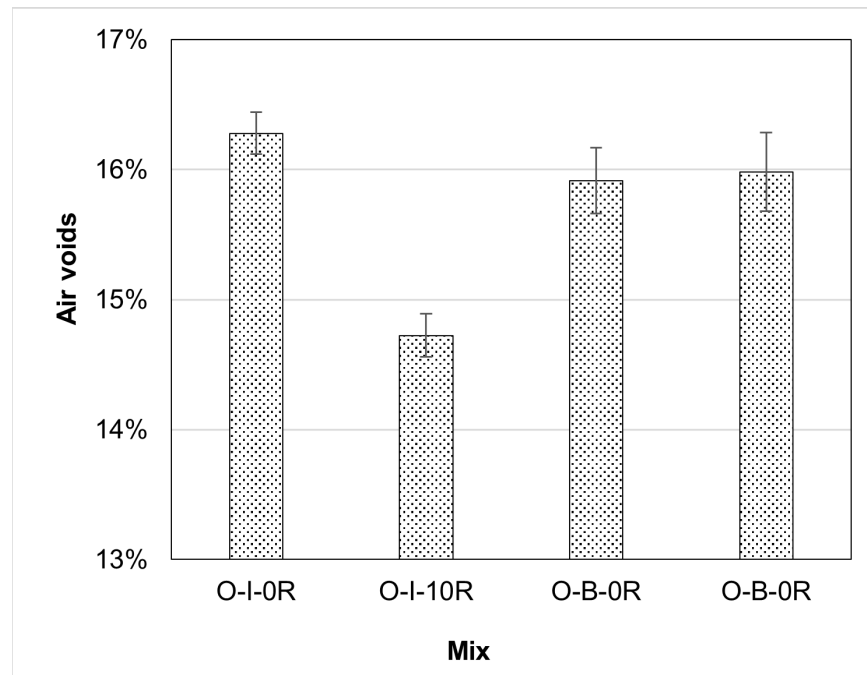
Figure 7.5: Relationship between gyration levels and Cantabro loss for BUT-162 open-graded mixes.

7.5. Air-Voids

According to AASHTO T269, the bulk specific gravity of open-graded mixes can be determined either using an automatic vacuum sealing method (Corelock) or a volume method. The Corelock method is conducted according to AASHTO T331. The volume method is an average method that assumes a regular shaped cylindrical specimen with an average height and diameter. The density of the specimen is determined based on its volume and dry mass. The AASHTO T166 saturated surface dry (SSD) method does not generally lead to accurate results for mixes containing interconnected air-voids, including open-graded mixes.

In this study, the volume method was used to estimate the air-void content of the Cantabro specimens. Figure 7.6 shows the average air-void content of the Cantabro specimens for all four mixes. The air-void content lies between 14.7% and 16.3% for all mixes. The BUT-162 specimens with and without RAP had similar air-void content. The IMP-86 mixes with RAP had an average air-void content that is about 1.5% lower than those without RAP. Overall, the air-void percentages obtained in this study were less than what was reported in the 2012 UCPRC study

for RHMA-O mixes using 50 gyrations. At 50 gyrations, the air-void content was between 18% and 20% for fine-graded mixes (35).



Notes: O-I indicates mixes with IMP-86 PG 70-10 base binder, O-B indicates mixes with BUT-162 PG 64-16 base binder, 0R indicates no RAP, 10R indicates 10% RAP.

Figure 7.6: Average air-voids of the Cantabro specimens for the open-graded mixes.

7.6. Summary

Based on the results presented in this chapter, the use of coarse RAP at 10% by mass of aggregate does not appear to adversely impact the abrasion resistance of the RHMA-O mixes.

8 PAVEMENT PERFORMANCE SIMULATIONS USING CalME

8.1. Introduction

The laboratory test results for flexural stiffness and fatigue for RHMA-G mixes with no RAP and with 10% of coarse RAP were presented in Chapter 6. The discussion in that chapter noted that the interactions of these two mix properties and the net effects of changes in both caused by adding RAP on fatigue and reflective cracking performance are best evaluated through ME simulation. *CalME* is the ME simulation software used by Caltrans for the design of asphalt-surfaced pavements.

This chapter presents comparisons of pavement performance of mixes with and without RAP using *CalME* simulations and the stiffness and fatigue data presented in Chapter 6 for the four plant-produced test track mixes and six laboratory-produced mixes. A range of pavement structures with the RHMA-G mixes as surface layers were simulated for bottom-up fatigue cracking for new or reconstructed pavements and for reflective cracking for overlays on cracked asphalt pavement and cracked and seated concrete pavement.

8.2. Pavement Structures and Experimental Factorials Used to Answer Research Questions

8.2.1. Pavement Structures Used to Answer Research Questions

A common set of three types of pavement structures was used for all *CalME* simulations to answer the research questions: new or reconstructed asphalt pavement, asphalt overlay on cracked asphalt pavement, and asphalt overlay on concrete pavement. Except for one set of simulations used to answer a research question about thin overlays, all of the simulations assumed two types of asphalt concrete layers to make up the total asphalt thickness of the overlay or new asphalt layer in a reconstructed pavement: a gap-graded rubberized hot mix (RHMA-G) as the surface layer and a typical hot mix asphalt (HMA) as the intermediate layer below it.

The details of the three types of structures are the following:

- New or reconstructed pavements:
 - + Surface: RHMA-G from results in this study

- + Intermediate layer: 2020 Standard HMA Type A Mix with PG 64-16 binder and up to 15% RAP for non-PRS projects
- + Aggregate Base (AB): 1.0 ft. of 2020 Standard AB-Class 2
- + Aggregate Subbase (AS): 0.50 ft. of 2020 Standard AS-Class 1
- + Subgrade (SG): 2020 Standard CL
- Asphalt overlays on cracked asphalt pavement:
 - + Same materials as new pavements except
 - Old HMA below the new intermediate layer: 0.35 ft. of 2020 Standard Old HMA
 - AB and SG same as for new or reconstructed pavement
 - No AS
- Asphalt overlays on concrete pavement:
 - + Same materials as asphalt-on-asphalt overlays except that old HMA is replaced with old portland cement concrete (PCC): 1.0 ft. of 2020 Standard PCC for the asphalt overlay on cracked and seated concrete slabs (CSOL)

To provide further insight into the effects of increasing RHMA-G thickness, an additional set of *CalME* simulations was conducted. The structures used in these additional runs are included in Appendix D, along with other details, as well as the results and findings from these additional simulations.

8.2.2. Research Questions and Materials Information Used for Simulations

The research questions addressed by the *CalME* simulations for the three types of pavement structure, and the mixes and new asphalt thicknesses used to develop the answers to the questions and draw conclusions, are presented in the following discussion.

Question: What is the effect of adding 10% RAP to the RHMA-G on expected pavement fatigue and reflective cracking performance?

To answer this question, the plant-produced test track mixes with and without RAP were compared with each other, all having the same PG 64-16 base binder, and the laboratory-produced mixes with and without RAP were compared with each other for the two types of RAP and the two base binders, PG 64-16 from BUT-162 and PG 70-10 from IMP-186. The following RHMA-G thicknesses were considered for these mixes: 0.15 ft. (1/2 in. mixes only), 0.2 ft. (both 1/2 in. and 3/4 in. mixes), and 0.25, 0.40, and 0.50 ft. (3/4 in. mix only). These RHMA-G thicknesses were combined with underlying new HMA thicknesses of 0.2 ft. and 0.4 ft. to form

total asphalt thicknesses (RHMA-G on top of HMA) of 0.35 ft., thicknesses of 0.4, 0.55, and 0.6 ft. for the 1/2 in. mixes, and thicknesses of 0.4, 0.45, 0.6, 0.65, 0.7, 0.8, and 0.9 ft. for the 3/4 in. mixes. It should be noted that these are thick new asphalt layers (greater than 0.25 ft. total new asphalt) where increased stiffness of the mix will generally be expected to increase fatigue or reflective cracking life.

A final comparison was made to answer the question for thin overlays on cracked asphalt pavement only, not for new or reconstructed pavement or overlays on concrete. The same RHMA-G mixes and the 0.15 and 0.2 ft. thicknesses for the 1/2 in. mixes and the 0.2 ft. and 0.25 ft. thicknesses for the 3/4 in. mixes were also compared in overlays with no underlying HMA thickness on cracked asphalt. The mixes with decreased stiffness would generally be expected to perform better in these thin RHMA-G-only overlays (0.25 ft. and thinner).

Question: What is the effect of the RHMA-G gradation on expected pavement fatigue and reflective cracking performance?

For the simulations completed to answer this question, the 1/2 in. and 3/4 in. RHMA-G plant-produced mixes were compared, which are the only mixes with different gradations. The simulations only considered the 0.2 ft. thick surface layer thickness because this thickness is the only one common in practice to both gradations. This RHMA-G thickness, combined with thicknesses of 0.2 and 0.4 ft. of underlying new HMA, formed total asphalt thicknesses of 0.4 and 0.6 ft.

Question: What is the effect of using the softer coarse RAP #1 versus the stiffer fine RAP #2?

This question was answered comparing simulations that used the laboratory-produced mixes with the two RAP sources and the two base binders (PG 64-16 from BUT-162 and PG 70-10 from IMP-86). Only 1/2 in. mixes were considered, with the following RHMA-G thicknesses: 0.15 and 0.2 ft. These RHMA-G surface thicknesses were combined with thicknesses of 0.2 and 0.4 ft. of underlying new HMA to form total asphalt thicknesses of 0.35, 0.4, 0.55, and 0.6 ft.

Question: What is the effect of using mixes with the PG 64-16 from BUT-162 base binder versus using the PG 70-10 base binder from IMP-86, both with and without RAP?

This question was answered by comparing simulations using the laboratory-produced mixes with the two RAP sources and the two base binders (PG 64-16 from BUT-162 and PG 70-10 from IMP-86), which only included 1/2 in. mixes. The following RHMA-G thicknesses were used: 0.15 and 0.2 ft., combined with thicknesses of 0.2 and 0.4 ft. for the underlying HMA to form total asphalt thicknesses of 0.35, 0.4, 0.55, and 0.6 ft.

Question: What is the effect of different ratios of RHMA to HMA thickness in new asphalt layers, with and without RAP?

To answer this question, the simulations were run using 3/4 in. plant-produced mixes with and without 10% RAP. The RHMA-G thicknesses used were 0.2, 0.25, 0.40, and 0.50 ft. combined with 0.2 and 0.4 ft. of underlying new HMA to form total HMA thicknesses of 0.4 to 0.9 ft. The simulation results were compared for simulations where the RHMA was 0.2 and 0.25 ft. versus when the RHMA was 0.4 and 0.5 ft. for the same total asphalt layer (RHMA + HMA) thicknesses.

Question: What is the effect of using full-depth RHMA compared with using an RHMA surface and HMA as the underlying layer, both with and without RAP?

This question was answered by comparing all plant-produced and laboratory-produced mixes with and without 10% RAP in pavements with 0.5 ft. of total new asphalt thickness. The 0.5 ft. total new asphalt thickness was compared for combinations of RHMA-G and HMA thicknesses of 0.2 ft. RHMA/0.3 ft. HMA, 0.25 ft. RHMA/0.25 ft. HMA, 0.5 ft. RHMA/no HMA.

8.2.3. Traffic Volumes

The purpose of the simulations is to compare the relative performance of the different mixes and mix variables. Each design was simulated to 20 years. To determine relative performance, the 20-year traffic volume needs to be high enough so that all designs reach the 5% of wheelpath with fatigue cracking failure definition used for Caltrans design with *CalME*. Some preliminary runs were conducted to determine the necessary traffic. As expected, the 20-year traffic volume used depends on the combined asphalt layer thicknesses and the structure type.

8.2.4. Simulation Methodology Summary

To evaluate the pavement performance and answer each question, the different pavement structures and RHMA-G mixes in each experiment factorial discussed above were set up in *CalME*. Each design is run using Monte Carlo simulation to determine cracking life (fatigue or reflective cracking), defined as the number of equivalent single axle loads (ESAL) to 5% cracking. All simulations were run using the Group 1 weigh-in-motion (WIM) load spectrum in *CalME*. Further details of the factorials run for each question are shown in Table 8.1.

Table 8.1: Details of Factorials for CalME Simulations

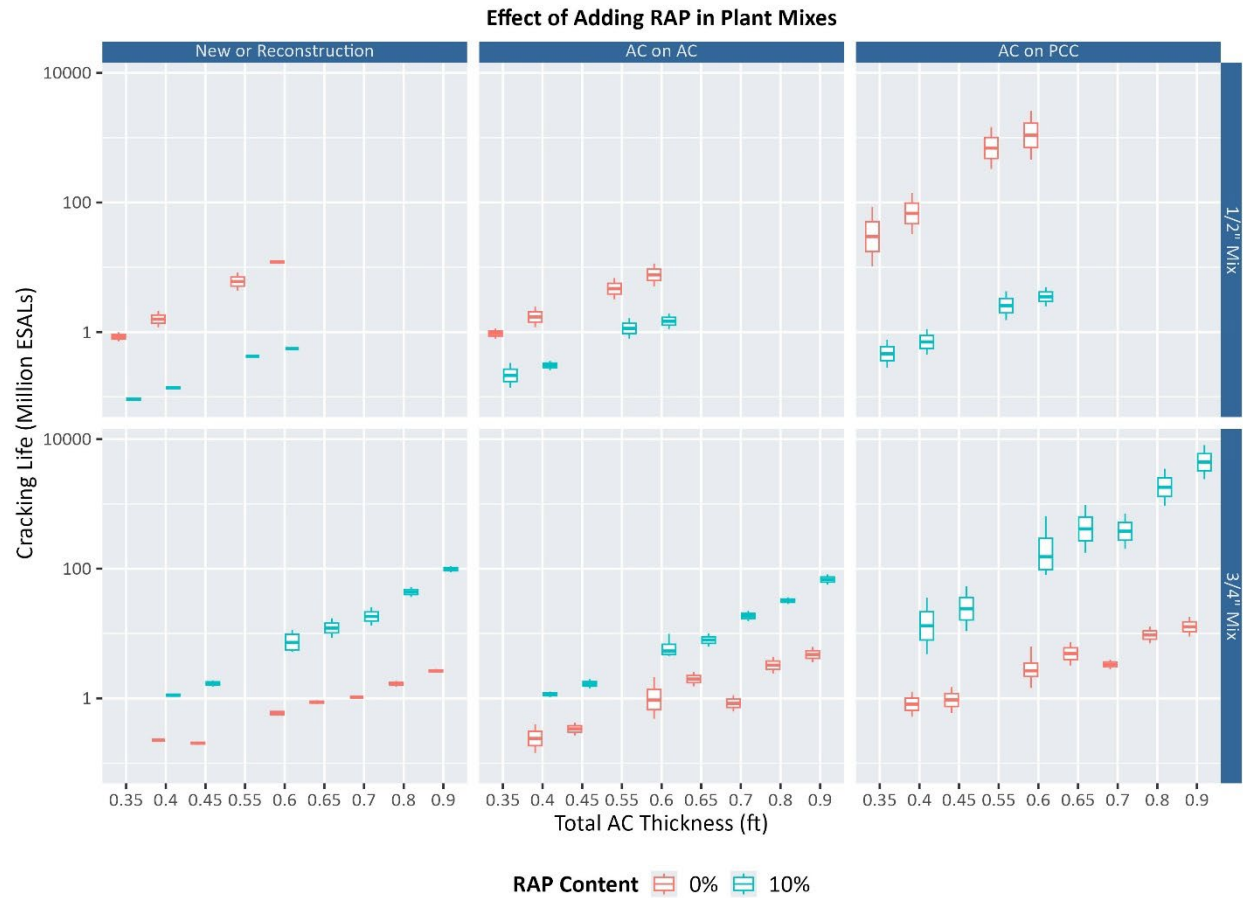
Variable	Number of Levels	Variable Levels
Surface Type	10	The four plant-produced test track mixes shown in Table 4.1, which appear in CalME as: • RHMA-G (Mix 36FL) RAP00% PG 64-16 w/CRM Blasted Granite with Alluvial Sand 1/2" NMAS (Mix A) • RHMA-G (Mix 38FL) RAP00% PG 64-16 w/CRM Blasted Granite with Alluvial Sand 3/4" NMAS (Mix B) • RHMA-G (Mix 37FL) RAP10% PG 64-16 w/CRM Blasted Granite with Alluvial Sand 1/2" NMAS (Mix C) • RHMA-G (Mix 39FL) RAP10% PG 64-16 w/CRM Blasted Granite with Alluvial Sand 3/4" NMAS (Mix D) The six laboratory-produced mixes shown in Table 4.1: • RHMA-G (Mix X) RAP00% PG 64-16 w/CRM Blasted Granite with Alluvial Sand 1/2" (Mix10B) • RHMA-G (Mix X) RAP10% PG 64-16 w/CRM Blasted Granite with Alluvial Sand 1/2" (Mix2B with RAP#1) • RHMA-G (Mix X) RAP10% PG 64-16 w/CRM Blasted Granite with Alluvial Sand 1/2" (Mix4 with RAP#2) • RHMA-G (Mix X) RAP00% PG 70-10 w/CRM Blasted Granite with Alluvial Sand 1/2" (Mix11) • RHMA-G (Mix X) RAP10% PG 70-10 w/CRM Blasted Granite with Alluvial Sand 1/2" (Mix3 with RAP#1) • RHMA-G (Mix X) RAP10% PG 70-10 w/CRM Blasted Granite with Alluvial Sand 1/2" (Mix5 with RAP#2)
RHMA-G Thickness	5	1/2" maximum aggregate size mixes: 0.15', 0.20'; for last question 0.25' or 0.5' also considered 3/4" maximum aggregate size mixes: 0.2', 0.25', 0.40', and 0.50'
Intermediate Layer Thickness	2	0.20' and 0.40' or zero when comparing with full-depth RHMA
Climate Zone	2	Inland Valley, and South Coast

8.3. Simulation Results

The results of the simulations run to answer each of the questions posed at the beginning of this chapter are presented here. As noted previously, the 1/2 in. plant-produced test track mix with no RAP (Mix A) had additional silo aging time compared with the other plant-produced mixes.

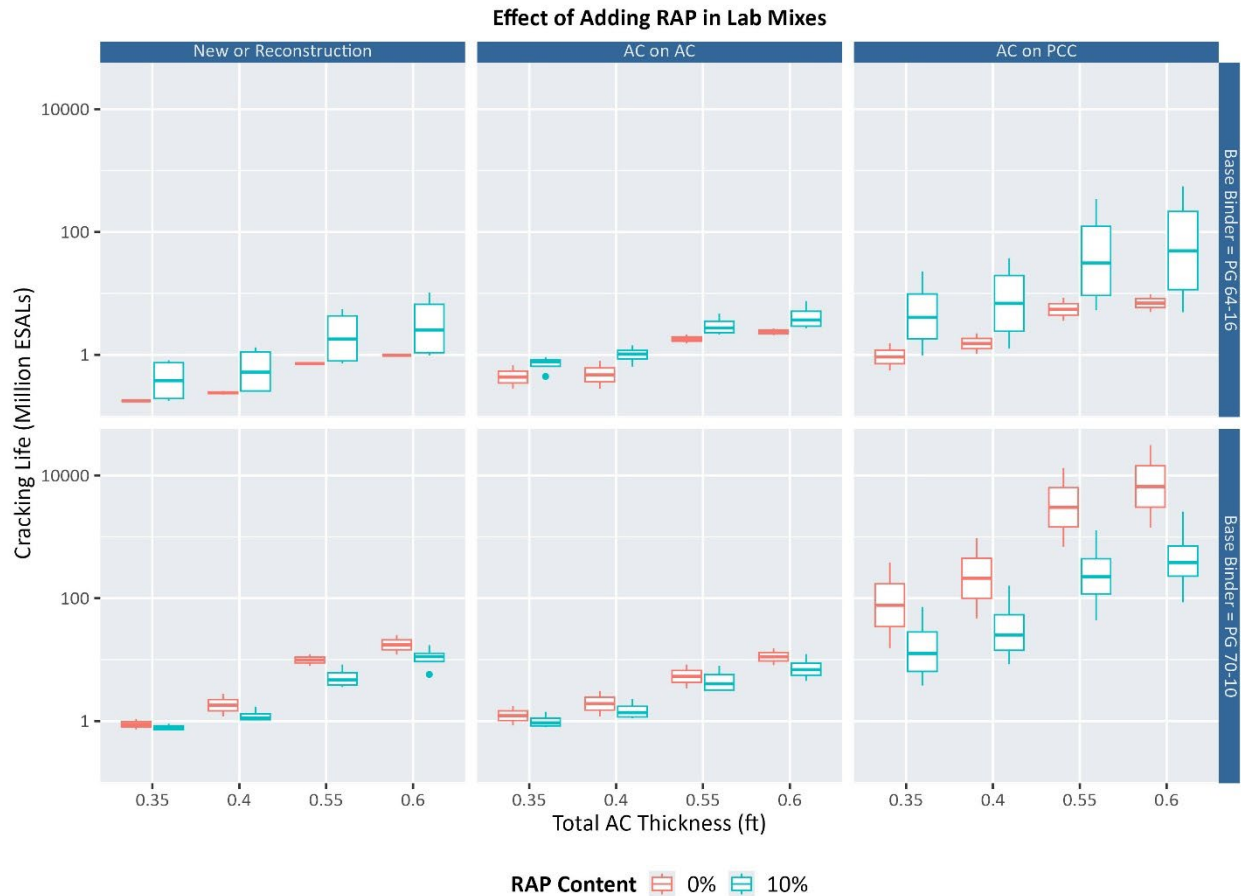
8.3.1. Effects of Adding RAP to the RHMA for Both Plant-Produced and Laboratory-Produced Mixes

The effects of adding RAP to RHMA mixes simulated by *CalME* for the asphalt layers consisting of RHMA on HMA and a combined thickness of 0.35 ft. (100 mm) or more are shown in Figure 8.1 for the plant-produced test track mixes, which include two aggregate sizes and with and without one type of RAP, and in Figure 8.2 for the laboratory-produced mixes, which include two base binders with two RAP sources and with no RAP. It should be noted that all these asphalt layers are thicker than 0.25 ft. and can therefore be considered “thick,” which means that, in general, stiffer mixes will have better performance, with exceptions if the fatigue life is reduced sufficiently.



Note: RHMA and HMA thickness combinations are different for 1/2 in. and 3/4 in. mixes.

Figure 8.1: Effects of adding RAP in plant-produced mixes.



Note: RHMA thickness are either 0.15 ft. or 0.20 ft. combined with 0.2 ft. and 0.4 ft. of HMA to form total asphalt thickness.

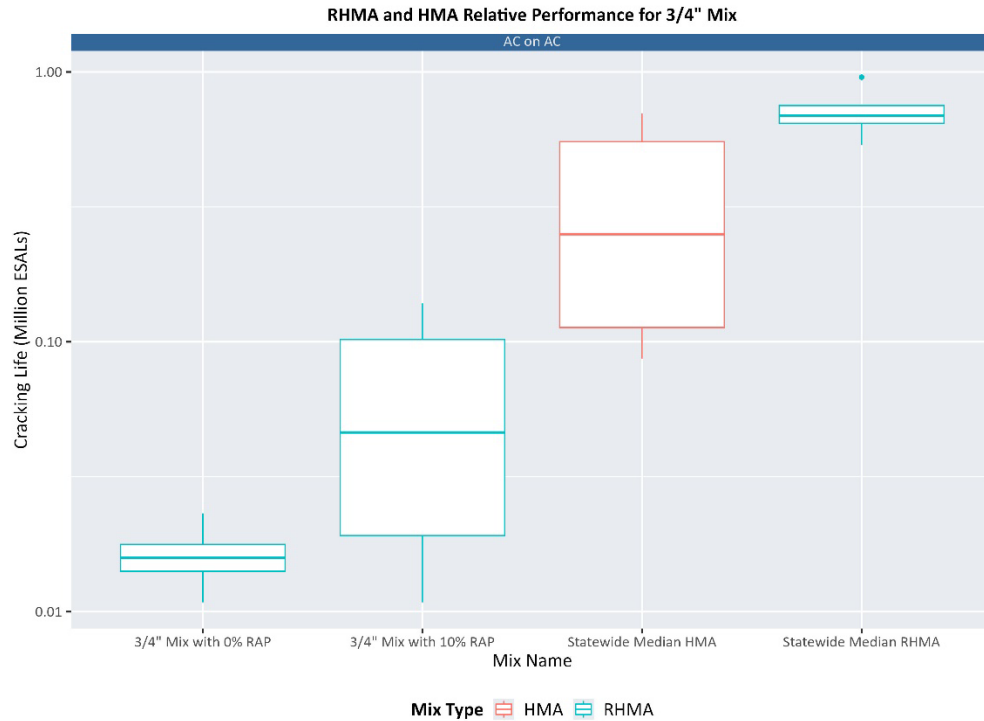
Figure 8.2: Effects of adding RAP in laboratory-produced mixes.

These simulations show the following:

- For the plant-produced test track mixes, which include both 1/2 in. and 3/4 in. gradations and all have the same PG 64-16 base binder, adding RAP improved the fatigue cracking life for the 3/4 in. mixes. No conclusion can be drawn for the 1/2 in. mixes because the mix with no RAP had additional silo aging compared with the mix with RAP. This is consistent with the laboratory test results for the 1/2 in. mixes, where the 1/2 in. mix with no RAP experienced additional silo aging that both increased stiffness and increased fatigue life at a given tensile strain compared with the mix with RAP. This indicates that the additional aging was more influential on simulated fatigue and reflective cracking performance than was the addition of 10% RAP. For the 3/4 in. mix, the addition of RAP improved the simulated performance, as expected based on the stiffness and fatigue life test results, which showed increased stiffness and a small improvement in fatigue life at a given tensile strain.

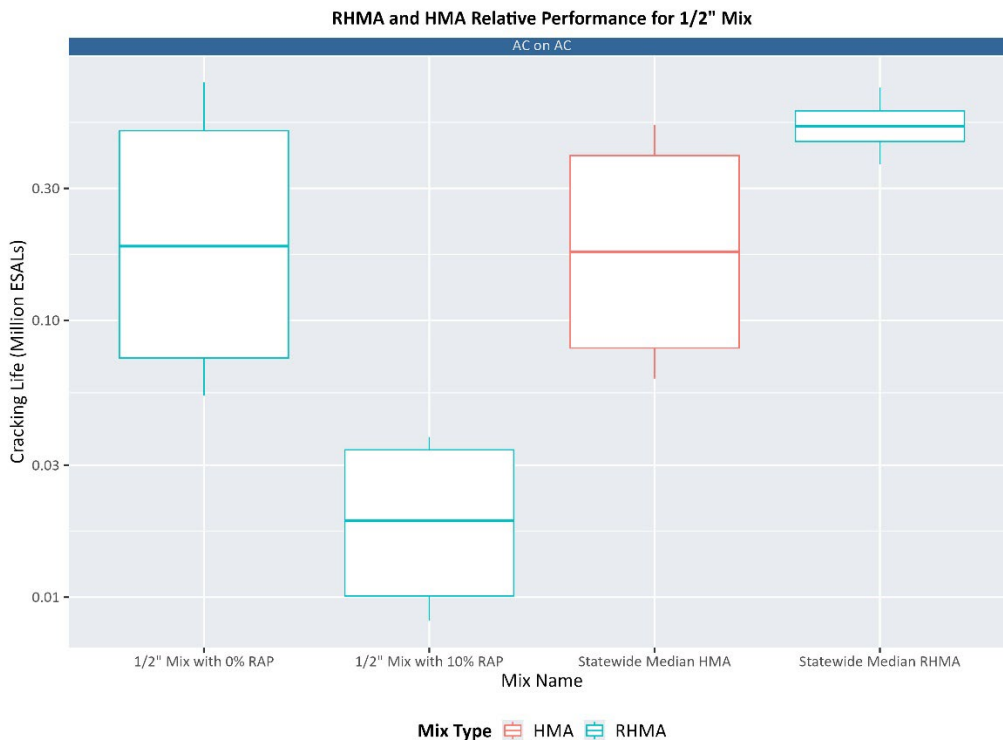
- For laboratory-produced mixes, which are all 1/2 in. mixes, adding RAP in these RHMA-G mixes was beneficial for mixes with the PG 64-16 base binder but detrimental for mixes with the PG 70-10 base binder, on average, for the two RAP sources included in simulations. In all these cases, the results match expectations for the effects of the RAP seen in the laboratory test results for stiffness and fatigue. The separate effects of the two different RAP sources are addressed in Section 8.3.3.

The effects of adding RAP to RHMA mixes were also simulated with *CalME* for thin asphalt overlays on cracked asphalt pavement overlays, where the asphalt layers consist of only RHMA. For these overlays, the simulated thicknesses were 0.15 ft. and 0.2 ft. for the 1/2 in. mixes and 0.2 ft. and 0.25 ft. for the 3/4 in. mixes, with results shown in Figure 8.3 and Figure 8.4 for the plant-produced test track mixes and Figure 8.5 for the laboratory-produced mixes with two base binders and two RAP sources. It should be noted that all these asphalt layers are 0.25 ft. or thinner and can therefore be considered “thin,” which means that, in general, stiffer mixes will have worse performance, although there can be exceptions to this general trend. New or reconstructed asphalt pavement and asphalt overlays on concrete were not simulated for these thicknesses because these thin RHMA layers do not occur on new or reconstructed Caltrans pavements, and thin overlays are not recommended on concrete because of rapid thermal reflective cracking.



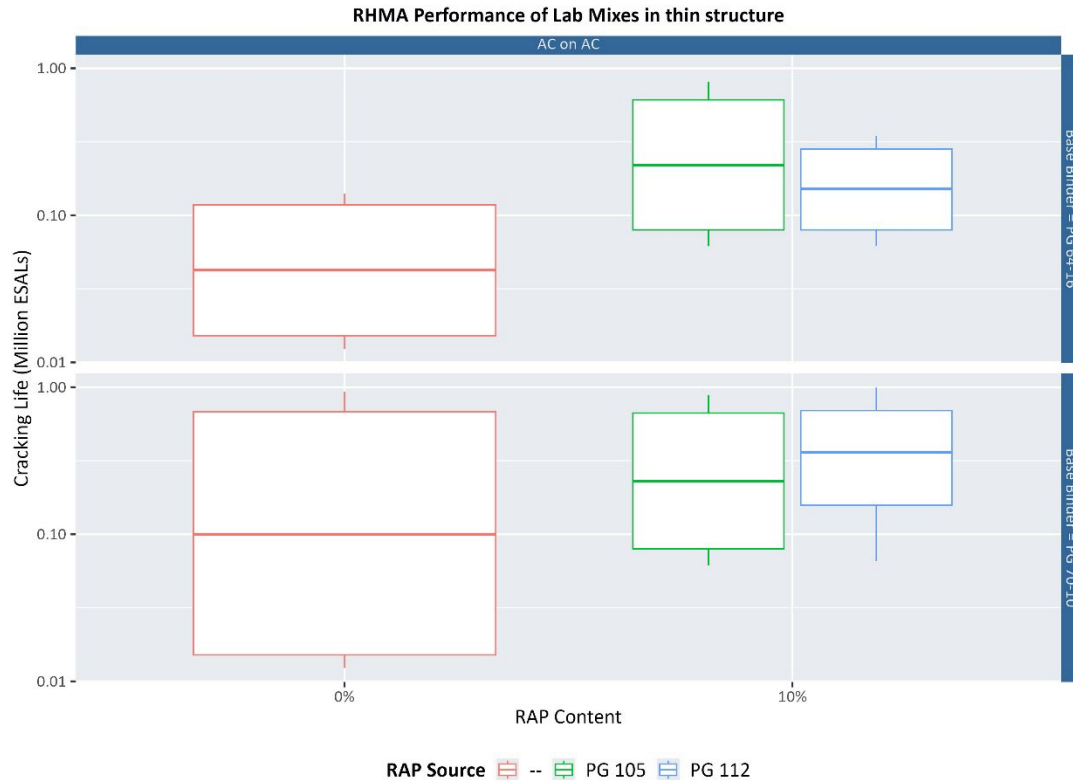
Notes: 3/4" mix thicknesses are 0.2 ft. and 0.25 ft.; RHMA only with no new underlying HMA for asphalt overlay on cracked asphalt (3/4" mix).

Figure 8.3: Effects of adding RAP in 3/4 in. plant-produced mixes for thin overlays on cracked asphalt pavement.



Notes: 1/2" mix thicknesses are 0.15' and 0.2'; RHMA only with no new underlying HMA for asphalt overlay on cracked asphalt (1/2" mix).

Figure 8.4: Effects of adding RAP in 1/2 in. plant-produced mixes for thin overlays on cracked asphalt pavement.



Notes: 0.15 ft. and 0.2 ft. RHMA only with no new underlying HMA for asphalt overlay on cracked asphalt.

Figure 8.5: Effects of adding RAP for laboratory-produced mixes for thin overlays on cracked asphalt pavement.

These simulations show the following:

- For the plant-produced test track mixes, which include both 1/2 in. and 3/4 in. gradations and all having the same PG 64-16 base binder, the plots also include simulations using the statewide median PG 64-16 HMA and the statewide median RHMA, which are both plant-produced mixes. Those results show that for thin overlays on cracked asphalt, *CalME* predicts better reflective cracking performance for the typical RHMA than for the typical HMA. The results also show that both the 1/2 in. and 3/4 in. plant-produced mixes used on the test track had significantly worse simulated performance than the statewide median mixes, except for the silo-aged 1/2 in. mix with no RAP, which has similar performance to the statewide median HMA. The results show that the inclusion of RAP substantially improved the simulated performance of the 3/4 in. RHMA mix.
- For the laboratory-produced mixes, which are all 1/2 in. mixes and use virgin binders from different sources, the inclusion of 10% RAP resulted in some improvement of simulated reflective cracking performance. The benefit was greater for the mixes with the BUT-162 PG 64-16 base binder than for those with the IMP-86 PG 70-10 base binder.

8.3.2. Effect of Gradation of the RHMA in Plant-Produced Mixes

The effects of aggregate gradation of the RHMA mix on pavement fatigue cracking life are shown in Figure 8.6 for the plant-produced test track mixes with the two maximum aggregate sizes of 1/2 in. and 3/4 in. Only the structures with 0.20 ft. of RHMA surface and 0.2 ft. and 0.4 ft. underlying new HMA are included for this plot for comparison because this is the only thickness for which both gradations are used in practice. These can be considered thick total new asphalt layers.

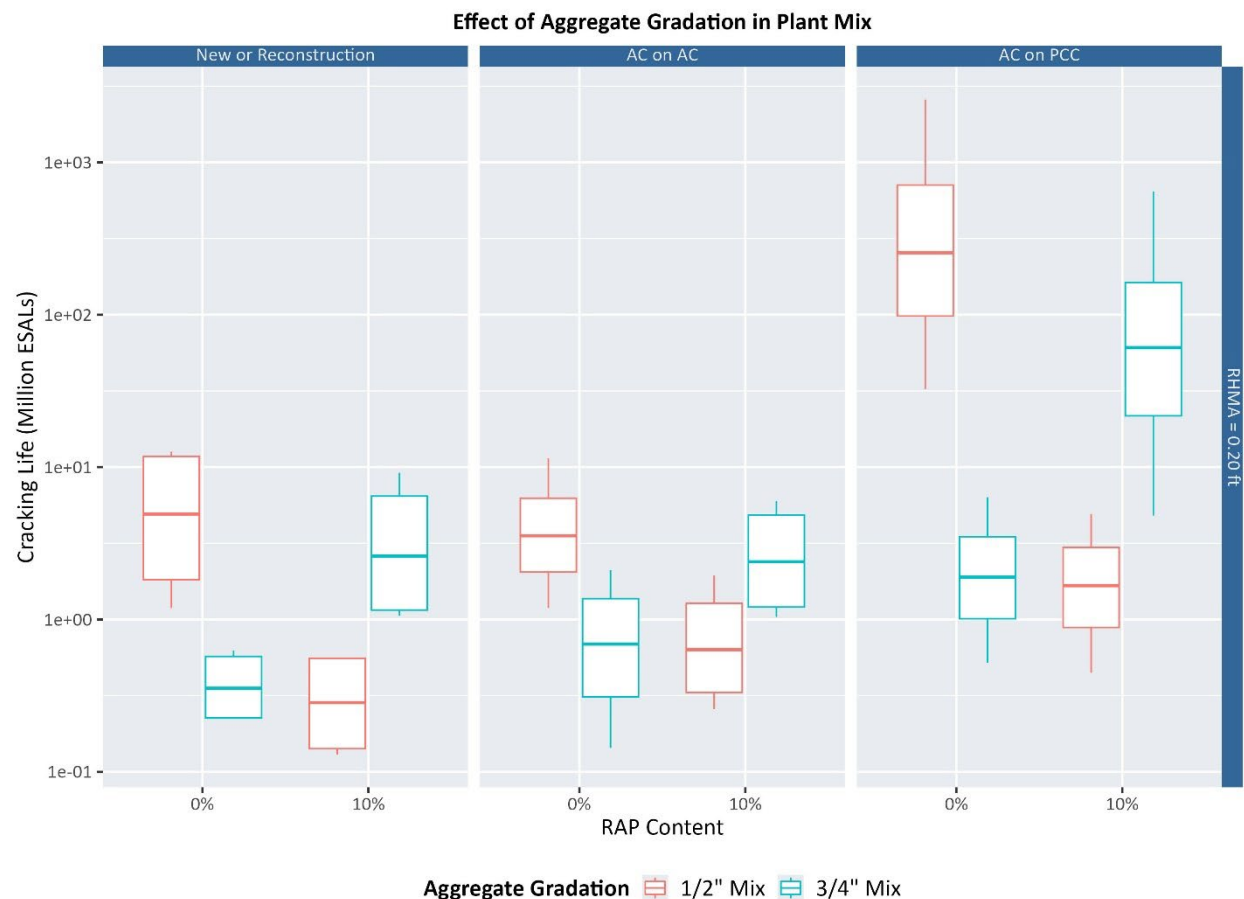


Figure 8.6: Effects of aggregate gradation on cracking life of pavements.

The simulation summary plots show the following:

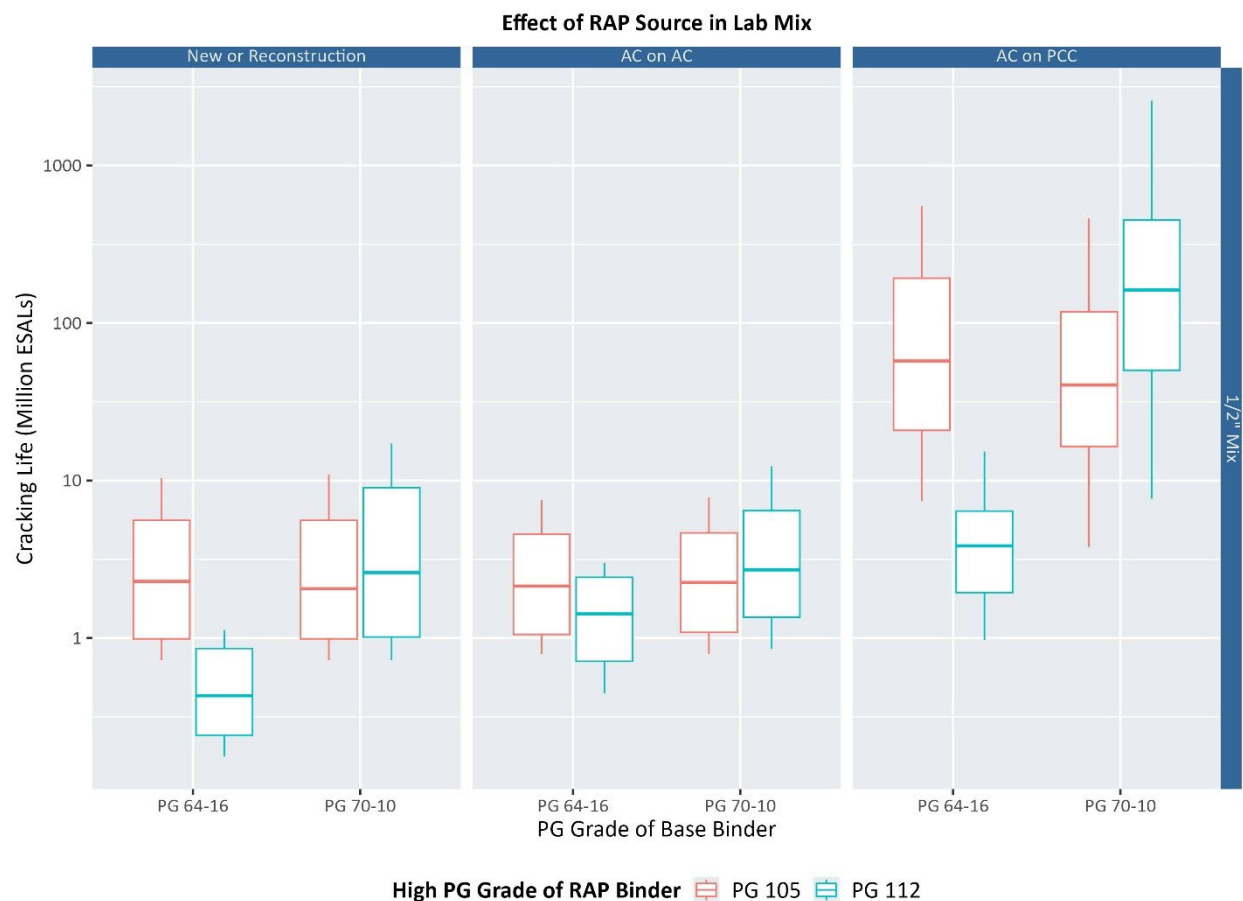
- The 1/2 in. and 3/4 in. mixes without RAP cannot be compared because of the difference in silo aging between them.
- The 3/4 in. mix with 10% RAP overall had better performance than the 1/2 in. mix with the same amount of RAP in these thick structures. The 3/4 inch mix had especially better

fatigue cracking performance for the new or reconstructed pavement and asphalt overlays on concrete pavement, and to a lesser extent for the asphalt-on-asphalt overlays. The laboratory results indicated that the 3/4 in. mix with RAP was both stiffer than the 1/2 in. mix with RAP and had better fatigue lives at strain levels of 500 microstrain and less.

- The 1/2 in. mix with RAP had a nearly identical range of simulated performance as that of the 3/4 in. mix without RAP.

8.3.3. Effect of RAP Source in Laboratory-Produced Mixes

The effect of RAP source, as indicated by the high PG grade of the RAP binder, is shown in Figure 8.7. Only the 1/2 in. laboratory-produced mixes were included in this analysis because the plant-produced mixes only used one RAP source. The RHMA thickness is either 0.15 ft. or 0.20 ft. with 0.2 ft. or 0.4 ft. of new underlying HMA included in the total thickness of new asphalt layers. These can be considered thick new asphalt layers.



Note: For 1/2" lab mixes with 10% RAP, RHMA thicknesses are either 0.15 ft. or 0.20 ft. combined with 0.2 ft. and 0.4 ft. of HMA to form total asphalt thickness.

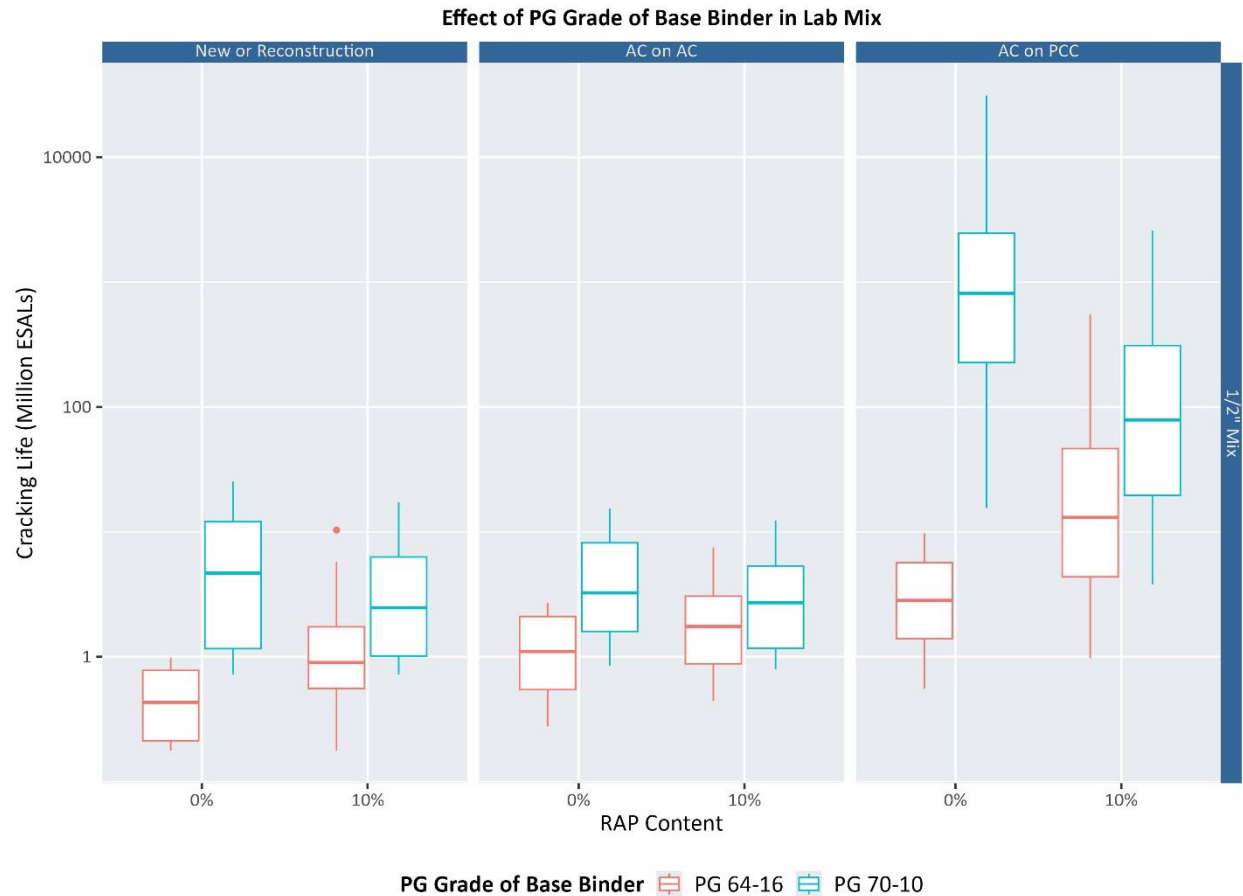
Figure 8.7: Effects of RAP source on cracking life of pavements.

The results of the simulations summarized in the plot indicate the following:

- For the PG 64-16 base binder mixes with 10% RAP, the use of the stiffer RAP #2 resulted in worse simulated fatigue and reflective cracking performance than the use of the softer RAP #1, although the difference was much less for the asphalt overlays on cracked asphalt.
- For the PG 70-10 base binder mixes with 10% RAP, the differences were small between the two RAP sources, except for the asphalt-on-concrete overlays, where there was better performance for RAP #2 compared with RAP #1.
- These results are for the combinations of the layer thickness variables, relative stiffnesses of the different mixes, and the relative fatigue lives at different strain levels, simulated across a range of temperatures in each climate region and across the range of traffic loads in the axle load spectrum. The PG 70-10 mix simulation results showed more sensitivity to the influence of the RAP sources than the simulation results from the PG 64-16 mixes. This is likely because the PG 70-10 mix stiffnesses were more sensitive to the contributions of the RAP source, with RAP #2 increasing stiffness much more than RAP #1. The laboratory fatigue lives of the PG 70-10 mixes were less for RAP #2 than for RAP #1. The PG 64-16 mix had slightly lower stiffness with RAP #2 than with RAP #1 and showed a very strong improvement in laboratory fatigue life with RAP #2 compared to RAP #1. It appears that the effects of the increased stiffness on the tensile strains were more important than the effects of fatigue life at a given strain.

8.3.4. Effect of PG 64 Versus PG 70 Base Binder in Laboratory-Produced Mixes

The effects of base binder high PG grade on simulated fatigue and reflective cracking performance are shown in Figure 8.8. Only the 1/2 in. laboratory-produced mixes were used in this analysis. The RHMA thickness is either 0.15 ft. or 0.20 ft., with 0.2 ft. and 0.4 ft. of new underlying HMA to make up the total new asphalt thickness. These structures can be considered thick, where increasing stiffness will generally improve simulated performance.



Note: RHMA thicknesses are either 0.15 ft. or 0.20 ft. combined with 0.2 ft. and 0.4 ft. of HMA to form total asphalt thickness.

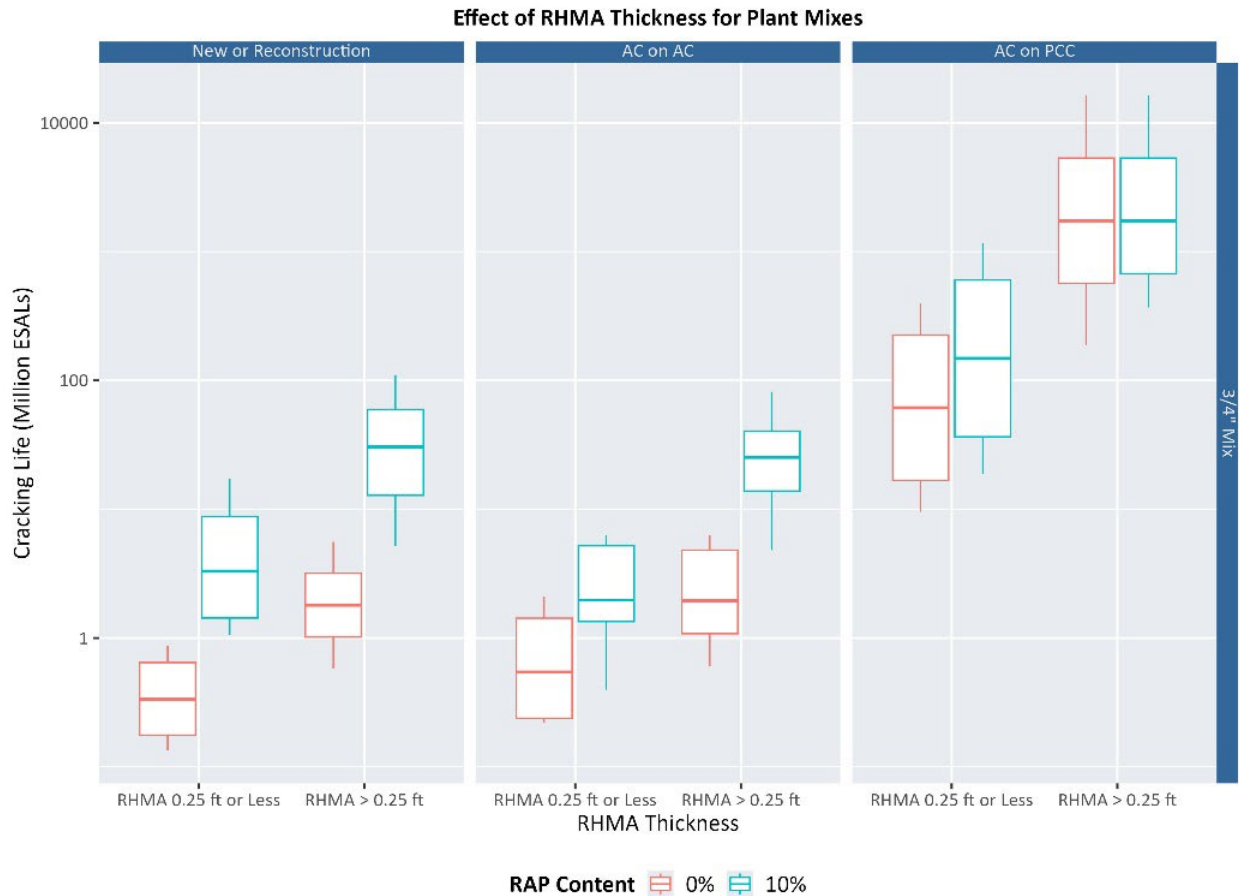
Figure 8.8: Effects of base binder high PG grade on cracking life performance of 1/2 in. laboratory-produced mixes.

The results in the summary plot of the simulations indicate the following:

- The stiffer PG 70-10 base binder increased the fatigue and reflective cracking performance for the ranges of simulations, regardless of whether RAP was included or not. The effect of the base binder was more pronounced for the mixes without RAP.

8.3.5. Effect of Different Ratios of RHMA to HMA Thickness in New Asphalt Layers

The effect of RHMA to HMA thickness ratios in new asphalt layers on simulated fatigue and reflective cracking performance was simulated for the 3/4" plant-produced mixes with and without RAP and is shown in Figure 8.9. The results are separated into when the RHMA thickness in the total new asphalt layers is 0.2 ft. or 0.25 ft. and when they are 0.4 ft. and 0.5 ft.



Notes: RHMA thicknesses shown in legend are combined with 0.2 ft. or 0.4 ft. HMA to form total HMA thickness.

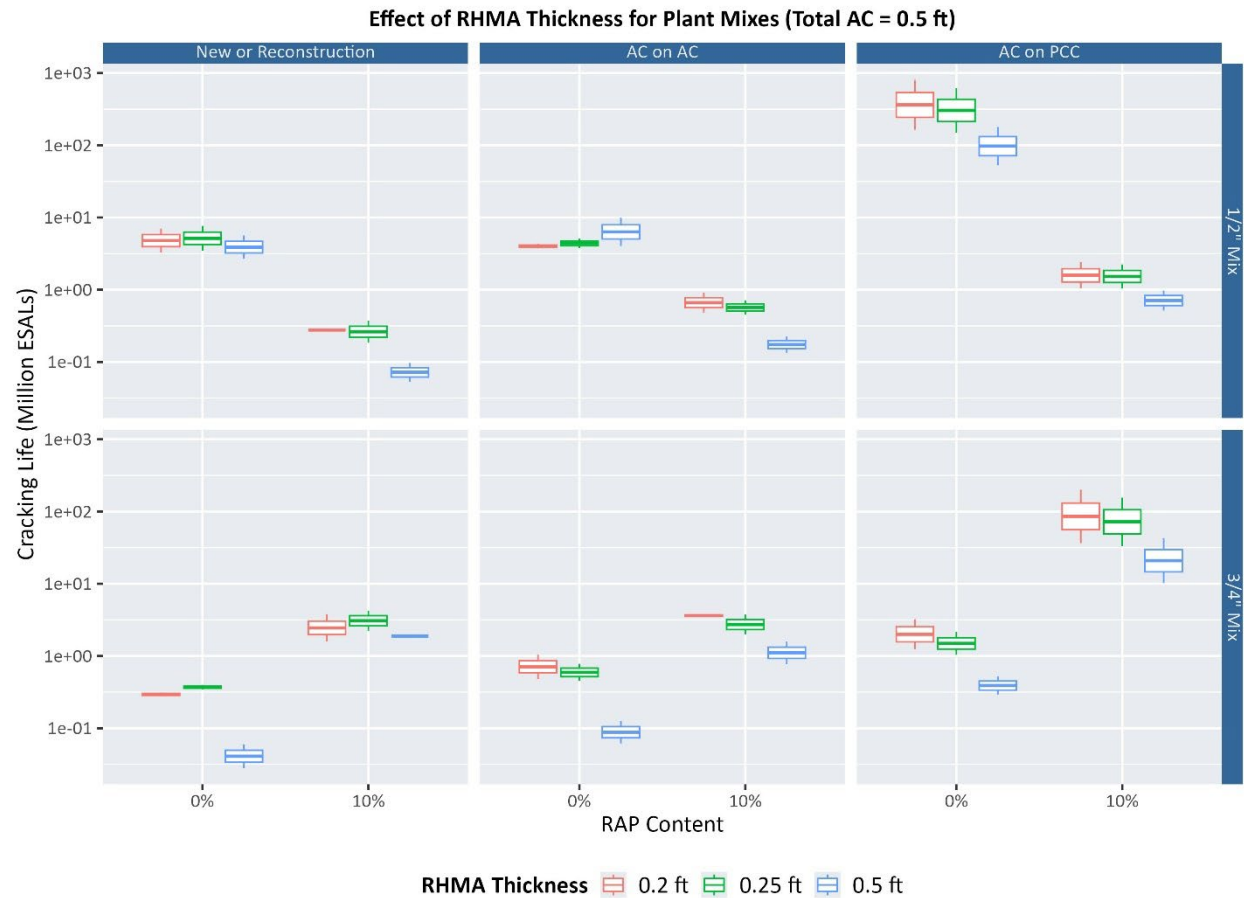
Figure 8.9: Effect of RHMA thickness and RAP content on cracking performance for 3/4 in. plant-produced mix.

The plot indicates the following:

- Adding 10% RAP in this RHMA mix resulted in equal or better simulated cracking performance for the pavement, regardless of RHMA thickness and structure type. The benefits of using RAP in this RHMA are stronger for the new and reconstructed pavement structures and weaker for the overlays, particularly the asphalt-on-concrete overlays. The benefits of adding RAP to the RHMA are stronger when the thickness of the RHMA is 0.20 ft. or 0.25 ft. compared to when the RHMA is 0.4 ft. or 0.5 ft. thick.
- These simulation results are consistent with the laboratory stiffness and fatigue test results, which showed that the 3/4 in. plant mix was stiffer when RAP was added and had a slightly better fatigue life at a given tensile strain when RAP was added.

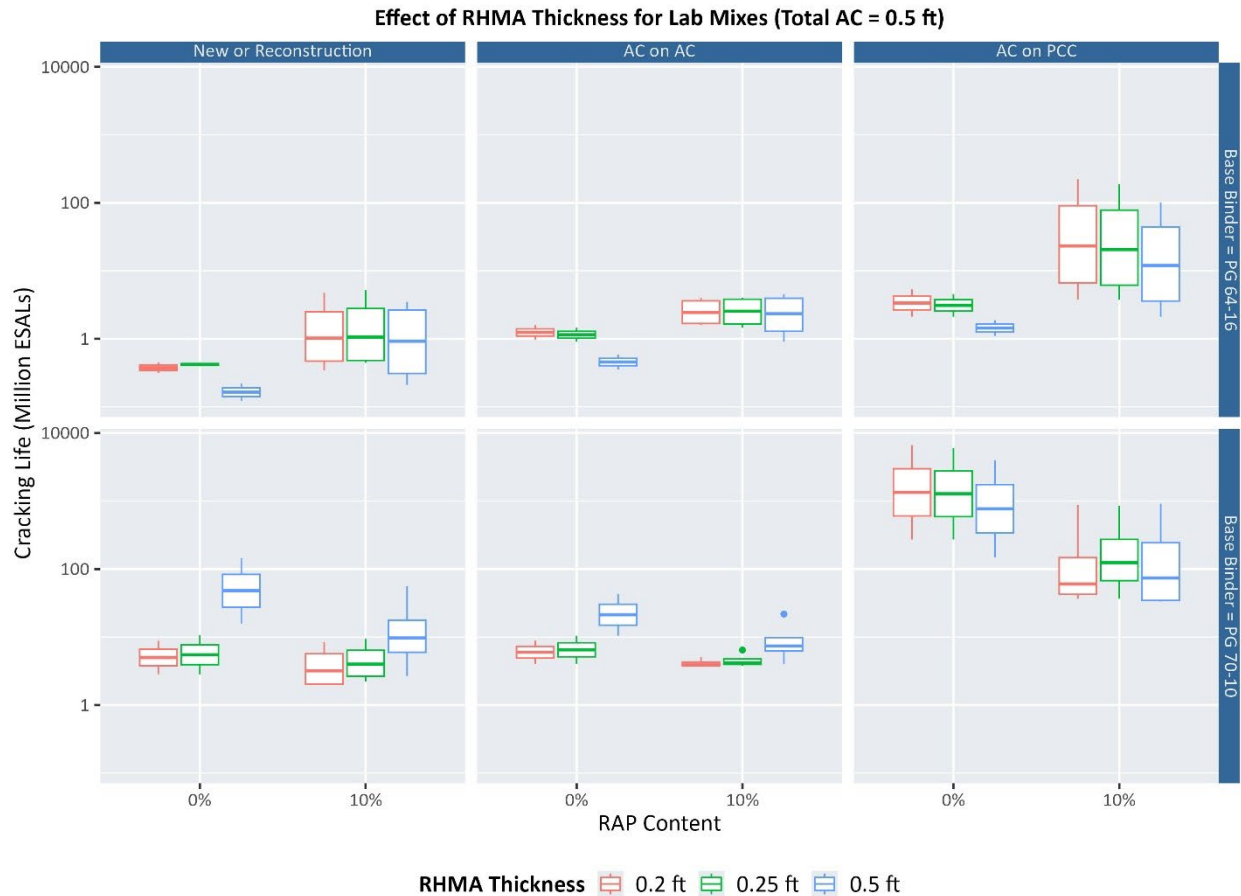
8.3.6. Effect of Using Full-Depth RHMA Versus RHMA Surface and Underlying HMA

The effect of using full-depth RHMA was compared to using RHMA in various thickness ratios with HMA in new asphalt layers on simulated fatigue and reflective cracking performance. The results are shown in Figure 8.10 for the plant-produced mixes and Figure 8.10 for the laboratory-produced mixes.



Note: All total new asphalt layers are 0.5 ft., with 0.2 ft., 0.25 ft., or 0.5 ft. of RHMA on 0.3 ft., 0.25 ft., or no new HMA.

Figure 8.10: Effect of full-depth RHMA versus combined RHMA and HMA in new asphalt layers (plant-produced mixes with and without RAP).



Note: All total new asphalt layers are 0.5 ft., with 0.2 ft., 0.25 ft., or 0.5 ft. of RHMA on 0.3 ft., 0.25 ft., or no new HMA.

Figure 8.11: Effect of full-depth RHMA versus combined RHMA and HMA in new asphalt layers (laboratory-produced mixes with and without RAP).

The plots indicate the following:

- For the plant-produced 1/2 in. mixes, using full-depth RHMA resulted in similar performance to using a combination of RHMA and HMA in the new asphalt layers that are 0.5 ft. thick when there was no RAP for the new or reconstructed pavements and the asphalt-on-asphalt concrete overlays. There was worse performance when there was no RAP in the 1/2 in. overlay on concrete and in all the cases where RAP was added. It should be noted that the 1/2 in. mix with no RAP had additional silo aging and generally good fatigue performance and high stiffness compared to the mix with RAP. For the plant-produced 3/4 in. mixes, the addition of RAP always resulted in worse performance for the full-depth RHMA to varying degrees.
- For the laboratory-produced 1/2 in. mixes with the PG 64-16 BUT-162 base binder, the performance of the full-depth RHMA with no RAP was always worse than the use of RHMA with HMA. For the mixes with RAP, the performance was similar for the full-depth RHMA and use of RHMA with HMA.

- For the laboratory-produced 1/2 in. mixes with the PG 70-10 IMP-86 base binder, the performance of the full-depth RHMA with no RAP was better than the use of RHMA with HMA for new or reconstructed pavement and asphalt overlays on cracked asphalt and similar for asphalt overlays on concrete. The trend for the mixes with RAP was similar to that of the mixes with no RAP. The RAP stiffened the RHMA mixes, but it also caused a reduction in fatigue life, with the net effects primarily depending on the structure type.

It should be noted that the relative performance of using full-depth RHMA versus using RHMA with HMA will be dependent on the specific RHMA and HMA mixes. In Section 8.3.1, the overall performance of the plant-produced test track mixes being worse than that of the statewide median RHMA mix was discussed.

8.4. Summary of CalME Simulation Results

Based on the preliminary *CalME* simulation results presented in this chapter, with a limited range of mixes included in the simulations, the answers to the questions raised earlier are the following:

- The simulation results were consistent in showing that the simulated fatigue and reflective cracking performance is influenced by the interaction of the laboratory stiffness and fatigue results as well as the thickness of the combined RHMA and HMA layers and the type of application (new and reconstructed pavement, asphalt-on-asphalt overlays, asphalt-on-concrete overlays). Adding 10% RAP and RAP from different sources had different effects on stiffness and fatigue life performance, depending on the AR binder and its base binder.
- The effects of adding RAP to the RHMA for both plant-produced and laboratory-produced mixes were the following:
 - + For applications where the new asphalt layers consisted of an RHMA surface with underlying new HMA making up the total new asphalt, adding 10% RAP and RAP from different sources had different effects on stiffness and fatigue life performance, depending on the AR binder and its base binder. Adding 10% RAP to the RHMA surface layer can improve the fatigue and reflective cracking simulated pavement performance to varying degrees depending on the pavement structure type and RHMA thickness. This was found to be true for the 3/4 in. plant-produced test track mix and the laboratory-produced PG 64-16 BUT-162 base binder mixes. Adding 10% RAP to the RHMA surface mix can also be detrimental to fatigue and reflective cracking performance, as was found for the laboratory-produced PG 70-10 IMP-86 base binder mixes. These are all example mixes, and these results, for what can be considered thick applications (greater than

0.25 ft. thick total new asphalt), suggest that the result of adding RAP to RHMA will vary and is at least partly dependent on the base binder in the AR binder and the RAP source.

- + For thin RHMA overlays (less than or equal to 0.25 ft. thick) on cracked asphalt pavement, consisting of RHMA only, all the plant-produced mixes showed substantially worse simulated performance than the statewide median RHMA and HMA plant-produced mixes, except the silo-aged 1/2 in. control mix. The addition of RAP substantially improved the 3/4 in. mix performance. For the laboratory-produced mixes, the addition of both the softer RAP #1 and the stiffer RAP #2 somewhat improved the reflective cracking performance for both base binders, with more improvement shown when added to the PG 64-16 base binder mix than when added to the PG 70-10 base binder mix.
- + The additional silo aging of the 1/2 in. plant-produced mix with no RAP showed a larger effect on RHMA simulated performance than adding 10% RAP in most of the simulation cases, and in many cases the additional silo aging was beneficial. The simulation results were driven by the fact that the stiffness and fatigue life laboratory test results for the plant-produced test track 1/2 in. mix with no RAP were both increased by additional silo aging compared to the counterpart 1/2 mix that had RAP but that also had less silo aging.
- The effect of gradation of the RHMA in plant-produced mixes is the following:
 - + The effect of RHMA aggregate gradation comparing a 1/2 in. maximum size gradation with a 3/4 in. maximum size gradation could only be compared for the plant-produced test track mixes with no RAP because of differences in aging for the 1/2 in. mix with RAP. For the two mixes without RAP that could be compared, the 3/4 in. mix had varying results, but was always better, depending on structure type, which matched expectations that showed it was both stiffer and had better laboratory fatigue performance at strain levels of 500 microstrain or less.
- The effect of RAP source in laboratory-produced mixes is the following:
 - + The overall results for the two RAP sources—RAP #1 with a coarse gradation, lower binder content, and less stiffness than RAP #2 and RAP #2 with a fine gradation, higher binder content, and more stiffness than RAP #1—were mixed. RAP #2 was detrimental when used with the PG 64-16 base binder mixes and had mixed results for the PG 70-10 base binder mixes. In these thick (greater than 0.35 ft. and thicker total RHMA and HMA new asphalt thickness) structures, the influence of stiffness test results seemed to be more influential than changes in laboratory fatigue life results.
- The effects of PG 64 versus PG 70 base binder in laboratory-produced mixes are the following:
 - + For the limited data used in this study and the thick new asphalt layers simulated, laboratory-produced RHMA mixes with the stiffer PG 70-10 base binder were found to

have better cracking performance than mixes with the PG 64-16 base binder, regardless of whether RAP was included or not. The effect of the base binder was more pronounced for the mixes without RAP.

- + This trend is inconsistent with the limited results from other *CalME* simulations using plant-produced mixes in other studies. More plant mixes with the PG 70-10 base binder are needed to confirm the relative performance of RHMA mixes with different base binder PG grades in different types of structures. It must be noted that the base PG 64-16 binder from BUT-162 and the PG 70-10 from IMP-86 were produced in different refineries, most likely using different crude sources.
- The effect of different ratios of RHMA to HMA thickness in new asphalt layers with and without RAP for 3/4 in. plant-produced mixes is the following:
 - + Adding 10% RAP improved the performance of this mix, regardless of the RHMA thickness and structure type, which was consistent with the laboratory test results that showed higher stiffness and slightly better fatigue life at a given tensile strain.
- The effects of using full-depth RHMA compared with using an RHMA surface and HMA as the underlying layer in a 0.5 ft. application, both with and without RAP, are the following:
 - + The results were mixed, depending on the AR base binder, the inclusion of RAP, and the application (new or reconstructed pavement, asphalt overlay on cracked asphalt, asphalt overlay on concrete pavement). The inclusion of RAP generally improved the performance of the full-depth RHMA when compared with full-depth RHMA with no RAP.
 - + It should be remembered that the relative performance of using full-depth RHMA versus using RHMA with HMA will be dependent on the specific RHMA and HMA mixes. In Section 8.3.1, the overall performance of the plant-produced test track mixes being worse than that of the statewide median RHMA mix was discussed. The simulations showed that when the plant-produced mix was used in full-depth RHMA, the performance was worse than when using RHMA on HMA. This may be the main reason that full-depth RHMA showed worse performance for that mix.

9 CONCLUSIONS AND RECOMMENDATIONS

9.1. Study Summary

This report includes laboratory binder and mix testing, as well as *CalME* fatigue and reflective cracking simulation results for four plant-produced RHMA-G mixes used on the HVS test track at the UCPRC. Two aggregate gradations were used in the mixes: a 1/2 in. maximum size gradation and a 3/4 in. maximum size gradation. The 1/2 in. mix with no RAP had additional aging in the silo compared with the other three. This report also includes laboratory mix testing and *CalME* performance simulations for six laboratory-produced mixes, all with the 1/2 in. maximum size gradation, in a factorial with two base binders with different PG grades and from different refineries collected from construction sites in Butte County (BUT-162 with PG 64-16 base binder) and Imperial County (IMP-86 with PG 70-10 base binder) and two different RAP sources. One RAP source had a coarse gradation and was less aged (RAP #1), and the other had a fine gradation and was more aged (RAP #2). Three mixes were produced with each base AR binder—one with no RAP and two with 10% RAP by dry weight of aggregate from each of the two RAP sources.

Four RHMA-O mixes were also tested in this study. The mixes used the BUT-162 and IMP-86 AR binders, with and without 10% by mass of dry aggregate of RAP #1. Binder contents were confirmed using drain down testing. All the mixes used the same aggregate source, with the RHMA-G mixes using the same gap-graded gradation with adjustments for the RAP, and the RHMA-O mixes using the same open-graded gradation with adjustments for the RAP as well.

9.2. Test Result and CalME Simulation Summary

Binder testing was performed on the AR binder used in the test track mixes and extracted binder from the two RAP sources, at 2.98% binder replacement representing 10% RAP in the mix by mass and 7.28% binder replacement representing 25% RAP in the mix by mass. Binder testing included high-, intermediate-, and low temperature PG grading; multiple stress creep recovery, frequency sweep, and FTIR testing; and development of blending charts for the laboratory-produced binders to estimate PG true grade temperatures.

RHMA-G mix testing was performed on all four plant-produced mixes and all six laboratory-produced mixes. RHMA-G mix testing included dynamic modulus (stiffness) using both the axial and flexural configurations, flexural fatigue and initial stiffness, rutting resistance using the unconfined and confined RLT test, and fracture cracking resistance from the semicircular bend test. RHMA-O mix testing consisted of the Cantabro test for raveling resistance and air-void contents.

Pavement fatigue and reflective cracking performance were simulated using the *CalME* ME software, also used by Caltrans for design. Simulations included all the different plant-produced and laboratory-produced RHMA-G mixes. The simulations addressed questions regarding the effect of adding 10% RAP to the mixes, the effects of maximum aggregate size gradation, the effects of different RAP sources, the effects of different AR binders, the effects of different ratios of RHMA to HMA in new asphalt layers, and the effects of using full-depth RHMA compared to using an RHMA surface on new HMA in new asphalt layers. Simulations included new or reconstructed pavement, asphalt overlays on cracked asphalt pavement, and asphalt overlays on cracked concrete pavement.

9.3. Summary of Conclusions

The conclusions from the results in each chapter are summarized as follows:

- Binder testing findings are as follows:
 - + The addition of a small percentage of RAP (2.9% binder replacement) to asphalt rubber-modified binder increases the high temperature continuous PG, indicating increased rutting resistance. This increase may push the final high temperature one PG higher than the control.
 - + The high temperature grade yields a lower than predicted value than suggested by the blending chart method. This finding may be because of the effect of the rubber particles on the high temperature grade.
 - + The intermediate temperature grade does not appear as susceptible to increases in a small percentage of RAP binder as the high- and low temperature grades.
 - + The addition of RAP to the binder negatively affects the low temperature grade and appears to make it less able to relax thermal contraction stresses at cold temperatures (m-value).

- + At a higher proportion of RAP binder in the total binder (7.3% binder replacement), the final high temperature PG of the binder increases, and the low temperature grade also increases as the binder becomes m-value controlled. This loss of elastic recovery from the addition of a stiffer binder occurs regardless of the addition of rubber particles in the binder.
- + The addition of RAP increases the amount of elastic recovery of the mix, which is expected to increase rutting resistance.
- + The addition of RAP increases the stiffness of the binder across nearly the entire stiffness master curve. Increasing the RAP content from 2.9% to 7.3% binder replacement increases the stiffness for all but the fastest frequencies and coldest temperatures.
- + Increasing aging products in the binder, measured by carbonyl content, were observed as increasing amounts of RAP are added and as blended binder aging is increased. The carbonyl contents of the RAP sources were much higher than those of even the PAV-aged control binder.
- + All the binder testing assumes complete blending of the virgin and RAP binders. Whether or not 100% diffusion of the RAP binder occurs within the mix requires additional research.
- RHMA-G mix testing findings are the following:
 - + The axial stiffnesses of the plant-produced mixes were not changed much by the addition of 10% RAP, and the stiffness of the 1/2 in. mix was increased much more by the additional 4 to 6 hours of silo aging time than by the addition of 10% RAP. The flexural stiffness results were generally similar to the axial results, with a few exceptions.
 - + The axial stiffnesses of the laboratory-produced mixes did not show much effect from adding RAP. The mixes with PG 70-10 base binder are stiffer than PG 64-16 base binder mixes, as expected. The flexural stiffnesses are more sensitive to the effects of adding RAP, and of adding the stiffer RAP compared to the softer RAP.
 - + The Black Space diagrams showed somewhat lower phase angles at colder temperatures and faster frequencies for the mixes containing RAP compared to the control mixes with no RAP, indicating less ability to relax thermal contraction stresses.
 - + Controlled deformation flexural fatigue testing for the plant-produced mixes showed that the additional silo aging of the 1/2 in. mix with no RAP had the best fatigue life of the four mixes across the range of 300 to 900 microstrain. It is uncertain why the aging would improve the fatigue life of this mix or if there is another variable influencing the results that was not documented in the plant production. For the 3/4 in. mixes that had the same amount of silo aging, the mixes with and without RAP had similar fatigue lives. The source of the base binder for these mixes was from a source that has been documented to generally have poor laboratory flexural fatigue results.

- + The fatigue results for the laboratory-prepared mixes generally showed expected results. The stiffer PG 70-10 base binder mixes had shorter fatigue lives compared with the softer PG 64-16 mixes; however, the sensitivity of fatigue life to strain is greater for the PG 70-10 base binder mixes, and the fatigue lives of the two sets of mixes move toward convergence as strains become smaller, crossing around 300 microstrain. Overall, the inclusion of 10% RAP generally, but not always, reduced fatigue lives in the controlled deformation flexural fatigue test, and whether there was an increase or decrease sometimes depended on the strain level. Stiffer mixes tended to have steeper slopes between fatigue life and tensile strain, which would lead them to trend toward better fatigue lives as strains became smaller than would softer mixes. The sources of the base binders for these mixes were different from the source of the plant-produced mixes.
- + With respect to laboratory testing for rutting using the RLT test, little trend was seen with the addition of RAP to the mixes. The effects of silo aging in the plant-produced test track mixes were more important for rutting resistance than the inclusion of RAP, which was clear from every mix test in this study for the plant-produced mixes. The effects of adding RAP were highly variable, depending on the test. The base binder high temperature PG did not do a good job of predicting the permanent deformation performance of the laboratory-produced mixes with the BUT-162 and IMP-86 binders, and other differences between those AR binders may be influencing on the performance.
- + The fracture cracking resistance tests using the semicircular bend for the plant-produced test track mixes showed that the silo-aged 1/2 in. control mix and the 3/4 in. mix with RAP have the highest strengths and lowest flexibility indices, as expected based on all previous results for stiffness. The fracture energies are similar for all the mixes. The post-peak slopes of the silo-aged control 1/2 in. mix and the 3/4 in. mix with RAP are steeper, indicating more brittle fracture, as expected. For the laboratory-produced mixes, the trends of the flexibility index and strength results for the PG 64-16 base binder mixes show the flexibility index decreasing and the strength increasing with the inclusion of RAP, and also show the expected effects of the stiffer RAP. For the PG 70-10 mixes, the results do not match expectations for the strengths compared with the flexural stiffnesses, with strength decreasing as RAP is added. The fracture energies and post-peak slopes of the PG 70-10 base binder mixes also show an opposite trend compared to expectations, with decreasing fracture energies and increasing post-peak slopes as RAP is added.

- + The Cantabro testing of the RHMA-O mixes indicated that the use of coarse RAP at 10% by mass of aggregate does not appear to adversely impact the abrasion resistance of the two sets of open-graded mixes included in the study.
- *CalME* fatigue and reflective cracking performance simulation findings are the following:
 - + The simulation results were consistent in showing that the simulated fatigue and reflective cracking performance is influenced by the interaction of the laboratory stiffness and fatigue results, as well as the thickness of the combined RHMA and HMA layers and the type of application (new and reconstructed pavement, asphalt-on-asphalt overlays, asphalt-on-concrete overlays). Adding 10% RAP and RAP from different sources had different effects on stiffness and fatigue life performance, depending on the AR binder and its base binder.
 - + For applications (new or reconstructed pavement, asphalt overlays on cracked asphalt or cracked concrete) where the new asphalt layers consisted of an RHMA surface with an underlying new HMA making up the total new asphalt, resulting in “thick” new asphalt overlays (greater than 0.25 ft. total new asphalt), adding 10% RAP and RAP from different sources had different effects on simulated performance, depending on the AR binder and its base binder, as well as pavement structure type and RHMA thickness. Adding RAP was found to improve performance for the 3/4 in. plant-produced test track mix and the laboratory-produced PG 64-16 BUT-162 base binder mixes but was detrimental to performance for the laboratory-produced PG 70-10 IMP-86 base binder mixes.
 - + For thin RHMA overlays (less than or equal to 0.25 ft. thick) on cracked asphalt pavement, consisting of RHMA only, all the plant-produced mixes showed substantially worse simulated performance than the statewide median RHMA and HMA plant-produced mixes, except the silo-aged 1/2 in. control mix. The addition of RAP substantially improved the 3/4 in. mix performance. For the laboratory-produced mixes, the addition of both the softer RAP #1 and the stiffer RAP #2 somewhat improved the reflective cracking performance for both base binders, with more improvement shown when added to the PG 64-16 base binder mix than when added to the PG 70-10 base binder mix.
 - + Silo aging can have a larger effect on RHMA simulated performance than adding 10% RAP, and sometimes the effect of additional aging can be beneficial, as was found for the plant-produced test track 1/2 in. mix with no RAP.
 - + The effects of RHMA maximum aggregate size gradation could only be compared for the 1/2 in. and 3/4 in. plant-produced mixes with no RAP, which showed that the 3/4 in. mix had better performance to varying degrees, depending on the structure type.

- + Looking at the effects of RAP source in the laboratory-produced mixes, the simulated performance results were mixed. Stiffer RAP #2 was detrimental when used with the PG 64-16 base binder mixes and had mixed results for the PG 70-10 base binder mixes. In the thick (greater than 0.35 ft. and thicker total RHMA and HMA new asphalt thickness) structures, the influence of stiffness test results seemed to be more influential than changes in laboratory fatigue life results.
- + For the limited data used in this study and the thick new asphalt layers simulated, laboratory-produced RHMA mixes with the stiffer PG 70-10 base binder were found to have better cracking performance than mixes with the PG 64-16 base binder, regardless of whether RAP was included or not. The effect of the base binder was more pronounced for the mixes without RAP. The two virgin binders used to produce the two AR binders came from different sources, which may have influenced the results more than the PG grade.
- + Adding RAP to the plant-produced 3/4 in. mix improved performance regardless of the ratio of RHMA to HMA in the combined thick new asphalt layers.
- + Comparing the use of full-depth RHMA versus RHMA on top of new HMA in an application of 0.5 ft. of total new asphalt, the simulations indicated that full-depth RHMA can be beneficial when the RHMA has good performance characteristics (the combination of flexural stiffness and flexural fatigue life) and worse when it does not. The inclusion of RAP generally had a beneficial effect on full-depth RHMA compared with RHMA with no RAP.

9.4. Preliminary Recommendations for Specification Language

Based in the limited sets of mixes evaluated in this report, the following are preliminary recommendations for the use of RAP in RHMA-G and RHMA-O mixes:

- Allow the use of 10% RAP in RHMA-G without restriction on gradation.
 - + Keep the same aggregate gradation limits.
 - + Consider collecting data on the combined virgin and RAP binder blended low temperature PG grade based on binder blending charts for at least several years of implementation and monitoring the results of those projects for age-related cracking. This will provide a better indication of how much the different RAP sources in the state will change the low temperature performance of the combined binders. This may be a somewhat conservative recommendation; however, RHMA-G is used exclusively as a surface mix where aging and age-related low temperature cracking are most important.
 - + Alternatively, consider implementing the UCPRC recommendations for extracting the rubber from the binder before performing the BBR test.

- Allow the use of 10% coarse RAP in RHMA-O.
 - + Develop a grading specification for coarse RAP that is practical but will not interfere with the open-graded gradation requirements.
 - + Consider collecting data on the combined virgin and RAP binder blended low temperature PG grade based on binder blending charts for at least several years of implementation and monitoring the results of those projects for age-related cracking. As noted for RHMA-G this may be a conservative recommendation but is important for these mixes used exclusively on the surface.
 - + Alternatively, implement the UCPRC recommendations for extracting the rubber from the binder before performing the BBR test.

9.5. Other Preliminary Recommendations

Other preliminary recommendations drawn from the results of the project are the following:

- Continue work on a repeated load fatigue test for mix or FAM for HMA and RHMA-G to identify and eventually develop specifications to minimize the use of binders with fatigue performance that is considerably worse than the current statewide median. It is important to identify mixes with poor laboratory fatigue performance that is likely contributing to poor performance in the state highway network. Fracture testing has been shown in this study and other recent studies to provide a good indicator of flexural stiffness, but it is unable to identify mixes with poor fatigue performance.
- Identify whether there is sufficient data in the Caltrans job mix formula data identifying binder sources to evaluate whether the high sensitivity of fatigue performance to binder source, as opposed to binder grade identified in laboratory testing and *CalME* simulations, is also evident in pavement management system (PMS) field performance data.
- Implement a medium-term oven aging protocol for mix design to capture the effects of silo aging and early to medium-term aging in place.
- Consider the use of full-depth RHMA with or without 10% RAP in overlays and new pavement up to 0.5 ft. thick.
- Continue work on characterizing the effect of 10% to 25% RAP on RHMA-G material performance-related properties, including consideration of recycling agents.

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APPENDIX A BINDER TEST RESULTS

Binder test results are summarized in the following tables:

- Table A.1: Unaged, High Temperature Performance Grading Results
- Table A.2: RTFO-Aged, High Temperature Performance Grading Results
- Table A.3: PAV-Aged, Intermediate Temperature Performance Grading Results
- Table A.4: Bending Beam Rheometer Test Results
- Table A.5: Multiple Stress Creep Recovery Test Results
- Table A.6: Summary FTIR Test Results

Table A.1: Unaged, High Temperature Performance Grading Results for Plant Mix AR Binder and RAP #1

Aging Condition	Binder ID	Test Temp. (°C)	Average G* (kPa)	Std. Dev. (kPa)	Average Phase Angle (°)	Std. Dev. (°)	Average G*/sin (δ) (kPa)	Std. Dev. (kPa)
Unaged	VSSI AR (Control)	70	1.10	0.04	85.0	0.1	1.11	0.04
		76	0.57	0.02	86.6	0.1	0.57	0.02
	VSSI AR w/ 2.91% RAP #1 TWB	70	1.31	0.04	83.5	0.4	1.32	0.04
		76	0.67	0.02	85.3	0.4	0.68	0.02
	VSSI AR w/ 7.28% RAP #1 TWB	70	1.48	0.03	83.5	0.1	1.49	0.03
		76	0.75	0.02	85.4	0.1	0.75	0.02

Note: TWB = total weight of binder.

Table A.2: RTFO-Aged, High Temperature Performance Grading Results for Plant Mix AR Binder and RAP #1

Aging Condition	Binder ID	Test Temp. (°C)	Average G* (kPa)	Std. Dev. (kPa)	Average Phase Angle (°)	Std. Dev. (°)	Average G*/sin (δ) (kPa)	Std. Dev. (kPa)
RTFO aged	VSSI AR (Control)	70	3.93	0.00	77.85	0.02	4.02	0.00
		76	1.96	0.00	80.45	0.02	1.98	0.00
	VSSI AR w/ 2.91% RAP #1 TWB	76	2.48	0.21	78.61	1.28	2.53	0.23
		82	1.28	0.12	81.13	1.08	1.30	0.12
	VSSI AR w/ 7.28% RAP #1 TWB	76	3.10	0.06	76.01	0.34	3.19	0.07
		82	1.61	0.03	79.05	0.23	1.64	0.04

Note: TWB = total weight of binder.

Table A.3: PAV-Aged, Intermediate Temperature Performance Grading Results for Plant Mix AR Binder and RAP #1

Aging Condition	Binder ID	Temp. (°C)	Average G* (kPa)	Std. Dev. (kPa)	Average δ (°)	Std. Dev. (°)	Average G*×sinδ (kPa)	Std. Dev. (kPa)	Continuous Grade (°C)	Std. Dev. (°)
PAV aged	VSSI AR (Control)	22	7185	318	34.4	0.1	4059	174	19.8	0.5
	VSSI AR w/ 2.91% RAP #1 TWB	22	6247	904	37.4	0.0	3791	551	19.4	1.6
	VSSI AR w/ 7.28% RAP #1 TWB	22	6200	146	36.3	0.0	3671	89	18.9	0.2

Note: TWB = total weight of binder.

Table A.4: Bending Beam Rheometer Test Results for Plant Mix AR Binder and RAP #1

Aging Condition	Binder ID	Test Temp. (°C)	Average Creep Stiffness (MPa)	Std. Dev. (MPa)	Average m-Value (°)	Std. Dev. (°)
PAV aged	VSSI AR (Control)	-12	63	8	0.309	0.007
		-36	600	79	0.202	0.011
	VSSI AR w/ 2.91% RAP #1 TWB	-12	136	29	0.319	0.011
		-36	1230	236	0.131	0.006
	VSSI AR w/ 7.28% RAP #1 TWB	-12	102	25	0.314	0.006
		-36	1207	150	0.131	0.008

Note: TWB = total weight of binder.

Table A.5: Multiple Stress Creep Recovery Test Results for Plant Mix AR Binder and RAP #1

Aging Condition	Binder ID	Temp. (°C)	Average Percentage Recovery (APR)				% Diff. Between APR	Jnr				% Diff. Between Jnr
			0.1 kPa	Std. Dev.	3.2 kPa	Std. Dev.		0.1 kPa	Std. Dev.	3.2 kPa	Std. Dev.	
RTFO aged	VSSI AR (Control)	64	26.3	1.5	17.0	0.9	35	0.65	0.06	0.75	0.06	15
	VSSI AR w/ 2.91% RAP #1 TWB	64	27.1	1.0	19.5	0.8	28	0.58	0.03	0.65	0.03	11
	VSSI AR w/ 7.28% RAP #1 TWB	64	32.8	0.3	24.6	0.1	25	0.45	0.01	0.49	0.00	11

Note: TWB = total weight of binder.

Table A.6: Summary FTIR Test Results for Plant Mix AR Binder and RAP #1 and RAP #2

Aging Condition	Index	VSSI AR (Control)	VSSI AR w/ 2.91% RAP #1 TWB	VSSI AR w/ 7.28% RAP #1 TWB	RAP #1	RAP #2
Unaged	CA	0.05	0.16	0.30	3.25	3.77
	SUF	0.94	1.02	1.62	9.58	8.84
RTFO	CA	0.19	0.37	0.52	N/T	N/T
	SUF	1.38	1.60	1.75	N/T	N/T
PAV	CA	0.68	0.83	0.89	N/T	N/T
	SUF	3.11	3.32	3.65	N/T	N/T

Note: TWB = total weight of binder.

APPENDIX B RHMA-G MIX TEST RESULTS

Mix test results are summarized in the following tables:

- Table B.1 to Table B.10: Dynamic Modulus Test Results
- Table B.11 to Table B.20: Flexural Modulus Test Results
- Table B.21 to Table B.22: Repeated Load Triaxial Test Results
- Table B.23 to B.25: Flexural Beam Fatigue Test Results
- Table B.26 to B.27: Semicircular Bend Test Results

Note: The Mix ID format is Type (Plant or Lab)-Mix # (NMAS, RAP %/ID, Binder Grade).

Table B.1: Dynamic Modulus Test Results for Plant-MixA (1/2",0% RAP, 64-16)

Fitting Parameters	δ	α	β	γ	C1	C2
	0.869	3.509	-1.309	-0.355	22.170	199.605
Temperature (°C)	Frequency (Hz)	Modulus (Mpa)	Phase Angle (°)	Reduced Frequency (Hz)	Modeled Modulus (MPa)	Square of Errors
4	25	12610.0	8.8	2058.3	12801.1	4.27E-05
	10	11690.8	9.4	829.5	11755.2	5.70E-06
	5	10968.3	10.0	414.8	10938.8	1.36E-06
	1	9186.0	11.5	85.5	9056.7	3.79E-05
	0.5	8444.3	12.2	41.5	8203.0	1.59E-04
	0.1	6781.0	14.2	8.4	6397.3	6.40E-04
21	25	7154.3	15.5	19.4	7324.6	1.04E-04
	10	6203.8	16.7	7.8	6314.7	5.92E-05
	5	5515.5	17.6	3.9	5585.0	2.95E-05
	1	4054.0	20.0	0.8	4071.1	3.35E-06
	0.5	3525.8	20.9	0.4	3477.7	3.56E-05
	0.1	2461.5	23.3	0.1	2366.3	2.93E-04
38	25	3281.5	24.5	0.4	3447.1	4.57E-04
	10	2652.0	25.5	0.1	2776.1	3.94E-04
	5	2254.5	26.1	0.1	2332.7	2.19E-04
	1	1446.0	28.1	0.0	1513.7	3.95E-04
	0.5	1214.0	28.4	0.0	1248.8	1.50E-04
	0.1	744.9	29.9	0.0	771.9	2.40E-04
54	25	1609.8	29.9	0.0	1525.0	5.52E-04
	10	1222.3	30.5	0.0	1170.9	3.47E-04
	5	996.5	30.5	0.0	954.5	3.50E-04
	1	582.3	31.4	0.0	584.8	3.53E-06
	0.5	478.7	30.8	0.0	472.4	3.27E-05
	0.1	278.1	30.6	0.0	286.2	1.55E-04

Note: Mix ID format = Type (Plant or Lab)-Mix # (NMAS, RAP %/ID, Binder Grade).

Table B.2: Dynamic Modulus Test Results for Plant-MixB (3/4", 0% RAP, 64-16)

Fitting Parameters	δ	α	β	γ	C1	C2
	0.000	4.262	-1.539	-0.379	25.013	199.661
Temperature (°C)	Frequency (Hz)	Modulus (Mpa)	Phase Angle (°)	Reduced Frequency (Hz)	Modeled Modulus (MPa)	Square of Errors
4	25	11213.3	10.1	3649.5	10889.1	1.62E-04
	10	10287.0	10.9	1472.3	10069.2	8.64E-05
	5	9552.5	11.6	736.1	9415.8	3.92E-05
	1	7733.0	13.7	149.8	7853.6	4.51E-05
	0.5	6977.8	14.8	74.2	7153.1	1.16E-04
	0.1	5310.8	17.6	14.8	5571.8	4.34E-04
21	25	5857.8	18.5	18.6	5789.9	2.56E-05
	10	4903.0	20.3	7.5	4924.2	3.50E-06
	5	4246.3	21.5	3.7	4302.3	3.24E-05
	1	2898.3	24.8	0.8	3018.8	3.13E-04
	0.5	2442.0	25.9	0.4	2537.5	2.77E-04
	0.1	1543.5	29.0	0.1	1613.7	3.73E-04
38	25	2297.0	29.4	0.2	2175.4	5.58E-04
	10	1750.8	30.9	0.1	1677.2	3.47E-04
	5	1422.3	31.7	0.0	1356.8	4.19E-04
	1	816.0	33.9	0.0	793.7	1.44E-04
	0.5	655.5	33.9	0.0	617.9	6.57E-04
	0.1	363.3	34.8	0.0	337.0	1.07E-03
54	25	689.1	36.8	0.0	691.5	2.19E-06
	10	474.7	36.8	0.0	493.8	2.96E-04
	5	366.4	36.1	0.0	378.5	2.01E-04
	1	185.4	35.0	0.0	200.2	1.12E-03
	0.5	147.2	33.6	0.0	151.8	1.77E-04
	0.1	81.5	32.1	0.0	79.3	1.42E-04

Note: Mix ID format = Type (Plant or Lab)-Mix # (NMAS, RAP %/ID, Binder Grade).

Table B.3: Dynamic Modulus Test Results for Plant-MixC (1/2", 10% 1/2" RAP #1, 64-16)

Fitting Parameters	δ	α	β	γ	C1	C2
	0.000	4.333	-1.443	-0.353	32.757	281.288
Temperature (°C)	Frequency (Hz)	Modulus (Mpa)	Phase Angle (°)	Reduced Frequency (Hz)	Modeled Modulus (MPa)	Square of Errors
4	25	11042.1	9.5	2284.9	10991.8	3.93E-06
	10	10037.0	10.3	920.9	10018.5	6.41E-07
	5	9278.8	11.0	460.4	9262.5	5.82E-07
	1	7570.8	12.9	92.8	7508.8	1.27E-05
	0.5	6851.9	13.9	47.3	6784.7	1.83E-05
	0.1	5322.0	16.4	9.3	5126.5	2.64E-04
21	25	5781.6	17.4	19.0	5837.4	1.74E-05
	10	4883.3	18.9	7.6	4935.9	2.17E-05
	5	4263.6	20.0	3.8	4294.8	1.00E-05
	1	2986.3	23.1	0.8	2995.7	1.87E-06
	0.5	2544.5	24.2	0.4	2518.3	2.02E-05
	0.1	1663.5	27.3	0.1	1616.0	1.58E-04
38	25	2201.6	28.5	0.3	2279.0	2.25E-04
	10	1693.5	29.8	0.1	1771.0	3.78E-04
	5	1386.6	30.5	0.1	1443.9	3.09E-04
	1	808.5	32.7	0.0	865.6	8.78E-04
	0.5	652.9	32.9	0.0	681.0	3.35E-04
	0.1	365.8	33.8	0.0	385.7	5.25E-04
54	25	838.7	35.1	0.0	762.3	1.72E-03
	10	593.0	35.2	0.0	554.0	8.72E-04
	5	460.5	34.9	0.0	432.1	7.69E-04
	1	236.3	34.8	0.0	237.4	3.95E-06
	0.5	185.2	33.6	0.0	183.7	1.20E-05
	0.1	96.8	33.6	0.0	99.0	9.73E-05

Note: Mix ID format = Type (Plant or Lab)-Mix # (NMAS, RAP %/ID, Binder Grade).

Table B.4: Dynamic Modulus Test Results for Plant-MixD (3/4", 10% 1/2" RAP #1, 64-16)

Fitting Parameters	δ	α	β	γ	C1	C2
	0.001	4.379	-1.473	-0.362	32.174	281.492
Temperature (°C)	Frequency (Hz)	Modulus (Mpa)	Phase Angle (°)	Reduced Frequency (Hz)	Modeled Modulus (MPa)	Square of Errors
4	25	12323.6	9.0	2082.5	12529.2	5.17E-05
	10	11285.1	9.8	833.0	11412.4	2.37E-05
	5	10501.4	10.5	421.8	10565.0	6.86E-06
	1	8644.6	12.4	84.7	8550.2	2.27E-05
	0.5	7860.4	13.3	42.5	7699.3	8.09E-05
	0.1	6118.6	15.9	8.6	5819.7	4.73E-04
21	25	6660.3	16.8	19.2	6742.1	2.81E-05
	10	5668.6	18.3	7.7	5695.0	4.07E-06
	5	4964.6	19.5	3.9	4958.9	2.55E-07
	1	3506.1	22.7	0.8	3439.2	7.01E-05
	0.5	2996.4	23.9	0.4	2872.0	3.39E-04
	0.1	1978.4	27.0	0.1	1825.3	1.22E-03
38	25	2509.4	28.6	0.3	2664.8	6.81E-04
	10	1929.6	30.0	0.1	2059.2	7.97E-04
	5	1576.1	30.8	0.1	1675.3	7.02E-04
	1	912.9	33.2	0.0	990.4	1.25E-03
	0.5	735.6	33.3	0.0	775.7	5.32E-04
	0.1	409.5	34.0	0.0	429.7	4.38E-04
54	25	948.8	35.2	0.0	886.7	8.64E-04
	10	679.4	35.2	0.0	639.7	6.82E-04
	5	527.7	34.8	0.0	496.3	7.09E-04
	1	267.5	34.6	0.0	267.5	5.02E-10
	0.5	207.8	33.4	0.0	203.6	7.83E-05
	0.1	106.1	46.2	0.0	107.6	4.15E-05

Note: Mix ID format = Type (Plant or Lab)-Mix # (NMAS, RAP %/ID, Binder Grade).

Table B.5: Dynamic Modulus Test Results for Lab-Mix10B (1/2", 0% RAP, 64-16)

Fitting Parameters	δ	α	β	γ	C1	C2
	1.161	3.185	-1.059	-0.366	33.384	281.225
Temperature (°C)	Frequency (Hz)	Modulus (Mpa)	Phase Angle (°)	Reduced Frequency (Hz)	Modeled Modulus (MPa)	Square of Errors
4	25	11490.8	10.0	2682.8	11470.8	5.67E-07
	10	10390.3	10.7	1073.1	10453.7	7.00E-06
	5	9587.3	11.3	536.6	9671.7	1.45E-05
	1	7829.0	12.9	107.3	7856.6	2.33E-06
	0.5	7109.3	13.6	53.7	7093.7	9.07E-07
	0.1	5598.5	15.5	10.3	5384.9	2.85E-04
21	25	5969.8	17.1	19.0	5998.0	4.21E-06
	10	5063.8	18.2	7.6	5090.9	5.41E-06
	5	4453.5	19.0	3.8	4452.7	5.56E-09
	1	3211.8	21.0	0.8	3157.3	5.51E-05
	0.5	2779.5	21.6	0.4	2685.8	2.22E-04
	0.1	1918.8	23.1	0.1	1792.3	8.77E-04
38	25	2304.0	25.6	0.2	2417.6	4.37E-04
	10	1818.8	26.2	0.1	1917.8	5.31E-04
	5	1526.8	26.3	0.0	1597.3	3.85E-04
	1	957.6	27.0	0.0	1024.9	8.71E-04
	0.5	804.1	26.6	0.0	840.5	3.72E-04
	0.1	506.7	26.6	0.0	525.7	2.56E-04
54	25	964.4	29.7	0.0	898.8	9.37E-04
	10	725.2	29.2	0.0	689.6	4.76E-04
	5	593.3	28.5	0.0	563.6	4.97E-04
	1	350.7	27.2	0.0	353.5	1.19E-05
	0.5	291.3	26.0	0.0	290.2	2.64E-06
	0.1	185.5	25.0	0.0	186.8	8.44E-06

Note: Mix ID format = Type (Plant or Lab)-Mix # (NMAS, RAP %/ID, Binder Grade).

Table B.6: Dynamic Modulus Test Results for Lab-Mix02B (1/2", 10% 1/2" RAP #1, 64-16)

Fitting Parameters	δ	α	β	γ	C1	C2
	1.115	3.232	-1.126	-0.373	24.138	199.659
Temperature (°C)	Frequency (Hz)	Modulus (Mpa)	Phase Angle (°)	Reduced Frequency (Hz)	Modeled Modulus (MPa)	Square of Errors
4	25	12361.0	9.7	3274.3	12218.0	2.55E-05
	10	11198.8	10.6	1309.7	11200.9	6.67E-09
	5	10312.8	11.2	654.9	10411.0	1.69E-05
	1	8430.3	12.8	128.8	8531.2	2.67E-05
	0.5	7644.0	13.6	64.9	7746.7	3.36E-05
	0.1	6026.3	15.6	12.7	5955.5	2.63E-05
21	25	6442.3	17.0	19.3	6404.3	6.57E-06
	10	5466.5	18.1	7.7	5449.1	1.93E-06
	5	4796.3	19.0	3.9	4772.6	4.63E-06
	1	3467.8	21.1	0.8	3393.7	8.79E-05
	0.5	2994.8	21.7	0.4	2890.5	2.37E-04
	0.1	2058.5	23.7	0.1	1922.3	8.84E-04
38	25	2475.0	26.1	0.3	2595.4	4.25E-04
	10	1949.5	26.7	0.1	2054.3	5.17E-04
	5	1637.0	27.0	0.1	1706.6	3.27E-04
	1	1022.1	27.8	0.0	1083.4	6.40E-04
	0.5	855.0	27.3	0.0	885.4	2.31E-04
	0.1	533.3	27.0	0.0	547.6	1.33E-04
54	25	1068.7	29.9	0.0	1002.1	7.82E-04
	10	797.0	29.5	0.0	763.9	3.40E-04
	5	644.6	28.9	0.0	620.4	2.75E-04
	1	375.5	27.9	0.0	382.3	6.04E-05
	0.5	311.2	26.7	0.0	310.6	5.68E-07
	0.1	195.9	25.2	0.0	195.5	1.00E-06

Note: Mix ID format = Type (Plant or Lab)-Mix # (NMAS, RAP %/ID, Binder Grade).

Table B.7: Dynamic Modulus Test Results for Lab-Mix04 (1/2", 10% 1/2" RAP #2, 64-16)

Fitting Parameters	δ	α	β	γ	C1	C2
	1.311	3.119	-0.991	-0.357	22.975	199.705
Temperature (°C)	Frequency (Hz)	Modulus (Mpa)	Phase Angle (°)	Reduced Frequency (Hz)	Modeled Modulus (MPa)	Square of Errors
4	25	13067.0	9.0	2605.8	13225.5	2.74E-05
	10	11878.5	9.8	1042.3	12012.9	2.39E-05
	5	11001.0	10.4	521.2	11087.9	1.17E-05
	1	9097.5	12.0	103.4	8954.3	4.75E-05
	0.5	8293.3	12.7	51.3	8061.7	1.51E-04
	0.1	6622.5	14.6	9.9	6112.7	1.21E-03
21	25	6765.0	16.6	20.0	6913.1	8.85E-05
	10	5750.0	17.7	8.0	5871.6	8.26E-05
	5	5066.5	18.5	4.0	5141.7	4.09E-05
	1	3686.0	20.7	0.8	3665.4	5.91E-06
	0.5	3198.0	21.3	0.4	3124.3	1.03E-04
	0.1	2228.8	23.1	0.1	2094.2	7.31E-04
38	25	2818.0	25.1	0.3	2962.9	4.74E-04
	10	2237.3	25.7	0.1	2374.9	6.73E-04
	5	1885.5	25.9	0.1	1992.9	5.79E-04
	1	1206.3	26.7	0.0	1301.6	1.09E-03
	0.5	1014.0	26.2	0.0	1075.4	6.52E-04
	0.1	651.7	25.8	0.0	687.3	5.34E-04
54	25	1383.5	29.3	0.0	1258.5	1.69E-03
	10	1048.1	29.0	0.0	978.7	8.86E-04
	5	861.0	28.3	0.0	808.7	7.40E-04
	1	519.4	27.4	0.0	517.6	2.17E-06
	0.5	435.3	26.2	0.0	429.3	3.61E-05
	0.1	276.2	24.9	0.0	280.6	4.57E-05

Note: Mix ID format = Type (Plant or Lab)-Mix # (NMAS, RAP %/ID, Binder Grade).

Table B.8: Dynamic Modulus Test Results for Lab-Mix11 (1/2", 0% RAP, 70-10)

Fitting Parameters	δ	α	β	γ	C1	C2
	0.855	3.547	-1.484	-0.385	33.144	281.244
Temperature (°C)	Frequency (Hz)	Modulus (Mpa)	Phase Angle (°)	Reduced Frequency (Hz)	Modeled Modulus (MPa)	Square of Errors
4	25	15779.5	7.5	2477.1	15756.6	3.98E-07
	10	14587.5	8.3	990.8	14647.3	3.16E-06
	5	13668.8	8.9	487.9	13746.3	6.04E-06
	1	11561.0	10.6	98.3	11605.8	2.82E-06
	0.5	10637.3	11.5	49.5	10664.7	1.25E-06
	0.1	8618.0	13.8	10.0	8476.2	5.19E-05
21	25	9365.5	14.1	19.1	9353.6	3.03E-07
	10	8106.5	15.6	7.6	8108.3	9.48E-09
	5	7224.0	16.6	3.8	7195.0	3.05E-06
	1	5381.3	19.5	0.8	5265.6	8.91E-05
	0.5	4693.8	20.6	0.4	4535.8	2.21E-04
	0.1	3288.5	23.5	0.1	3054.3	1.03E-03
38	25	3882.5	25.0	0.2	4097.0	5.45E-04
	10	3108.0	26.3	0.1	3268.2	4.77E-04
	5	2619.0	26.9	0.0	2721.9	2.80E-04
	1	1632.5	29.0	0.0	1718.1	4.93E-04
	0.5	1340.5	29.0	0.0	1390.8	2.56E-04
	0.1	795.1	29.5	0.0	837.7	5.13E-04
54	25	1611.3	32.0	0.0	1526.6	5.50E-04
	10	1198.8	31.9	0.0	1143.6	4.20E-04
	5	957.2	31.3	0.0	914.0	4.02E-04
	1	528.5	30.5	0.0	531.0	4.32E-06
	0.5	421.5	29.2	0.0	419.1	6.02E-06
	0.1	241.4	27.8	0.0	241.8	5.18E-07

Note: Mix ID format = Type (Plant or Lab)-Mix # (NMAS, RAP %/ID, Binder Grade).

Table B.9: Dynamic Modulus Test Results for Lab-Mix03 (1/2", 10% 1/2" RAP #1, 70-10)

Fitting Parameters	δ	α	β	γ	C1	C2
	0.835	3.523	-1.665	-0.402	25.583	199.526
Temperature (°C)	Frequency (Hz)	Modulus (Mpa)	Phase Angle (°)	Reduced Frequency (Hz)	Modeled Modulus (MPa)	Square of Errors
4	25	16700.0	7.3	4067.9	16141.0	2.19E-04
	10	15475.8	8.0	1627.2	15249.8	4.08E-05
	5	14541.8	8.5	820.7	14533.5	6.00E-08
	1	12358.5	10.3	168.5	12726.2	1.62E-04
	0.5	11397.3	11.1	83.5	11868.3	3.09E-04
	0.1	9312.8	13.3	17.0	9841.5	5.75E-04
21	25	10261.8	13.5	18.9	9979.4	1.47E-04
	10	8925.0	14.9	7.6	8794.8	4.08E-05
	5	7982.0	16.0	3.8	7916.0	1.30E-05
	1	6009.5	18.9	0.8	5937.8	2.72E-05
	0.5	5244.8	20.0	0.4	5147.5	6.60E-05
	0.1	3699.0	23.1	0.1	3542.3	3.53E-04
38	25	4269.3	24.2	0.2	4379.9	1.23E-04
	10	3464.3	25.6	0.1	3514.5	3.92E-05
	5	2932.0	26.3	0.0	2941.4	1.91E-06
	1	1849.5	28.7	0.0	1862.3	9.01E-06
	0.5	1519.5	28.8	0.0	1509.2	8.75E-06
	0.1	893.2	29.6	0.0	899.0	8.09E-06
54	25	1647.5	31.5	0.0	1630.2	2.10E-05
	10	1226.3	31.5	0.0	1217.1	1.07E-05
	5	977.2	30.9	0.0	970.5	8.88E-06
	1	539.7	30.1	0.0	558.0	2.10E-04
	0.5	431.2	28.8	0.0	436.9	3.25E-05
	0.1	252.1	27.1	0.0	246.7	8.87E-05

Note: Mix ID format = Type (Plant or Lab)-Mix # (NMAS, RAP %/ID, Binder Grade).

Table B.10: Dynamic Modulus Test Results for Lab-Mix05 (1/2", 10% 1/2" RAP #2, 70-10)

Fitting Parameters	δ	α	β	γ	C1	C2
	0.799	3.632	-1.527	-0.369	23.881	199.581
Temperature (°C)	Frequency (Hz)	Modulus (Mpa)	Phase Angle (°)	Reduced Frequency (Hz)	Modeled Modulus (MPa)	Square of Errors
4	25	16659.5	6.5	3192.3	16853.6	2.53E-05
	10	15600.3	7.1	1276.9	15720.8	1.12E-05
	5	14764.3	7.6	633.3	14811.1	1.89E-06
	1	12814.5	9.0	126.7	12616.8	4.56E-05
	0.5	11947.0	9.6	62.8	11631.8	1.35E-04
	0.1	9987.0	11.5	12.1	9313.9	9.18E-04
21	25	9707.8	13.1	19.5	9985.8	1.50E-04
	10	8482.0	14.5	7.8	8716.6	1.40E-04
	5	7623.8	15.6	3.9	7785.3	8.29E-05
	1	5776.0	18.5	0.8	5761.7	1.15E-06
	0.5	5066.5	19.6	0.4	4978.0	5.86E-05
	0.1	3613.5	22.7	0.1	3417.3	5.88E-04
38	25	4381.5	23.1	0.3	4589.2	4.05E-04
	10	3553.8	24.5	0.1	3706.4	3.34E-04
	5	3017.3	25.4	0.1	3117.6	2.02E-04
	1	1927.5	27.9	0.0	2012.2	3.49E-04
	0.5	1586.5	28.1	0.0	1642.7	2.28E-04
	0.1	943.0	29.4	0.0	997.6	5.98E-04
54	25	1996.5	30.0	0.0	1885.0	6.23E-04
	10	1513.0	30.5	0.0	1434.4	5.37E-04
	5	1220.0	30.3	0.0	1157.0	5.31E-04
	1	686.5	30.3	0.0	687.8	7.31E-07
	0.5	548.3	29.3	0.0	546.5	2.18E-06
	0.1	316.0	27.7	0.0	318.4	1.11E-05

Note: Mix ID format = Type (Plant or Lab)-Mix # (NMAS, RAP %/ID, Binder Grade).

Table B.11: Flexural Modulus Test Results for Plant-Mix A (1/2",0% RAP, 64-16)

Fitting Parameters	δ	α	β	γ	C1	C2
	0.799	3.632	-1.527	-0.369	23.881	199.581
Temperature (°C)	Frequency (Hz)	Modulus (Mpa)	Phase Angle (°)	Reduced Frequency (Hz)	Modeled Modulus (MPa)	Square of Errors
30.6	0.02	169.8	35.7	0.0	175.5	2.0E-04
30.0	0.05	210.9	27.9	0.0	254.5	6.7E-03
30.4	0.10	294.8	34.5	0.0	310.7	5.2E-04
30.3	0.20	389.6	33.3	0.0	398.3	9.1E-05
30.4	0.50	536.1	33.2	0.0	541.7	2.0E-05
30.3	0.99	686.3	33.8	0.0	687.0	2.2E-07
30.3	1.96	871.6	31.2	0.1	862.5	2.0E-05
30.3	4.95	1172.2	32.1	0.2	1156.8	3.3E-05
30.4	10.01	1423.8	33.9	0.4	1429.7	3.1E-06
30.4	15.11	1558.3	35.6	0.6	1601.1	1.4E-04
19.8	0.01	508.2	27.6	0.0	446.7	3.1E-03
19.8	0.02	616.1	26.2	0.0	567.0	1.3E-03
19.5	0.05	770.5	21.7	0.1	799.6	2.6E-04
19.7	0.10	924.6	17.5	0.1	979.3	6.2E-04
19.7	0.20	1339.8	27.7	0.2	1218.9	1.7E-03
19.8	0.50	1647.9	27.0	0.5	1584.4	2.9E-04
19.9	0.99	2023.9	25.5	1.0	1898.6	7.7E-04
19.8	1.96	2432.4	23.7	2.1	2298.1	6.1E-04
19.8	4.98	3021.2	21.9	5.3	2883.8	4.1E-04
19.8	10.09	3477.9	23.7	10.7	3374.0	1.7E-04
19.9	15.08	3760.6	24.9	15.5	3650.9	1.7E-04
9.7	0.01	1505.6	22.4	0.3	1393.0	1.1E-03
9.8	0.02	1739.9	18.5	0.7	1695.8	1.2E-04
9.5	0.05	2073.5	14.5	1.9	2236.8	1.1E-03
9.6	0.10	2462.5	13.4	3.6	2636.2	8.8E-04
9.6	0.20	3086.3	19.9	7.2	3092.2	6.9E-07
9.6	0.50	3683.1	19.2	17.9	3759.9	8.0E-05
9.5	0.98	4237.2	17.6	36.2	4311.6	5.7E-05
9.5	1.95	4794.4	16.6	71.9	4872.1	4.9E-05
9.4	5.00	5591.7	16.4	191.4	5692.4	6.0E-05
9.6	10.01	6190.5	17.4	365.3	6238.5	1.1E-05
9.5	15.16	6511.8	18.7	557.0	6593.0	2.9E-05
30.4	0.02	#N/A	#N/A	0.0	178.0	#N/A
30.0	0.05	#N/A	#N/A	0.0	255.4	#N/A
29.0	0.10	#N/A	#N/A	0.0	360.0	#N/A
29.1	0.20	#N/A	#N/A	0.0	451.8	#N/A

Fitting Parameters	δ	α	β	γ	C1	C2
	0.799	3.632	-1.527	-0.369	23.881	199.581
Temperature (°C)	Frequency (Hz)	Modulus (Mpa)	Phase Angle (°)	Reduced Frequency (Hz)	Modeled Modulus (MPa)	Square of Errors
29.4	0.50	#N/A	#N/A	0.0	603.1	#N/A
29.4	0.99	#N/A	#N/A	0.1	756.6	#N/A
29.6	1.96	#N/A	#N/A	0.1	928.3	#N/A
29.7	5.12	#N/A	#N/A	0.2	1244.9	#N/A
29.9	10.08	#N/A	#N/A	0.4	1497.9	#N/A
30.0	15.18	#N/A	#N/A	0.6	1665.9	#N/A
19.5	0.01	476.7	31.1	0.0	460.3	2.3E-04
19.6	0.02	588.9	27.9	0.0	579.8	4.5E-05
19.9	0.05	720.6	21.7	0.1	766.3	7.1E-04
19.8	0.10	871.6	14.0	0.1	972.0	2.2E-03
19.8	0.20	1259.3	28.6	0.2	1209.3	3.1E-04
19.7	0.50	1603.8	27.1	0.6	1600.9	6.3E-07
19.7	0.99	1950.3	25.3	1.1	1938.1	7.4E-06
19.7	1.96	2325.3	24.5	2.2	2325.4	1.1E-09
19.7	5.06	2938.2	23.6	5.7	2930.5	1.3E-06
19.6	9.94	3353.1	23.9	11.3	3414.5	6.2E-05
19.5	15.18	3591.7	25.0	17.9	3759.3	3.9E-04
9.6	0.01	1626.8	26.1	0.4	1412.3	3.8E-03
9.4	0.02	1815.6	19.3	0.8	1755.7	2.1E-04
9.4	0.05	2202.6	17.4	2.0	2257.5	1.1E-04
9.7	0.10	2500.4	12.1	3.4	2595.9	2.7E-04
10.0	0.20	3223.6	21.1	6.2	2987.1	1.1E-03
9.9	0.50	3769.8	19.2	16.3	3687.2	9.2E-05
9.7	0.98	4372.4	18.0	33.6	4251.5	1.5E-04
9.8	1.95	4967.6	17.2	65.9	4799.7	2.2E-04
9.7	5.01	5827.1	16.2	171.8	5601.0	3.0E-04
9.6	10.01	6430.7	17.2	354.4	6212.8	2.2E-04
9.6	15.16	6781.0	18.7	535.7	6560.3	2.1E-04
30.2	0.01	157.2	32.0	0.0	143.8	1.5E-03
29.9	0.02	188.9	22.3	0.0	187.5	1.0E-05
30.3	0.05	242.9	30.9	0.0	245.3	1.9E-05
30.5	0.10	300.3	29.1	0.0	305.6	5.7E-05
30.2	0.20	449.1	33.1	0.0	402.5	2.3E-03
30.0	0.50	581.5	31.6	0.0	566.5	1.3E-04
29.9	1.95	933.2	32.4	0.1	896.2	3.1E-04
30.0	5.03	1262.0	33.8	0.2	1201.4	4.6E-04
30.0	9.93	1521.8	31.2	0.4	1474.2	1.9E-04
30.0	15.29	1661.3	33.6	0.6	1669.4	4.5E-06

Fitting Parameters	δ	α	β	γ	C1	C2
	0.799	3.632	-1.527	-0.369	23.881	199.581
Temperature (°C)	Frequency (Hz)	Modulus (Mpa)	Phase Angle (°)	Reduced Frequency (Hz)	Modeled Modulus (MPa)	Square of Errors
19.7	0.01	470.8	29.1	0.0	451.2	3.4E-04
19.4	0.02	579.5	23.8	0.0	595.8	1.5E-04
19.4	0.05	731.1	24.7	0.1	809.2	1.9E-03
19.5	0.10	836.2	14.6	0.1	999.0	6.0E-03
19.5	0.20	1234.5	28.6	0.2	1244.0	1.1E-05
19.6	0.50	1559.5	28.3	0.6	1610.3	1.9E-04
19.8	0.99	1903.6	26.6	1.1	1922.5	1.8E-05
19.8	1.96	2281.7	24.9	2.1	2298.4	1.0E-05
19.8	4.92	2838.1	19.5	5.2	2875.1	3.2E-05
20.1	9.95	3329.5	24.2	9.6	3301.8	1.3E-05
20.2	15.16	3584.8	25.4	14.0	3575.2	1.4E-06
9.7	0.01	1435.1	23.6	0.3	1387.2	2.2E-04
9.6	0.02	1648.3	19.7	0.7	1720.6	3.5E-04
9.9	0.05	2014.8	17.7	1.6	2157.1	8.8E-04
10.0	0.10	2241.5	9.7	3.1	2528.6	2.7E-03
10.1	0.20	3012.0	20.7	6.1	2977.6	2.5E-05
10.0	0.50	3593.4	19.8	15.5	3652.7	5.0E-05
10.0	0.99	4115.9	18.3	30.3	4171.1	3.4E-05
10.0	1.95	4668.1	16.9	60.5	4728.8	3.1E-05
10.0	5.05	5455.6	17.1	156.8	5523.8	2.9E-05
10.0	10.05	6018.8	18.4	317.1	6119.0	5.1E-05
10.0	15.17	6359.0	19.1	477.8	6464.4	5.1E-05

Note: Mix ID format = Type (Plant or Lab)-Mix # (NMAS, RAP %/ID, Binder Grade).

Table B.12: Flexural Modulus Test Results for Plant-MixB (3/4",0% RAP, 64-16)

Fitting Parameters	δ	α	β	γ	C1	C2
	0.538	3.375	-0.932	-0.434	3659.277	26432.230
Temperature (°C)	Frequency (Hz)	Modulus (Mpa)	Phase Angle (°)	Reduced Frequency (Hz)	Modeled Modulus (MPa)	Square of Errors
29.8	0.02	80.1	35.7	0.0	79.0	3.44E-05
30.4	0.05	110.1	37.2	0.0	102.0	1.09E-03
29.8	0.10	149.4	37.9	0.0	141.3	5.78E-04
29.9	0.20	152.0	42.5	0.0	179.0	5.04E-03
30.0	0.50	216.6	38.9	0.0	248.1	3.48E-03
29.9	0.99	293.4	37.0	0.0	319.2	1.34E-03
30.0	1.96	376.5	36.6	0.1	403.8	9.23E-04
30.0	4.92	523.2	25.4	0.2	550.4	4.84E-04
30.0	10.17	669.5	40.6	0.4	698.5	3.39E-04
30.0	15.01	734.7	37.2	0.6	788.3	9.36E-04
19.8	0.01	188.3	35.2	0.0	195.4	2.58E-04
20.0	0.02	231.3	28.8	0.0	244.7	6.00E-04
19.9	0.05	306.8	27.6	0.1	343.5	2.40E-03
19.4	0.10	383.2	26.3	0.1	461.1	6.46E-03
19.2	0.20	535.1	32.1	0.3	598.1	2.33E-03
19.6	0.50	689.1	29.5	0.6	769.3	2.28E-03
19.6	0.99	854.2	28.7	1.1	939.2	1.70E-03
19.6	1.96	1044.8	27.0	2.2	1142.7	1.51E-03
19.6	4.87	1326.1	24.7	5.4	1451.7	1.54E-03
19.7	10.09	1564.6	26.1	11.0	1724.6	1.79E-03
19.7	15.16	1705.5	27.0	16.7	1896.6	2.13E-03
9.6	0.01	592.9	25.2	0.3	610.9	1.68E-04
9.8	0.02	697.5	21.9	0.5	747.7	9.10E-04
9.5	0.05	860.2	19.3	1.4	1007.0	4.68E-03
9.5	0.10	948.4	#N/A	2.9	1230.4	1.28E-02
9.6	0.20	1324.6	22.6	5.6	1459.2	1.77E-03
9.6	0.50	1623.3	21.6	13.6	1809.3	2.22E-03
9.8	0.98	1886.8	20.2	25.8	2085.0	1.88E-03
9.8	1.95	2181.8	18.4	50.8	2392.5	1.60E-03
9.9	5.00	2570.2	17.7	126.1	2827.7	1.72E-03
10.0	10.08	2897.8	19.3	246.6	3158.3	1.40E-03
10.0	15.16	3049.4	19.9	363.2	3351.2	1.68E-03
9.7	0.01	704.1	25.3	0.3	606.0	4.25E-03
10.0	0.20	1554.4	22.2	4.8	1405.5	1.91E-03
9.9	0.49	1900.4	21.8	12.3	1767.7	9.88E-04
9.8	0.98	2216.0	18.7	25.8	2084.3	7.09E-04

Fitting Parameters	δ	α	β	γ	C1	C2
	0.538	3.375	-0.932	-0.434	3659.277	26432.230
Temperature (°C)	Frequency (Hz)	Modulus (Mpa)	Phase Angle (°)	Reduced Frequency (Hz)	Modeled Modulus (MPa)	Square of Errors
9.8	1.95	2522.0	19.1	50.4	2388.8	5.55E-04
9.8	4.99	2971.0	18.7	128.5	2836.8	4.03E-04
9.8	10.06	3332.1	18.4	256.9	3178.6	4.20E-04
9.9	15.16	3514.8	19.2	382.5	3376.9	3.02E-04
19.6	0.01	210.5	40.4	0.0	198.6	6.41E-04
19.9	0.02	262.4	30.9	0.0	247.4	6.48E-04
19.8	0.05	351.2	26.2	0.1	350.0	2.23E-06
19.5	0.10	410.3	18.9	0.1	460.7	2.54E-03
19.6	0.20	624.3	32.6	0.2	572.8	1.40E-03
19.8	0.99	1000.9	29.0	1.1	927.8	1.09E-03
19.8	1.96	1223.5	27.2	2.1	1129.5	1.20E-03
19.8	5.05	1581.5	21.3	5.4	1449.8	1.43E-03
19.8	10.14	1855.2	25.5	10.9	1718.6	1.10E-03
19.8	15.16	1999.7	26.5	16.2	1883.5	6.76E-04
30.0	0.01	55.0	32.3	0.0	60.8	1.89E-03
30.2	0.05	105.7	42.4	0.0	104.5	2.61E-05
30.1	0.10	122.8	34.0	0.0	136.6	2.15E-03
29.9	0.20	176.6	39.6	0.0	178.9	3.19E-05
29.8	0.50	252.5	37.3	0.0	254.5	1.13E-05
29.5	0.99	332.5	37.5	0.0	334.3	5.03E-06
29.5	1.97	433.1	36.2	0.1	425.9	5.38E-05
29.4	3.06	417.3	34.8	0.2	503.3	6.63E-03
29.5	4.88	595.0	23.7	0.2	580.5	1.15E-04
29.4	15.28	845.6	37.7	0.8	843.1	1.71E-06
29.8	0.02	80.1	35.7	0.0	79.0	3.44E-05
30.4	0.05	110.1	37.2	0.0	102.0	1.09E-03
29.8	0.10	149.4	37.9	0.0	141.3	5.78E-04
30.1	0.20	193.9	36.1	0.0	174.7	2.06E-03
30.0	0.50	272.4	38.4	0.0	247.7	1.71E-03
30.0	0.99	349.9	37.6	0.0	317.4	1.79E-03
29.8	1.97	449.3	36.5	0.1	411.0	1.49E-03
29.7	4.97	636.0	22.6	0.2	568.7	2.36E-03
29.7	10.10	779.5	36.3	0.5	719.9	1.19E-03
29.5	15.04	870.8	36.9	0.7	828.8	4.61E-04
9.6	0.01	704.7	25.0	0.3	609.7	3.96E-03
9.7	0.02	832.1	22.4	0.5	754.3	1.82E-03
9.6	0.05	1034.5	19.7	1.4	999.5	2.24E-04
9.4	0.10	1174.2	15.3	2.9	1234.2	4.67E-04

Fitting Parameters	δ	α	β	γ	C1	C2
	0.538	3.375	-0.932	-0.434	3659.277	26432.230
Temperature (°C)	Frequency (Hz)	Modulus (Mpa)	Phase Angle (°)	Reduced Frequency (Hz)	Modeled Modulus (MPa)	Square of Errors
9.5	0.20	1588.8	23.0	5.7	1467.9	1.18E-03
9.5	0.50	1881.8	21.4	14.2	1827.9	1.59E-04
9.5	0.98	2208.2	19.8	28.3	2126.4	2.69E-04
9.6	1.95	2544.3	18.0	54.1	2421.9	4.58E-04
9.6	5.00	2992.1	17.3	138.9	2875.0	3.01E-04
9.6	10.06	3339.8	17.7	281.3	3223.9	2.35E-04
9.6	15.16	3520.0	19.3	417.7	3420.8	1.54E-04
19.8	0.01	209.9	32.9	0.0	195.9	8.95E-04
19.4	0.02	257.3	28.2	0.0	262.0	6.04E-05
20.0	0.05	339.0	28.5	0.0	340.0	1.82E-06
20.1	0.10	471.4	35.4	0.1	430.7	1.53E-03
20.1	0.20	625.3	31.7	0.2	544.3	3.62E-03
20.0	0.50	801.7	29.9	0.5	736.5	1.36E-03
19.9	0.99	1002.9	29.5	1.0	914.9	1.59E-03
19.8	1.95	1229.3	27.1	2.1	1123.9	1.51E-03
19.8	5.03	1584.7	28.0	5.4	1448.0	1.53E-03
19.7	10.14	1870.0	25.6	11.0	1722.9	1.27E-03
19.7	15.16	2017.1	26.6	16.7	1896.0	7.23E-04

Note: Mix ID format = Type (Plant or Lab)-Mix # (NMAS, RAP %/ID, Binder Grade).

Table B.13: Flexural Modulus Test Results for Plant-MixC (1/2", 10% 1/2" RAP #1, 64-16)

Fitting Parameters	δ	α	β	γ	C1	C2
	0.346	3.773	-1.109	-0.433	37.477	288.853
Temperature (°C)	Frequency (Hz)	Modulus (Mpa)	Phase Angle (°)	Reduced Frequency (Hz)	Modeled Modulus (MPa)	Square of Errors
29.8	0.01	101.3	#N/A	0.0	90.8	2.24E-03
29.9	0.02	135.4	43.4	0.0	119.4	2.97E-03
30.2	0.05	184.4	46.5	0.0	168.3	1.57E-03
29.7	0.10	246.9	35.7	0.0	236.3	3.61E-04
29.5	0.20	337.1	38.7	0.0	317.6	6.67E-04
30.1	0.50	467.3	36.9	0.0	427.6	1.49E-03
30.2	1.00	607.5	34.7	0.1	553.4	1.64E-03
30.1	1.99	776.5	34.2	0.1	720.9	1.04E-03
30.1	5.00	1061.4	35.4	0.3	995.3	7.80E-04
30.1	10.00	1314.6	35.9	0.5	1253.5	4.27E-04
30.0	15.15	1450.6	38.4	0.8	1445.3	2.49E-06
19.9	0.01	300.9	36.0	0.0	291.8	1.77E-04
20.0	0.02	388.2	35.0	0.0	378.2	1.27E-04
19.8	0.05	555.8	34.1	0.1	554.0	1.85E-06
20.0	0.10	703.7	33.8	0.1	699.1	7.83E-06
20.1	0.20	931.7	31.0	0.2	889.9	3.98E-04
20.1	0.50	1248.0	29.5	0.5	1213.7	1.47E-04
20.0	1.00	1563.2	28.2	1.0	1520.2	1.47E-04
20.0	1.99	1923.3	28.7	2.0	1860.7	2.07E-04
20.0	5.00	2455.7	26.8	4.9	2389.0	1.43E-04
20.1	9.99	2907.6	27.4	9.8	2831.3	1.33E-04
20.1	15.13	3145.9	28.7	14.7	3110.1	2.47E-05
9.6	0.01	1058.3	29.4	0.3	978.4	1.16E-03
9.5	0.02	1289.8	26.4	0.5	1234.7	3.61E-04
9.4	0.05	1643.4	25.1	1.3	1657.5	1.39E-05
9.5	0.10	1970.9	25.3	2.6	2016.7	9.96E-05
9.4	0.20	2535.1	23.9	5.3	2434.4	3.10E-04
9.5	0.50	3136.0	22.0	13.0	3024.7	2.46E-04
9.5	1.00	3650.8	19.8	26.3	3531.3	2.09E-04
9.5	1.99	4207.8	19.8	51.7	4044.7	2.95E-04
9.5	5.00	4985.9	18.9	128.8	4767.2	3.79E-04
9.6	10.00	5618.8	19.3	254.9	5319.2	5.66E-04
9.6	15.15	5946.5	20.3	382.6	5648.8	4.98E-04
30.1	0.02	112.7	45.3	0.0	116.5	2.14E-04
29.7	0.05	138.8	35.8	0.0	177.6	1.14E-02
30.0	0.10	205.9	37.5	0.0	228.6	2.07E-03

Fitting Parameters	δ	α	β	γ	C1	C2
	0.346	3.773	-1.109	-0.433	37.477	288.853
Temperature (°C)	Frequency (Hz)	Modulus (Mpa)	Phase Angle (°)	Reduced Frequency (Hz)	Modeled Modulus (MPa)	Square of Errors
29.9	0.20	281.5	38.8	0.0	305.6	1.27E-03
29.8	0.50	412.2	38.7	0.0	439.9	7.98E-04
29.8	1.00	542.3	36.6	0.1	578.7	7.98E-04
29.8	2.00	704.9	37.2	0.1	747.1	6.38E-04
29.7	5.00	975.3	36.0	0.3	1038.3	7.39E-04
29.7	9.99	1202.4	35.9	0.6	1299.9	1.15E-03
29.7	15.15	1331.0	39.0	0.9	1484.0	2.23E-03
19.9	0.01	274.3	35.5	0.0	290.5	6.15E-04
20.3	0.02	353.8	35.1	0.0	367.1	2.57E-04
20.1	0.05	506.7	35.3	0.0	536.0	5.97E-04
19.8	0.10	643.9	35.4	0.1	719.6	2.33E-03
20.0	0.20	866.5	32.0	0.2	903.5	3.29E-04
20.1	0.50	1155.0	30.5	0.5	1214.9	4.81E-04
20.1	1.00	1446.2	29.1	1.0	1506.4	3.14E-04
20.1	1.99	1777.7	29.6	1.9	1849.3	2.94E-04
20.1	5.00	2289.7	27.3	4.8	2376.2	2.59E-04
20.1	10.00	2693.7	27.6	9.6	2819.0	3.90E-04
20.2	15.17	2927.9	27.4	14.5	3098.8	6.07E-04
9.6	0.01	942.9	29.0	0.3	972.2	1.77E-04
9.9	0.02	1146.2	26.7	0.5	1186.8	2.29E-04
10.1	0.05	1450.4	24.2	1.1	1558.3	9.71E-04
9.6	0.10	1794.0	22.0	2.5	1983.7	1.91E-03
9.5	0.20	2232.9	23.6	5.1	2413.6	1.14E-03
9.6	0.50	2758.4	21.8	12.6	3005.5	1.39E-03
9.6	1.00	3208.2	19.8	25.3	3502.5	1.45E-03
9.6	2.00	3690.9	18.6	50.6	4027.7	1.44E-03
9.6	5.00	4388.3	18.9	126.1	4749.8	1.18E-03
9.6	9.98	4914.7	19.7	250.0	5303.4	1.09E-03
9.7	15.16	5233.4	20.0	369.0	5619.4	9.55E-04
9.9	0.01	1038.9	28.1	0.2	942.3	1.80E-03
9.6	0.02	1259.0	25.9	0.5	1228.4	1.15E-04
9.7	0.05	1598.3	23.2	1.2	1619.4	3.24E-05
9.8	0.10	1932.6	20.9	2.4	1964.4	5.03E-05
9.8	0.20	2443.8	23.4	4.7	2354.5	2.61E-04
10.0	0.50	3033.8	21.7	11.1	2914.0	3.06E-04
10.0	1.00	3530.1	19.8	22.1	3402.0	2.58E-04
10.1	2.00	4073.9	18.5	42.5	3893.5	3.87E-04
10.2	4.99	4788.2	18.9	103.4	4591.3	3.33E-04

Fitting Parameters	δ	α	β	γ	C1	C2
	0.346	3.773	-1.109	-0.433	37.477	288.853
Temperature (°C)	Frequency (Hz)	Modulus (Mpa)	Phase Angle (°)	Reduced Frequency (Hz)	Modeled Modulus (MPa)	Square of Errors
10.2	9.99	5403.3	19.7	205.0	5142.5	4.62E-04
10.2	15.16	5756.0	19.7	309.2	5475.9	4.69E-04
19.8	0.01	308.7	30.7	0.0	293.5	4.80E-04
20.3	0.02	383.0	31.0	0.0	365.2	4.30E-04
20.2	0.05	556.4	33.5	0.0	532.4	3.67E-04
19.8	0.10	706.6	33.1	0.1	718.5	5.21E-05
19.9	0.20	938.6	32.6	0.2	906.6	2.26E-04
20.0	0.50	1267.6	30.6	0.5	1226.2	2.08E-04
20.0	1.00	1581.7	29.3	1.0	1528.9	2.17E-04
20.0	2.00	1952.1	28.9	2.0	1873.1	3.22E-04
20.0	5.00	2494.5	26.8	5.0	2402.3	2.68E-04
20.0	9.98	2949.0	27.5	10.1	2851.2	2.15E-04
20.0	15.14	3194.3	28.4	15.3	3138.6	5.84E-05
30.1	0.01	85.1	32.4	0.0	88.4	2.74E-04
29.7	0.02	115.5	#N/A	0.0	121.8	5.19E-04
30.1	0.05	166.5	43.8	0.0	168.8	3.63E-05
30.0	0.10	219.3	36.4	0.0	227.2	2.34E-04
29.9	0.20	301.2	38.9	0.0	305.1	3.11E-05
29.7	0.50	455.6	34.5	0.0	445.4	9.56E-05
30.2	1.00	579.5	36.8	0.1	553.5	3.96E-04
30.3	2.00	760.0	34.6	0.1	707.1	9.83E-04
30.3	5.00	1036.5	35.4	0.3	980.1	5.90E-04
30.2	9.99	1287.7	36.6	0.5	1244.1	2.24E-04
30.2	15.15	1414.9	38.5	0.8	1426.7	1.30E-05

Note: Mix ID format = Type (Plant or Lab)-Mix # (NMAS, RAP %/ID, Binder Grade).

Table B.14: Flexural Modulus Test Results for Plant-MixD (3/4", 10% 1/2" RAP #1, 64-16)

Fitting Parameters	δ	α	β	γ	C1	C2
	0.339	3.822	-1.152	-0.431	116.534	847.022
Temperature (°C)	Frequency (Hz)	Modulus (Mpa)	Phase Angle (°)	Reduced Frequency (Hz)	Modeled Modulus (MPa)	Square of Errors
29.7	0.01	81.3	#N/A	0.0	96.4	5.45E-03
30.0	0.02	106.4	#N/A	0.0	123.6	4.22E-03
30.0	0.05	154.0	40.6	0.0	180.4	4.74E-03
29.8	0.10	205.8	42.4	0.0	245.0	5.73E-03
30.0	0.20	283.3	40.1	0.0	318.0	2.51E-03
29.8	0.50	406.4	39.2	0.0	470.4	4.04E-03
30.0	1.00	537.3	37.9	0.0	599.3	2.25E-03
30.0	1.99	708.1	38.2	0.1	777.6	1.65E-03
29.9	5.01	970.2	36.3	0.2	1086.6	2.42E-03
29.8	10.01	1226.5	38.5	0.5	1375.6	2.48E-03
29.7	15.16	1358.0	40.0	0.7	1593.1	4.81E-03
20.0	0.01	295.2	41.1	0.0	334.3	2.92E-03
20.0	0.02	386.9	36.9	0.0	440.8	3.21E-03
19.7	0.05	510.9	31.1	0.1	656.0	1.18E-02
20.3	0.10	707.6	36.4	0.1	784.0	1.98E-03
20.6	0.20	891.4	33.1	0.2	970.2	1.35E-03
20.6	0.50	1224.7	30.0	0.4	1332.0	1.33E-03
20.4	1.00	1552.0	28.7	0.9	1678.5	1.16E-03
20.4	1.99	1878.8	29.4	1.7	2059.5	1.59E-03
20.4	5.00	2431.0	27.2	4.4	2643.6	1.33E-03
20.4	10.00	2888.6	27.2	8.9	3149.6	1.41E-03
20.3	15.16	3139.1	28.1	13.9	3487.8	2.09E-03
9.6	0.01	1055.9	29.6	0.3	1171.0	2.02E-03
9.9	0.02	1265.4	25.2	0.5	1426.4	2.70E-03
10.0	0.05	1641.1	24.6	1.2	1864.9	3.08E-03
9.6	0.10	1980.4	20.7	2.8	2354.7	5.65E-03
9.4	0.20	2529.4	24.2	6.0	2861.7	2.87E-03
9.4	0.50	3153.9	21.1	15.1	3553.9	2.69E-03
9.4	1.00	3663.9	20.2	29.8	4101.3	2.40E-03
9.4	1.99	4241.8	19.6	59.3	4684.3	1.86E-03
9.4	5.00	5001.7	18.5	148.2	5487.0	1.62E-03
9.5	10.00	5626.2	19.0	294.8	6098.7	1.23E-03
9.5	15.16	5969.8	20.0	447.1	6468.8	1.22E-03
30.0	0.01	105.7	43.8	0.0	93.7	2.76E-03
30.0	0.02	123.4	39.8	0.0	123.5	1.12E-07
30.0	0.05	190.1	44.0	0.0	179.6	6.12E-04

Fitting Parameters	δ	α	β	γ	C1	C2
	0.339	3.822	-1.152	-0.431	116.534	847.022
Temperature (°C)	Frequency (Hz)	Modulus (Mpa)	Phase Angle (°)	Reduced Frequency (Hz)	Modeled Modulus (MPa)	Square of Errors
29.6	0.10	232.5	36.8	0.0	251.6	1.18E-03
29.4	0.20	335.2	37.3	0.0	340.4	4.48E-05
29.7	0.50	465.1	37.4	0.0	476.3	1.08E-04
29.8	1.00	625.6	36.1	0.0	610.7	1.11E-04
30.0	1.99	811.2	37.3	0.1	777.1	3.47E-04
30.1	5.00	1109.5	35.0	0.2	1066.1	3.00E-04
30.2	10.01	1383.5	37.0	0.4	1329.2	3.02E-04
30.3	15.15	1533.7	38.5	0.6	1498.9	9.94E-05
20.1	0.01	360.6	32.7	0.0	332.9	1.21E-03
19.8	0.02	458.5	32.5	0.0	455.7	7.08E-06
20.1	0.05	650.4	32.7	0.0	625.1	2.99E-04
20.4	0.10	788.0	31.8	0.1	774.4	5.78E-05
20.3	0.20	1052.5	30.6	0.2	1004.4	4.12E-04
20.1	0.50	1414.3	29.0	0.5	1392.5	4.57E-05
20.0	1.00	1764.6	27.7	1.0	1741.7	3.21E-05
19.8	2.00	2130.6	26.7	2.1	2180.6	1.01E-04
19.6	5.00	2708.6	25.7	5.6	2813.8	2.74E-04
19.6	10.00	3210.5	26.3	11.3	3327.0	2.40E-04
19.6	15.16	3479.8	26.9	17.1	3648.4	4.22E-04
9.9	0.01	1226.2	28.7	0.3	1136.4	1.09E-03
9.7	0.02	1476.9	25.8	0.5	1449.7	6.51E-05
9.6	0.05	1893.6	23.7	1.4	1944.9	1.35E-04
9.7	0.10	2269.8	21.9	2.7	2334.8	1.50E-04
9.7	0.20	2836.9	22.7	5.4	2790.2	5.19E-05
9.7	0.50	3498.8	20.7	13.7	3473.0	1.04E-05
9.6	1.00	4053.4	19.6	28.0	4048.4	2.95E-07
9.6	1.99	4644.4	18.8	55.5	4627.2	2.62E-06
9.7	5.00	5460.8	17.6	134.5	5401.3	2.27E-05
9.8	10.00	6098.3	18.6	263.0	5997.2	5.27E-05
9.8	15.15	6453.6	19.5	399.3	6368.4	3.33E-05
29.9	0.01	102.7	38.6	0.0	94.4	1.34E-03
30.1	0.02	138.7	41.7	0.0	121.9	3.12E-03
30.0	0.05	211.9	39.9	0.0	179.9	5.04E-03
29.5	0.10	286.6	45.2	0.0	255.2	2.54E-03
29.4	0.20	361.6	40.0	0.0	344.0	4.69E-04
29.5	0.50	535.6	39.5	0.0	483.4	1.98E-03
29.7	1.00	716.3	39.2	0.0	621.3	3.82E-03
29.6	1.99	923.2	38.9	0.1	809.5	3.26E-03

Fitting Parameters	δ	α	β	γ	C1	C2
	0.339	3.822	-1.152	-0.431	116.534	847.022
Temperature (°C)	Frequency (Hz)	Modulus (Mpa)	Phase Angle (°)	Reduced Frequency (Hz)	Modeled Modulus (MPa)	Square of Errors
29.7	5.00	1277.9	36.7	0.2	1108.2	3.83E-03
29.8	10.03	1607.1	37.9	0.5	1374.6	4.61E-03
29.8	15.16	1773.9	38.2	0.7	1566.7	2.91E-03
19.9	0.01	378.6	36.9	0.0	337.6	2.48E-03
20.4	0.02	489.0	37.7	0.0	418.1	4.63E-03
20.0	0.05	718.6	38.7	0.1	629.9	3.28E-03
19.9	0.10	875.0	31.2	0.1	823.5	6.94E-04
19.7	0.20	1166.3	33.1	0.2	1079.9	1.12E-03
19.5	0.50	1586.6	29.9	0.6	1481.0	8.94E-04
19.6	1.00	1965.0	29.2	1.1	1811.3	1.25E-03
19.6	2.00	2403.3	27.0	2.2	2207.3	1.36E-03
19.7	5.00	3062.1	25.8	5.6	2809.7	1.40E-03
19.8	9.99	3602.5	26.0	10.7	3287.9	1.57E-03
19.8	15.14	3919.1	27.3	16.2	3605.1	1.32E-03
9.7	0.01	1351.0	28.3	0.3	1161.7	4.30E-03
9.8	0.02	1619.1	26.2	0.5	1433.5	2.80E-03
9.6	0.05	2069.2	23.1	1.4	1936.1	8.33E-04
9.7	0.10	2482.6	21.2	2.7	2328.2	7.77E-04
9.9	0.20	3106.9	22.9	5.0	2740.1	2.98E-03
9.9	0.50	3841.7	20.9	12.7	3416.9	2.59E-03
9.9	1.00	4417.5	19.4	25.3	3966.1	2.19E-03
9.9	2.00	5049.6	17.6	50.8	4550.9	2.04E-03
9.9	5.00	5946.9	17.7	127.7	5355.5	2.07E-03
9.9	9.99	6623.3	18.5	251.0	5955.5	2.13E-03
9.9	15.15	6992.4	19.2	385.9	6338.1	1.82E-03

Note: Mix ID format = Type (Plant or Lab)-Mix # (NMAS, RAP %/ID, Binder Grade).

Table B.15: Flexural Modulus Test Results for Lab-Mix10B (1/2", 0% RAP, 64-16)

Fitting Parameters	δ	α	β	γ	C1	C2
	0.964	3.213	-1.011	-0.391	1366.473	9113.279
Temperature (°C)	Frequency (Hz)	Modulus (Mpa)	Phase Angle (°)	Reduced Frequency (Hz)	Modeled Modulus (MPa)	Square of Errors
9.8	0.01	1602.3	21.6	0.3	1583.9	2.52E-05
20.0	0.01	542.4	27.6	0.0	563.0	2.61E-04
30.5	0.01	170.4	30.7	0.0	184.2	1.16E-03
9.7	0.02	1873.7	20.2	0.7	1907.4	6.01E-05
20.0	0.02	646.3	27.3	0.0	699.4	1.18E-03
30.4	0.02	201.6	26.5	0.0	229.6	3.20E-03
9.8	0.05	2272.9	18.3	1.7	2376.1	3.72E-04
20.3	0.05	855.4	25.3	0.0	895.3	3.93E-04
30.6	0.05	273.3	24.8	0.0	296.7	1.27E-03
9.8	0.10	2633.5	16.5	3.4	2776.9	5.30E-04
19.7	0.10	1075.8	24.5	0.1	1163.1	1.15E-03
9.8	0.20	3187.4	19.0	6.7	3211.2	1.04E-05
19.5	0.20	1349.2	26.7	0.2	1437.8	7.63E-04
29.9	0.20	445.4	32.3	0.0	498.1	2.36E-03
9.6	0.50	3806.5	18.1	18.1	3904.6	1.22E-04
19.8	0.50	1737.6	25.5	0.5	1784.9	1.36E-04
30.0	0.50	602.0	30.3	0.0	654.6	1.32E-03
9.7	1.00	4313.0	17.2	35.6	4411.0	9.53E-05
30.0	1.00	757.1	30.1	0.0	808.8	8.23E-04
19.7	1.00	2081.3	23.8	1.1	2136.9	1.31E-04
9.6	1.99	4877.4	16.7	72.3	4963.6	5.79E-05
19.6	2.00	2465.2	24.0	2.3	2530.0	1.27E-04
30.0	2.00	934.7	30.5	0.1	988.6	5.94E-04
19.7	4.99	3031.0	23.2	5.6	3087.0	6.32E-05
30.0	4.99	1234.0	30.9	0.2	1284.8	3.07E-04
9.6	5.00	5660.0	16.6	181.7	5706.0	1.24E-05
29.9	9.99	1485.6	33.5	0.3	1568.6	5.57E-04
9.6	10.00	6274.7	17.6	367.1	6281.4	2.10E-07
19.7	10.05	3504.5	24.9	11.1	3551.0	3.27E-05
19.7	15.16	3795.1	24.9	16.9	3852.2	4.21E-05
9.6	15.16	6623.5	18.6	558.3	6625.1	1.14E-08
29.9	15.16	1617.9	34.3	0.5	1749.1	1.15E-03
9.8	0.01	1569.2	21.7	0.3	1584.5	1.76E-05
19.9	0.01	554.2	28.6	0.0	569.4	1.37E-04
30.4	0.01	191.6	35.4	0.0	185.7	1.84E-04
9.8	0.02	1833.5	19.8	0.7	1885.2	1.46E-04

Fitting Parameters	δ	α	β	γ	C1	C2
	0.964	3.213	-1.011	-0.391	1366.473	9113.279
Temperature (°C)	Frequency (Hz)	Modulus (Mpa)	Phase Angle (°)	Reduced Frequency (Hz)	Modeled Modulus (MPa)	Square of Errors
20.0	0.02	679.4	27.3	0.0	696.5	1.16E-04
30.4	0.02	228.3	29.9	0.0	228.0	3.76E-07
9.8	0.05	2239.8	18.0	1.7	2361.2	5.26E-04
19.9	0.05	876.5	23.9	0.1	931.5	6.98E-04
30.0	0.05	304.1	32.6	0.0	318.2	3.86E-04
9.8	0.10	2578.2	17.0	3.4	2777.1	1.04E-03
20.3	0.10	1063.3	23.1	0.1	1091.1	1.26E-04
29.7	0.10	391.9	33.1	0.0	408.5	3.23E-04
9.7	0.20	3127.7	18.8	7.0	3236.8	2.22E-04
20.3	0.20	1372.0	26.0	0.2	1335.2	1.40E-04
29.7	0.20	503.1	32.5	0.0	508.2	1.88E-05
9.7	0.50	3726.2	17.6	17.8	3892.2	3.58E-04
20.2	0.50	1754.0	24.3	0.5	1711.3	1.15E-04
29.8	0.50	661.0	30.6	0.0	666.0	1.06E-05
9.7	1.00	4207.1	17.0	34.6	4387.7	3.33E-04
20.1	1.00	2084.9	23.3	1.0	2060.0	2.73E-05
29.7	1.00	814.5	29.8	0.0	826.8	4.24E-05
9.8	1.99	4764.6	17.3	68.6	4922.1	1.99E-04
20.2	2.00	2463.4	22.6	1.9	2427.0	4.18E-05
29.7	2.00	1010.8	29.1	0.1	1016.1	5.23E-06
29.7	5.00	1331.2	30.5	0.2	1322.7	7.64E-06
20.1	5.00	3023.2	23.2	4.8	2985.2	3.00E-05
9.8	5.01	5507.6	16.8	169.3	5648.1	1.20E-04
29.5	10.00	1598.4	32.2	0.4	1620.8	3.66E-05
20.1	10.00	3491.6	23.6	9.6	3449.3	2.80E-05
9.9	10.00	6121.4	17.5	331.0	6196.6	2.81E-05
29.5	15.15	1737.2	34.0	0.6	1805.3	2.78E-04
9.8	15.16	6478.3	18.7	512.0	6554.1	2.56E-05
20.1	15.17	3758.1	24.4	14.4	3739.7	4.58E-06
9.8	0.01	1722.6	21.8	0.3	1582.9	1.35E-03
19.9	0.01	620.5	29.3	0.0	569.1	1.41E-03
30.4	0.01	205.4	36.8	0.0	184.3	2.22E-03
9.8	0.02	2015.4	19.5	0.7	1888.7	7.95E-04
19.9	0.02	741.4	26.2	0.0	710.4	3.45E-04
30.5	0.02	244.6	29.1	0.0	227.7	9.73E-04
9.7	0.05	2436.5	18.0	1.8	2394.9	5.61E-05
20.2	0.05	938.2	24.2	0.0	907.5	2.09E-04
30.2	0.05	335.5	26.0	0.0	310.3	1.15E-03

Fitting Parameters	δ	α	β	γ	C1	C2
	0.964	3.213	-1.011	-0.391	1366.473	9113.279
Temperature (°C)	Frequency (Hz)	Modulus (Mpa)	Phase Angle (°)	Reduced Frequency (Hz)	Modeled Modulus (MPa)	Square of Errors
9.7	0.10	2808.3	16.4	3.5	2790.8	7.44E-06
20.5	0.10	1173.0	28.0	0.1	1075.1	1.43E-03
30.4	0.10	419.0	29.5	0.0	377.6	2.05E-03
9.9	0.20	3364.6	19.0	6.6	3203.6	4.54E-04
20.7	0.20	1444.5	26.4	0.2	1277.9	2.83E-03
30.1	0.20	529.1	30.8	0.0	485.9	1.37E-03
20.4	0.50	1835.6	25.0	0.4	1683.5	1.41E-03
9.7	0.50	4014.9	17.6	17.3	3870.7	2.52E-04
30.0	0.50	701.7	29.4	0.0	654.7	9.08E-04
9.7	1.00	4539.0	17.0	35.3	4404.7	1.70E-04
20.1	1.00	2158.9	23.5	1.0	2060.9	4.07E-04
29.9	1.00	879.0	30.4	0.0	811.7	1.20E-03
9.6	1.99	5097.8	16.6	72.2	4962.5	1.36E-04
20.0	1.99	2534.0	23.2	2.0	2461.1	1.61E-04
30.0	2.00	1085.2	28.7	0.1	992.0	1.52E-03
9.6	5.00	5899.8	16.6	180.7	5701.5	2.20E-04
20.0	5.00	3100.4	22.9	5.0	3023.2	1.20E-04
29.9	5.00	1402.6	30.3	0.2	1299.8	1.09E-03
29.9	9.99	1679.4	31.7	0.3	1563.0	9.74E-04
9.6	10.00	6538.3	17.2	361.1	6267.9	3.37E-04
20.0	10.00	3597.9	23.3	10.1	3488.9	1.79E-04
29.9	15.15	1835.3	33.1	0.5	1741.6	5.18E-04
9.6	15.16	6893.1	18.4	553.6	6618.2	3.13E-04
19.9	15.16	3866.2	24.3	15.8	3803.3	5.07E-05

Note: Mix ID format = Type (Plant or Lab)-Mix # (NMAS, RAP %/ID, Binder Grade).

Table B.16: Flexural Modulus Test Results for Lab-Mix02B (1/2", 10% 1/2" RAP #1, 64-16)

Fitting Parameters	δ	α	β	γ	C1	C2
	0.699	3.552	-1.216	-0.361	309.781	2050.893
Temperature (°C)	Frequency (Hz)	Modulus (Mpa)	Phase Angle (°)	Reduced Frequency (Hz)	Modeled Modulus (MPa)	Square of Errors
10.1	0.01	2257.1	19.5	0.3	2103.0	9.43E-04
20.0	0.01	853.2	26.7	0.0	804.3	6.58E-04
30.3	0.01	291.9	32.7	0.0	262.9	2.07E-03
10.0	0.02	2539.8	17.5	0.7	2502.4	4.14E-05
20.1	0.02	1009.9	25.9	0.0	976.4	2.15E-04
30.3	0.02	361.3	27.8	0.0	328.4	1.72E-03
10.0	0.05	2997.6	16.2	1.6	3072.4	1.15E-04
20.1	0.05	1340.4	27.1	0.0	1281.0	3.87E-04
30.3	0.05	469.0	27.5	0.0	439.5	7.93E-04
9.9	0.10	3419.3	13.6	3.4	3572.9	3.64E-04
20.0	0.10	1529.4	21.9	0.1	1553.2	4.51E-05
29.7	0.10	566.1	27.2	0.0	580.8	1.23E-04
10.0	0.20	4070.1	17.2	6.6	4074.5	2.21E-07
20.0	0.20	1944.5	24.5	0.2	1861.9	3.56E-04
29.8	0.20	763.6	30.7	0.0	717.6	7.27E-04
20.1	0.50	2422.4	23.0	0.5	2317.9	3.67E-04
9.9	0.50	4755.7	15.5	17.0	4831.6	4.73E-05
29.7	0.50	995.4	29.1	0.0	955.2	3.20E-04
9.8	1.00	5320.6	15.1	35.4	5454.4	1.16E-04
20.1	1.00	2854.0	21.7	1.0	2730.4	3.70E-04
29.6	1.00	1218.0	29.2	0.0	1168.4	3.26E-04
9.8	1.99	5891.8	14.5	70.7	6063.3	1.55E-04
20.1	1.99	3334.4	20.7	1.9	3169.4	4.86E-04
29.6	2.00	1497.5	27.8	0.1	1421.2	5.15E-04
20.1	5.00	4008.6	20.8	4.8	3829.0	3.96E-04
9.8	5.00	6712.4	14.9	175.7	6882.6	1.18E-04
29.6	5.00	1918.2	27.9	0.2	1810.5	6.30E-04
9.8	10.00	7374.2	15.9	354.1	7520.3	7.25E-05
29.7	10.00	2278.7	28.7	0.4	2150.9	6.28E-04
20.1	10.01	4585.5	21.5	9.6	4367.3	4.48E-04
29.7	15.16	2488.0	29.9	0.5	2371.6	4.33E-04
20.1	15.16	4883.9	22.1	14.5	4701.5	2.73E-04
9.7	15.29	7793.7	17.5	551.3	7922.9	5.10E-05
10.1	0.01	2317.6	19.5	0.3	2096.6	1.89E-03
20.0	0.01	843.1	26.6	0.0	806.5	3.72E-04
30.3	0.01	291.9	32.5	0.0	261.8	2.23E-03

Fitting Parameters	δ	α	β	γ	C1	C2
	0.699	3.552	-1.216	-0.361	309.781	2050.893
Temperature (°C)	Frequency (Hz)	Modulus (Mpa)	Phase Angle (°)	Reduced Frequency (Hz)	Modeled Modulus (MPa)	Square of Errors
9.9	0.02	2636.8	17.9	0.7	2514.1	4.28E-04
19.9	0.02	1003.2	24.3	0.0	1005.6	1.06E-06
30.3	0.02	362.1	34.8	0.0	326.9	1.97E-03
10.7	0.05	3147.2	16.1	1.3	2920.7	1.05E-03
19.9	0.05	1307.0	26.5	0.1	1294.1	1.84E-05
30.0	0.05	482.0	33.5	0.0	455.3	6.13E-04
10.3	0.10	3605.3	14.1	2.9	3470.3	2.75E-04
20.5	0.10	1524.1	20.7	0.1	1491.7	8.67E-05
30.0	0.10	557.2	28.9	0.0	565.4	3.98E-05
10.0	0.20	4338.7	16.9	6.7	4078.5	7.21E-04
20.6	0.20	1930.4	24.3	0.2	1771.8	1.39E-03
29.8	0.20	732.9	31.0	0.0	714.4	1.24E-04
20.3	0.50	2430.4	23.1	0.4	2277.1	8.00E-04
9.7	0.50	5073.3	15.4	18.2	4889.8	2.56E-04
29.8	0.50	961.3	29.5	0.0	941.9	7.84E-05
9.6	1.00	5673.4	14.5	37.2	5497.1	1.88E-04
20.0	1.00	2854.6	22.3	1.0	2745.7	2.85E-04
29.7	1.00	1165.9	28.6	0.0	1159.1	6.38E-06
9.6	1.99	6292.0	14.8	75.4	6120.3	1.44E-04
19.9	2.00	3325.9	21.4	2.0	3214.7	2.18E-04
29.8	2.00	1431.8	27.8	0.1	1397.3	1.12E-04
20.0	5.00	4030.1	20.9	5.0	3862.4	3.41E-04
9.6	5.00	7153.3	14.6	190.6	6956.2	1.47E-04
29.8	5.01	1848.7	28.6	0.2	1790.7	1.91E-04
29.8	10.00	2201.8	29.4	0.3	2131.6	1.98E-04
19.9	10.00	4607.1	21.7	10.2	4417.1	3.35E-04
9.6	10.00	7854.0	15.7	384.0	7594.2	2.13E-04
9.6	15.15	8246.2	17.0	582.4	7972.8	2.14E-04
19.9	15.16	4927.3	22.8	15.7	4767.2	2.06E-04
29.7	15.16	2393.9	30.6	0.5	2373.7	1.36E-05
10.1	0.01	2008.0	20.4	0.3	2099.6	3.75E-04
20.2	0.01	748.4	28.4	0.0	791.9	6.03E-04
30.4	0.01	242.3	27.8	0.0	258.9	8.24E-04
10.2	0.02	2327.1	17.4	0.6	2468.0	6.52E-04
19.8	0.02	891.5	24.5	0.0	1007.9	2.84E-03
30.2	0.02	304.2	35.3	0.0	330.8	1.33E-03
10.1	0.05	2801.4	17.0	1.6	3054.0	1.41E-03
19.8	0.05	1128.8	23.0	0.1	1307.1	4.06E-03

Fitting Parameters	δ	α	β	γ	C1	C2
	0.699	3.552	-1.216	-0.361	309.781	2050.893
Temperature (°C)	Frequency (Hz)	Modulus (Mpa)	Phase Angle (°)	Reduced Frequency (Hz)	Modeled Modulus (MPa)	Square of Errors
29.9	0.05	382.2	30.4	0.0	457.0	6.02E-03
10.1	0.10	3237.1	15.3	3.2	3526.3	1.38E-03
20.1	0.10	1354.9	22.9	0.1	1545.7	3.28E-03
29.9	0.10	491.9	26.7	0.0	571.0	4.19E-03
10.0	0.20	3882.8	18.1	6.6	4068.2	4.10E-04
20.5	0.20	1738.7	24.8	0.2	1786.9	1.41E-04
29.8	0.20	632.5	30.8	0.0	713.8	2.76E-03
29.8	0.50	848.7	30.4	0.0	939.7	1.96E-03
10.0	0.50	4578.1	17.0	16.5	4808.8	4.56E-04
20.6	0.50	2205.6	23.9	0.4	2227.4	1.82E-05
9.9	1.00	5153.3	15.3	33.5	5406.1	4.33E-04
20.6	1.00	2602.4	22.4	0.8	2625.2	1.44E-05
29.7	1.00	1043.7	29.7	0.0	1164.6	2.27E-03
9.9	1.99	5745.2	15.9	68.2	6031.2	4.45E-04
20.5	2.00	3044.0	21.8	1.7	3089.0	4.05E-05
29.7	2.00	1288.3	28.8	0.1	1405.2	1.42E-03
9.9	5.00	6564.3	15.2	171.7	6861.4	3.69E-04
20.4	5.00	3697.8	22.1	4.3	3748.4	3.48E-05
29.7	5.00	1669.9	29.1	0.2	1801.6	1.09E-03
29.8	10.00	1991.9	29.8	0.3	2134.4	9.00E-04
20.5	10.00	4236.4	22.7	8.5	4270.1	1.19E-05
9.9	10.00	7211.6	16.2	345.4	7497.5	2.85E-04
29.7	15.15	2183.8	32.3	0.5	2369.4	1.25E-03
9.8	15.15	7552.0	17.2	533.4	7892.9	3.68E-04
20.5	15.16	4552.1	23.1	12.7	4589.9	1.29E-05

Note: Mix ID format = Type (Plant or Lab)-Mix # (NMAS, RAP %/ID, Binder Grade).

Table B.17: Flexural Modulus Test Results for Lab-Mix04 (1/2", 10% 1/2" RAP #2, 64-16)

Fitting Parameters	δ	α	β	γ	C1	C2
	0.025	4.304	-1.329	-0.317	34.436	230.644
Temperature (°C)	Frequency (Hz)	Modulus (Mpa)	Phase Angle (°)	Reduced Frequency (Hz)	Modeled Modulus (MPa)	Square of Errors
10.0	0.01	2233.5	20.3	0.4	2117.0	5.41E-04
19.9	0.01	815.0	28.5	0.0	795.1	1.15E-04
29.9	0.01	277.2	32.8	0.0	274.5	1.73E-05
9.8	0.02	2556.3	17.9	0.8	2535.6	1.25E-05
20.0	0.02	967.2	25.4	0.0	970.5	2.27E-06
30.0	0.02	346.3	32.4	0.0	344.5	5.53E-06
9.8	0.05	3041.7	16.4	1.9	3098.9	6.55E-05
20.2	0.05	1225.1	24.7	0.0	1229.9	2.85E-06
30.0	0.05	440.4	31.4	0.0	463.7	5.01E-04
9.9	0.10	3468.3	14.6	3.8	3566.3	1.46E-04
20.2	0.10	1460.2	22.1	0.1	1500.0	1.37E-04
29.5	0.10	543.7	29.5	0.0	609.5	2.46E-03
10.1	0.20	4150.7	17.4	7.1	4039.4	1.39E-04
19.9	0.20	1860.4	24.3	0.2	1836.4	3.20E-05
29.7	0.20	710.2	29.9	0.0	744.1	4.09E-04
10.0	0.50	4869.3	15.9	18.3	4795.6	4.39E-05
29.7	0.50	937.8	31.4	0.0	977.7	3.28E-04
19.6	0.50	2324.2	23.3	0.6	2355.6	3.38E-05
10.0	1.00	5459.3	15.0	35.8	5375.0	4.57E-05
19.6	1.00	2729.9	22.3	1.1	2756.3	1.75E-05
29.7	1.00	1160.7	29.0	0.0	1189.0	1.09E-04
19.8	1.99	3185.9	21.6	2.2	3175.0	2.22E-06
9.9	2.00	6056.0	14.9	76.6	6057.9	1.90E-08
29.7	2.00	1419.7	28.9	0.1	1442.2	4.65E-05
19.9	4.99	3847.0	21.5	5.1	3786.0	4.81E-05
29.7	5.00	1824.2	29.0	0.2	1833.8	5.14E-06
9.9	5.00	6908.7	14.9	191.5	6915.2	1.68E-07
29.7	9.99	2176.1	30.2	0.4	2175.0	4.81E-08
19.9	10.00	4397.8	22.0	10.4	4331.7	4.32E-05
9.9	10.00	7583.9	15.9	380.9	7575.7	2.19E-07
9.8	15.15	7938.7	17.2	595.0	8009.1	1.47E-05
29.7	15.16	2375.9	31.0	0.6	2405.3	2.87E-05
19.8	15.16	4695.3	22.8	16.0	4686.6	6.51E-07
9.8	0.01	2265.9	20.1	0.4	2147.9	5.39E-04
19.9	0.01	798.3	28.2	0.0	795.8	1.89E-06
30.1	0.01	275.6	34.8	0.0	270.4	6.87E-05

Fitting Parameters	δ	α	β	γ	C1	C2
	0.025	4.304	-1.329	-0.317	34.436	230.644
Temperature (°C)	Frequency (Hz)	Modulus (Mpa)	Phase Angle (°)	Reduced Frequency (Hz)	Modeled Modulus (MPa)	Square of Errors
9.8	0.02	2607.8	18.5	0.8	2532.8	1.61E-04
19.9	0.02	981.6	29.0	0.0	980.1	3.99E-07
30.1	0.02	339.9	30.0	0.0	342.3	9.23E-06
9.8	0.05	3100.2	16.8	1.9	3103.2	1.70E-07
19.9	0.05	1214.5	23.4	0.1	1272.8	4.14E-04
30.0	0.05	446.1	29.1	0.0	466.0	3.60E-04
9.9	0.10	3559.5	15.1	3.8	3574.1	3.18E-06
20.4	0.10	1468.8	24.9	0.1	1470.2	1.77E-07
29.5	0.10	560.8	31.1	0.0	607.2	1.19E-03
9.9	0.20	4255.3	17.6	7.4	4069.0	3.78E-04
20.1	0.20	1836.3	25.4	0.2	1805.7	5.30E-05
29.6	0.20	722.6	30.7	0.0	747.5	2.18E-04
9.8	0.50	4986.5	16.2	19.3	4843.6	1.59E-04
19.9	0.50	2336.3	23.9	0.5	2300.7	4.47E-05
29.6	0.50	983.5	30.8	0.0	984.4	1.57E-07
9.8	1.00	5590.4	15.2	39.0	5449.8	1.22E-04
19.9	1.00	2757.7	22.8	1.0	2704.1	7.26E-05
29.6	1.00	1188.7	29.5	0.0	1200.9	1.96E-05
9.7	2.00	6212.1	15.4	80.6	6104.7	5.73E-05
19.9	2.00	3239.3	22.0	2.1	3155.6	1.29E-04
29.7	2.00	1456.2	28.5	0.1	1442.1	1.77E-05
9.8	5.00	7109.7	15.1	193.3	6924.1	1.32E-04
19.8	5.00	3914.3	22.1	5.4	3822.8	1.06E-04
29.7	5.00	1873.6	28.4	0.2	1832.5	9.29E-05
29.6	9.98	2235.3	29.7	0.4	2195.6	6.05E-05
19.8	10.00	4483.8	22.3	10.7	4361.0	1.45E-04
9.9	10.00	7803.8	16.5	383.9	7583.2	1.55E-04
29.5	15.15	2439.8	31.3	0.6	2428.1	4.33E-06
9.8	15.16	8209.7	17.4	588.0	7997.6	1.29E-04
19.8	15.16	4798.4	23.1	16.3	4702.8	7.63E-05
10.0	0.01	2214.6	20.1	0.4	2112.6	4.20E-04
20.0	0.01	806.4	23.5	0.0	790.4	7.59E-05
29.9	0.01	302.0	32.4	0.0	277.2	1.38E-03
10.0	0.02	2506.6	17.7	0.7	2501.1	9.04E-07
20.0	0.02	943.4	27.7	0.0	965.8	1.04E-04
30.4	0.02	354.4	28.5	0.0	330.0	9.63E-04
9.9	0.05	2950.0	16.0	1.9	3083.5	3.69E-04
20.1	0.05	1185.0	24.3	0.0	1250.3	5.44E-04

Fitting Parameters	δ	α	β	γ	C1	C2
	0.025	4.304	-1.329	-0.317	34.436	230.644
Temperature (°C)	Frequency (Hz)	Modulus (Mpa)	Phase Angle (°)	Reduced Frequency (Hz)	Modeled Modulus (MPa)	Square of Errors
29.6	0.05	472.4	32.0	0.0	483.7	1.05E-04
10.0	0.10	3355.7	14.7	3.6	3540.1	5.39E-04
20.0	0.10	1428.3	23.0	0.1	1523.3	7.83E-04
29.6	0.10	593.6	26.5	0.0	602.1	3.74E-05
10.0	0.20	3989.3	17.4	7.2	4045.5	3.69E-05
20.1	0.20	1791.3	24.8	0.2	1813.5	2.88E-05
29.6	0.20	770.2	29.4	0.0	744.9	2.10E-04
10.0	0.50	4656.2	15.8	18.3	4798.2	1.70E-04
20.0	0.50	2253.4	22.7	0.5	2276.1	1.90E-05
29.6	0.50	1005.5	28.5	0.0	980.5	1.20E-04
10.0	1.00	5211.1	15.5	36.5	5390.5	2.16E-04
20.0	1.00	2635.3	22.8	1.0	2682.6	5.97E-05
29.6	1.00	1248.1	28.3	0.0	1195.5	3.49E-04
10.0	1.99	5802.2	15.0	71.9	5999.6	2.11E-04
20.0	1.99	3085.5	21.8	2.0	3114.9	1.70E-05
29.6	2.00	1525.6	27.4	0.1	1454.5	4.30E-04
29.6	4.99	1942.1	27.3	0.2	1849.8	4.47E-04
20.0	5.00	3739.5	21.3	5.1	3780.5	2.25E-05
10.0	5.00	6632.0	15.3	180.7	6859.8	2.15E-04
29.5	9.99	2319.8	28.4	0.4	2216.5	3.92E-04
19.9	10.00	4275.6	22.4	10.3	4324.0	2.39E-05
10.0	10.00	7315.0	16.1	368.6	7544.0	1.79E-04
9.9	15.16	7662.6	17.3	567.8	7963.6	2.80E-04
29.4	15.16	2507.9	29.3	0.7	2448.0	1.10E-04
19.9	15.16	4569.2	22.8	15.7	4672.1	9.35E-05

Note: Mix ID format = Type (Plant or Lab)-Mix # (NMAS, RAP %/ID, Binder Grade).

Table B.18: Flexural Modulus Test Results for Lab-Mix11 (1/2", 0% RAP, 70-10)

Fitting Parameters	δ	α	β	γ	C1	C2
	0.728	3.470	-1.487	-0.446	93.633	617.324
Temperature (°C)	Frequency (Hz)	Modulus (Mpa)	Phase Angle (°)	Reduced Frequency (Hz)	Modeled Modulus (MPa)	Square of Errors
9.5	0.01	2914.9	20.5	0.4	2904.1	2.58E-06
19.7	0.01	929.3	30.8	0.0	954.0	1.29E-04
30.4	0.01	228.8	43.1	0.0	239.7	4.14E-04
9.6	0.02	3362.0	17.9	0.8	3427.1	6.94E-05
19.7	0.02	1122.0	28.5	0.0	1208.0	1.03E-03
30.2	0.02	304.8	39.5	0.0	319.0	3.95E-04
9.5	0.05	3978.5	15.3	2.1	4248.8	8.15E-04
19.7	0.05	1472.7	25.7	0.1	1637.5	2.12E-03
29.6	0.05	428.8	38.1	0.0	491.0	3.47E-03
9.4	0.10	4535.0	13.9	4.3	4933.1	1.33E-03
19.8	0.10	1793.8	23.6	0.1	2004.9	2.33E-03
29.7	0.10	561.4	34.5	0.0	635.4	2.89E-03
9.6	0.20	5372.2	15.8	8.1	5542.5	1.84E-04
19.8	0.20	2311.3	25.8	0.2	2447.7	6.20E-04
29.7	0.20	751.3	34.8	0.0	815.7	1.27E-03
9.5	0.50	6199.4	14.2	20.5	6454.9	3.08E-04
19.8	0.50	2936.7	24.0	0.5	3120.3	6.94E-04
29.8	0.50	1064.8	34.1	0.0	1109.5	3.19E-04
9.6	1.00	6874.7	13.2	40.5	7127.8	2.46E-04
30.0	1.00	1336.6	32.5	0.0	1373.9	1.43E-04
19.8	1.00	3472.1	22.1	1.1	3675.2	6.10E-04
9.7	1.99	7551.1	13.0	78.1	7770.6	1.55E-04
19.8	2.00	4024.8	21.0	2.2	4284.6	7.38E-04
30.0	2.00	1671.9	30.9	0.1	1715.6	1.26E-04
30.0	4.98	2203.2	30.2	0.2	2257.4	1.11E-04
9.6	5.00	8417.8	13.0	202.4	8675.9	1.72E-04
19.8	5.00	4841.5	20.0	5.3	5129.1	6.28E-04
29.7	10.00	2654.2	30.1	0.4	2795.7	5.08E-04
9.6	10.00	9132.7	13.9	407.0	9310.6	7.02E-05
19.9	10.00	5497.8	20.6	10.5	5788.5	5.01E-04
9.6	15.15	9502.4	15.3	615.5	9671.8	5.89E-05
30.3	15.16	2917.6	30.9	0.4	2964.3	4.76E-05
19.9	15.16	5854.4	20.7	15.6	6183.1	5.63E-04
9.7	0.01	2997.6	20.4	0.4	2872.0	3.45E-04
19.8	0.01	939.8	30.4	0.0	948.9	1.78E-05
30.3	0.01	242.4	41.0	0.0	243.9	7.08E-06

Fitting Parameters	δ	α	β	γ	C1	C2
	0.728	3.470	-1.487	-0.446	93.633	617.324
Temperature (°C)	Frequency (Hz)	Modulus (Mpa)	Phase Angle (°)	Reduced Frequency (Hz)	Modeled Modulus (MPa)	Square of Errors
9.6	0.02	3423.6	17.6	0.8	3441.6	5.23E-06
19.8	0.02	1156.3	28.8	0.0	1203.9	3.07E-04
30.3	0.02	334.2	36.5	0.0	315.0	6.58E-04
9.6	0.05	4053.6	14.7	2.0	4219.5	3.04E-04
19.9	0.05	1520.6	26.6	0.1	1609.0	6.03E-04
29.8	0.05	502.9	40.9	0.0	482.6	3.19E-04
9.7	0.10	4634.4	13.6	3.9	4828.5	3.17E-04
20.0	0.10	1841.9	24.0	0.1	1964.3	7.81E-04
30.0	0.10	618.9	32.0	0.0	610.3	3.65E-05
9.6	0.20	5464.2	15.7	7.9	5517.5	1.78E-05
20.0	0.20	2392.9	26.3	0.2	2406.2	5.81E-06
30.0	0.20	833.7	36.2	0.0	786.6	6.39E-04
9.7	0.50	6376.1	13.9	19.4	6399.7	2.58E-06
19.9	0.50	3030.0	24.3	0.5	3071.4	3.47E-05
29.9	0.50	1146.1	33.2	0.0	1104.5	2.58E-04
9.7	1.00	6940.3	13.3	38.8	7085.7	8.12E-05
29.7	1.00	1451.6	33.1	0.0	1412.0	1.44E-04
19.9	1.00	3585.9	22.2	1.0	3634.5	3.41E-05
9.7	1.99	7627.6	12.9	78.6	7776.6	7.05E-05
19.9	1.99	4192.8	21.2	2.1	4255.4	4.14E-05
29.7	2.00	1812.9	30.7	0.1	1767.1	1.23E-04
29.7	4.99	2381.4	29.5	0.2	2314.5	1.53E-04
19.8	5.00	5042.7	20.0	5.3	5134.3	6.12E-05
9.7	5.00	8533.7	12.8	192.9	8631.3	2.44E-05
29.7	10.00	2872.2	29.9	0.4	2800.4	1.21E-04
9.7	10.00	9269.9	14.2	381.3	9252.8	6.43E-07
19.8	10.01	5719.3	20.3	10.8	5818.8	5.61E-05
9.7	15.15	9667.3	15.2	583.7	9626.2	3.43E-06
19.7	15.16	6113.5	21.0	16.6	6242.3	8.20E-05
29.7	15.16	3166.3	30.3	0.5	3109.9	6.09E-05
9.9	0.01	3172.3	20.5	0.4	2809.4	2.78E-03
19.8	0.01	1006.5	32.1	0.0	942.2	8.23E-04
30.4	0.01	257.3	37.1	0.0	239.1	1.01E-03
9.9	0.02	3667.2	18.2	0.7	3340.3	1.64E-03
19.8	0.02	1214.4	30.3	0.0	1194.4	5.22E-05
30.2	0.02	339.6	35.9	0.0	322.3	5.20E-04
9.9	0.05	4341.6	15.4	1.8	4115.7	5.39E-04
20.1	0.05	1595.2	26.9	0.0	1567.9	5.61E-05

Fitting Parameters	δ	α	β	γ	C1	C2
	0.728	3.470	-1.487	-0.446	93.633	617.324
Temperature (°C)	Frequency (Hz)	Modulus (Mpa)	Phase Angle (°)	Reduced Frequency (Hz)	Modeled Modulus (MPa)	Square of Errors
29.8	0.05	474.2	36.4	0.0	481.2	4.07E-05
9.9	0.10	4956.2	13.6	3.6	4765.9	2.89E-04
20.1	0.10	1953.4	25.0	0.1	1945.5	3.09E-06
30.0	0.10	629.6	31.3	0.0	609.4	2.01E-04
9.9	0.20	5833.1	15.6	7.2	5423.0	1.00E-03
20.0	0.20	2519.9	26.3	0.2	2388.3	5.43E-04
29.9	0.20	865.4	35.8	0.0	797.7	1.25E-03
9.8	0.50	6753.1	13.9	19.0	6377.7	6.17E-04
19.9	0.50	3181.8	23.4	0.5	3076.0	2.16E-04
29.9	0.50	1183.3	32.6	0.0	1102.0	9.55E-04
9.8	1.00	7420.1	13.0	37.9	7062.7	4.60E-04
19.8	1.00	3747.6	22.0	1.1	3675.9	7.05E-05
29.9	1.00	1504.0	31.7	0.0	1381.9	1.35E-03
9.7	1.99	8154.0	12.8	76.8	7754.1	4.77E-04
19.7	1.99	4353.1	20.6	2.2	4320.3	1.08E-05
29.9	2.00	1863.7	30.4	0.1	1734.7	9.70E-04
19.6	5.00	5227.2	19.7	5.7	5197.8	5.99E-06
29.9	5.00	2451.0	29.1	0.2	2284.3	9.35E-04
9.8	5.00	9095.7	12.7	189.8	8616.0	5.54E-04
29.8	10.00	2945.9	29.1	0.3	2764.8	7.59E-04
9.8	10.00	9811.0	13.6	370.0	9225.7	7.14E-04
19.6	10.01	5906.8	19.8	11.5	5878.4	4.38E-06
29.8	15.15	3239.8	30.2	0.5	3076.4	5.05E-04
9.8	15.15	10205.5	14.8	577.2	9616.5	6.66E-04
19.7	15.16	6277.4	20.5	16.9	6262.2	1.12E-06

Note: Mix ID format = Type (Plant or Lab)-Mix # (NMAS, RAP %/ID, Binder Grade).

Table B.19: Flexural Modulus Test Results for Lab-Mix03 (1/2", 10% 1/2" RAP #1, 70-10)

Fitting Parameters	δ	α	β	γ	C1	C2
	0.494	3.713	-1.586	-0.428	12269.566	82053.598
Temperature (°C)	Frequency (Hz)	Modulus (Mpa)	Phase Angle (°)	Reduced Frequency (Hz)	Modeled Modulus (MPa)	Square of Errors
10.0	0.01	2933.3	21.4	0.3	2854.7	1.39E-04
20.1	0.01	979.8	30.1	0.0	990.2	2.10E-05
30.5	0.01	268.0	34.2	0.0	253.3	6.00E-04
10.0	0.02	3390.7	18.5	0.6	3395.8	4.23E-07
20.1	0.02	1204.3	28.1	0.0	1244.2	2.00E-04
30.4	0.02	347.2	36.6	0.0	337.1	1.63E-04
9.9	0.05	4011.3	14.7	1.6	4177.9	3.13E-04
20.3	0.05	1586.5	26.1	0.0	1636.5	1.82E-04
30.9	0.05	506.1	35.2	0.0	452.6	2.35E-03
9.8	0.10	4577.0	14.2	3.3	4840.6	5.91E-04
20.4	0.10	1938.2	23.2	0.1	2010.6	2.54E-04
30.4	0.10	672.8	32.2	0.0	626.6	9.56E-04
9.8	0.20	5441.8	16.0	6.7	5501.8	2.27E-05
20.5	0.20	2499.5	25.8	0.2	2416.9	2.13E-04
30.3	0.20	940.3	35.2	0.0	824.3	3.27E-03
20.3	0.50	3172.4	23.1	0.4	3119.4	5.35E-05
9.8	0.50	6302.2	14.2	17.0	6408.3	5.26E-05
29.9	0.50	1291.8	32.6	0.0	1179.5	1.56E-03
9.7	1.00	6981.2	13.9	34.5	7103.4	5.67E-05
20.1	1.00	3719.6	21.8	1.0	3734.9	3.17E-06
29.8	1.00	1613.9	30.9	0.0	1502.0	9.74E-04
20.0	1.99	4335.2	21.0	2.0	4371.7	1.33E-05
9.9	2.00	7651.2	13.3	65.3	7724.1	1.70E-05
29.5	2.00	2030.6	29.5	0.1	1918.5	6.08E-04
29.5	5.00	2640.4	28.5	0.2	2489.5	6.53E-04
9.9	5.00	8588.0	13.2	163.7	8596.5	1.86E-07
19.9	5.00	5181.5	19.9	5.1	5244.0	2.71E-05
9.7	10.00	9301.8	14.2	343.7	9272.9	1.83E-06
29.7	10.00	3159.1	28.7	0.4	2950.2	8.83E-04
19.8	10.01	5863.7	20.0	10.7	5957.8	4.78E-05
9.6	15.15	9714.2	15.3	543.2	9674.2	3.21E-06
29.7	15.16	3451.5	28.9	0.5	3261.5	6.05E-04
19.8	15.17	6253.4	20.7	16.3	6368.4	6.27E-05
9.8	0.01	2856.1	21.1	0.3	2894.2	3.31E-05
20.1	0.01	951.7	31.7	0.0	988.6	2.74E-04
30.4	0.01	234.8	#N/A	0.0	256.3	1.45E-03

Fitting Parameters	δ	α	β	γ	C1	C2
	0.494	3.713	-1.586	-0.428	12269.566	82053.598
Temperature (°C)	Frequency (Hz)	Modulus (Mpa)	Phase Angle (°)	Reduced Frequency (Hz)	Modeled Modulus (MPa)	Square of Errors
9.9	0.02	3308.7	18.5	0.7	3416.8	1.95E-04
20.1	0.02	1189.1	27.3	0.0	1248.5	4.49E-04
30.6	0.02	322.1	36.3	0.0	329.0	8.41E-05
9.8	0.05	3961.1	15.8	1.7	4224.3	7.81E-04
20.2	0.05	1534.2	28.1	0.0	1665.5	1.27E-03
30.4	0.05	455.5	33.2	0.0	482.3	6.16E-04
9.8	0.10	4519.7	14.1	3.3	4832.3	8.43E-04
20.4	0.10	1926.3	24.1	0.1	2005.6	3.07E-04
29.9	0.10	614.5	36.2	0.0	671.9	1.51E-03
9.9	0.20	5325.8	15.9	6.5	5474.0	1.42E-04
20.2	0.20	2420.5	25.0	0.2	2490.7	1.54E-04
29.7	0.20	806.4	35.5	0.0	882.5	1.53E-03
20.1	0.50	3058.3	23.1	0.5	3176.4	2.71E-04
9.9	0.50	6171.5	14.3	16.2	6362.7	1.76E-04
29.8	0.50	1112.1	32.9	0.0	1196.3	1.01E-03
9.8	1.00	6845.4	13.6	33.5	7073.7	2.03E-04
20.2	1.00	3587.6	21.2	0.9	3711.1	2.16E-04
29.8	1.00	1408.3	32.1	0.0	1503.0	7.99E-04
20.4	1.99	4186.6	20.2	1.7	4247.5	3.93E-05
9.8	2.00	7500.8	13.2	66.7	7743.9	1.92E-04
29.8	2.00	1762.8	30.7	0.1	1864.2	5.91E-04
29.7	4.99	2294.6	30.0	0.2	2447.0	7.79E-04
20.4	5.00	4974.7	19.8	4.3	5086.3	9.28E-05
9.8	5.00	8403.0	12.8	165.8	8608.6	1.10E-04
29.7	9.99	2776.4	29.8	0.4	2936.9	5.96E-04
9.8	10.00	9078.0	13.7	331.0	9239.2	5.85E-05
20.4	10.00	5621.3	19.9	8.7	5753.0	1.01E-04
9.8	15.15	9435.6	15.0	508.0	9616.3	6.79E-05
29.7	15.16	3037.0	30.0	0.5	3263.5	9.76E-04
20.3	15.16	5989.5	20.4	13.8	6202.9	2.31E-04
9.8	0.01	3184.5	20.2	0.3	2889.6	1.78E-03
20.2	0.01	1077.3	31.8	0.0	977.7	1.77E-03
9.9	0.02	3644.6	17.2	0.7	3415.5	7.95E-04
19.9	0.02	1317.2	27.5	0.0	1282.7	1.33E-04
30.6	0.02	334.9	34.9	0.0	326.9	1.11E-04
9.8	0.05	4303.8	15.0	1.7	4212.1	8.76E-05
20.0	0.05	1701.8	26.2	0.0	1694.0	3.96E-06
30.4	0.05	475.3	34.0	0.0	483.7	5.86E-05

Fitting Parameters	δ	α	β	γ	C1	C2
	0.494	3.713	-1.586	-0.428	12269.566	82053.598
Temperature (°C)	Frequency (Hz)	Modulus (Mpa)	Phase Angle (°)	Reduced Frequency (Hz)	Modeled Modulus (MPa)	Square of Errors
9.9	0.10	4904.7	13.5	3.3	4818.2	5.97E-05
20.5	0.10	2085.9	22.5	0.1	1992.2	3.99E-04
29.9	0.10	628.6	31.8	0.0	671.0	8.03E-04
9.8	0.20	5751.1	15.4	6.7	5497.2	3.85E-04
20.6	0.20	2657.3	25.3	0.2	2400.0	1.96E-03
29.7	0.20	872.8	35.1	0.0	885.9	4.15E-05
9.8	0.50	6627.9	13.8	17.0	6410.4	2.10E-04
20.6	0.50	3324.8	22.4	0.4	3053.5	1.37E-03
29.7	0.50	1204.4	32.5	0.0	1219.2	2.84E-05
9.8	1.00	7334.4	13.0	33.2	7066.3	2.62E-04
20.4	1.00	3898.3	21.0	0.9	3645.0	8.52E-04
29.7	1.00	1518.3	30.9	0.0	1524.4	3.07E-06
20.3	2.00	4520.4	19.9	1.8	4277.4	5.76E-04
9.9	2.00	7987.8	12.5	65.0	7719.7	2.20E-04
29.6	2.00	1891.4	29.7	0.1	1895.5	8.78E-07
9.9	5.00	8929.7	12.0	163.5	8595.3	2.75E-04
20.3	5.00	5367.3	18.9	4.6	5136.0	3.66E-04
29.7	5.00	2449.6	29.4	0.2	2462.4	5.16E-06
9.8	9.99	9579.8	13.3	331.4	9240.3	2.45E-04
29.7	10.00	2946.5	28.8	0.4	2951.6	5.71E-07
20.2	10.00	6034.8	19.2	9.2	5809.3	2.74E-04
9.9	15.15	9900.3	14.4	491.5	9587.6	1.94E-04
29.7	15.16	3223.1	29.5	0.5	3270.5	4.02E-05
20.1	15.16	6388.8	19.9	14.5	6255.1	8.44E-05

Note: Mix ID format = Type (Plant or Lab)-Mix # (NMAS, RAP %/ID, Binder Grade).

Table B.20: Flexural Modulus Test Results for Lab-Mix05 (1/2", 10% 1/2" RAP #2, 70-10)

Fitting Parameters	δ	α	β	γ	C1	C2
	0.967	3.212	-1.643	-0.478	31950.501	211314.997
Temperature (°C)	Frequency (Hz)	Modulus (Mpa)	Phase Angle (°)	Reduced Frequency (Hz)	Modeled Modulus (MPa)	Square of Errors
9.9	0.01	3821.1	18.5	0.3	3578.8	8.10E-04
20.4	0.01	1304.3	30.0	0.0	1216.2	9.22E-04
30.4	0.01	317.7	#N/A	0.0	331.2	3.26E-04
9.9	0.02	4369.4	15.5	0.7	4188.1	3.39E-04
20.0	0.02	1671.9	31.2	0.0	1595.0	4.18E-04
30.5	0.02	406.5	36.4	0.0	428.4	5.21E-04
9.8	0.05	5076.1	13.1	1.8	5095.1	2.62E-06
20.7	0.05	2205.5	27.5	0.0	1984.8	2.10E-03
30.4	0.05	609.7	36.6	0.0	613.9	8.69E-06
9.8	0.10	5730.5	11.4	3.5	5792.7	2.19E-05
19.9	0.10	2551.0	20.8	0.1	2633.8	1.93E-04
29.5	0.10	784.3	34.1	0.0	886.3	2.82E-03
9.9	0.20	6663.4	14.0	6.8	6459.2	1.83E-04
19.8	0.20	3258.2	23.3	0.2	3175.6	1.24E-04
29.7	0.20	1061.4	33.8	0.0	1119.1	5.27E-04
20.3	0.50	4031.0	20.9	0.4	3815.9	5.67E-04
29.7	0.50	1460.8	33.0	0.0	1517.1	2.70E-04
9.8	0.50	7574.4	12.2	17.5	7398.0	1.05E-04
9.8	1.00	8292.5	11.5	34.9	8072.5	1.36E-04
20.6	1.00	4688.9	18.9	0.8	4355.1	1.03E-03
29.7	1.00	1834.7	30.3	0.0	1894.1	1.92E-04
20.7	2.00	5350.2	18.1	1.6	4976.6	9.88E-04
9.7	2.00	8946.8	11.3	71.7	8750.5	9.28E-05
29.7	2.00	2252.8	28.8	0.1	2344.9	3.02E-04
20.7	5.00	6266.0	17.2	3.9	5879.4	7.65E-04
9.8	5.00	9847.4	10.9	176.9	9551.2	1.76E-04
29.5	5.01	2922.6	28.1	0.2	3055.9	3.75E-04
9.8	10.00	10519.9	12.1	353.6	10122.3	2.80E-04
29.6	10.00	3480.6	27.3	0.4	3616.7	2.77E-04
20.7	10.00	6961.1	17.6	7.7	6578.2	6.04E-04
9.7	15.15	10811.8	13.6	546.0	10459.8	2.07E-04
20.7	15.15	7378.8	18.4	11.7	7000.6	5.22E-04
29.5	15.17	3798.2	27.6	0.6	3999.4	5.02E-04
9.8	0.01	3524.6	19.2	0.3	3589.9	6.36E-05
20.3	0.01	1248.2	30.2	0.0	1231.3	3.51E-05
30.4	0.01	330.1	38.3	0.0	330.9	1.06E-06

Fitting Parameters	δ	α	β	γ	C1	C2
	0.967	3.212	-1.643	-0.478	31950.501	211314.997
Temperature (°C)	Frequency (Hz)	Modulus (Mpa)	Phase Angle (°)	Reduced Frequency (Hz)	Modeled Modulus (MPa)	Square of Errors
9.8	0.02	3956.1	15.9	0.7	4202.3	6.87E-04
19.9	0.02	1563.7	27.9	0.0	1625.7	2.85E-04
30.6	0.02	439.7	38.1	0.0	422.3	3.06E-04
9.7	0.05	4576.8	13.9	1.8	5113.9	2.32E-03
20.1	0.05	1998.5	22.7	0.0	2116.1	6.17E-04
30.6	0.05	635.1	32.4	0.0	601.2	5.67E-04
9.9	0.10	5178.1	11.6	3.3	5736.1	1.98E-03
20.4	0.10	2489.7	21.7	0.1	2492.2	1.98E-07
29.7	0.10	837.6	35.7	0.0	869.4	2.62E-04
9.9	0.20	6069.5	14.4	6.7	6434.2	6.42E-04
20.6	0.20	3129.9	23.8	0.2	2966.5	5.42E-04
29.6	0.20	1147.4	33.4	0.0	1127.3	5.92E-05
20.4	0.50	3925.1	21.2	0.4	3775.8	2.84E-04
29.7	0.50	1582.2	31.2	0.0	1521.1	2.92E-04
9.9	0.50	6894.4	12.6	16.7	7350.0	7.72E-04
9.8	1.00	7564.2	11.7	34.9	8074.9	8.05E-04
20.3	1.00	4540.2	19.3	0.9	4444.7	8.52E-05
29.6	1.00	1961.0	28.7	0.0	1909.1	1.36E-04
20.3	1.99	5197.6	18.4	1.8	5122.8	3.96E-05
29.7	1.99	2395.7	28.1	0.1	2340.6	1.02E-04
9.9	2.00	8171.8	11.5	68.3	8706.7	7.58E-04
29.7	4.98	3087.8	26.1	0.2	3013.7	1.11E-04
9.9	5.00	9029.7	11.6	169.4	9514.3	5.16E-04
20.3	5.00	6099.0	17.4	4.5	6046.5	1.41E-05
9.9	9.99	9721.8	12.7	341.8	10095.3	2.68E-04
29.7	10.00	3640.8	26.3	0.3	3588.4	3.96E-05
20.3	10.01	6781.8	17.7	9.1	6750.1	4.14E-06
9.8	15.15	10036.6	14.0	520.1	10422.9	2.69E-04
20.2	15.16	7128.1	18.5	13.9	7173.0	7.44E-06
29.7	15.16	3958.3	26.5	0.5	3948.9	1.07E-06
9.9	0.01	3752.7	19.2	0.3	3575.8	4.39E-04
20.0	0.01	1251.9	30.7	0.0	1262.4	1.32E-05
30.4	0.01	341.4	42.1	0.0	331.0	1.83E-04
9.7	0.02	4265.6	15.8	0.7	4237.3	8.34E-06
20.2	0.02	1536.0	25.8	0.0	1571.6	9.92E-05
30.6	0.02	430.3	35.3	0.0	422.7	6.06E-05
9.8	0.05	4951.2	12.9	1.8	5099.5	1.64E-04
20.1	0.05	1987.2	23.8	0.0	2116.1	7.45E-04

Fitting Parameters	δ	α	β	γ	C1	C2
	0.967	3.212	-1.643	-0.478	31950.501	211314.997
Temperature (°C)	Frequency (Hz)	Modulus (Mpa)	Phase Angle (°)	Reduced Frequency (Hz)	Modeled Modulus (MPa)	Square of Errors
30.7	0.05	617.2	36.7	0.0	592.2	3.22E-04
9.9	0.10	5634.6	11.8	3.3	5736.8	6.09E-05
20.0	0.10	2558.3	25.9	0.1	2608.0	6.98E-05
30.2	0.10	805.0	33.4	0.0	813.7	2.18E-05
10.0	0.20	6525.0	13.9	6.6	6417.7	5.18E-05
20.1	0.20	3097.3	24.0	0.2	3104.9	1.11E-06
29.7	0.20	1122.1	34.5	0.0	1115.4	6.72E-06
9.9	0.50	7444.5	12.5	16.7	7355.6	2.72E-05
20.1	0.50	3825.5	21.5	0.5	3882.2	4.08E-05
29.8	0.50	1532.0	32.3	0.0	1497.3	9.90E-05
9.9	1.00	8135.4	11.8	33.4	8030.6	3.17E-05
20.1	1.00	4458.0	20.1	1.0	4518.4	3.41E-05
29.7	1.00	1896.8	29.8	0.0	1890.9	1.86E-06
20.0	1.99	5076.4	19.0	2.0	5205.2	1.18E-04
9.9	2.00	8813.6	11.3	67.8	8699.4	3.21E-05
29.8	2.00	2334.7	28.4	0.1	2310.6	2.05E-05
9.9	5.00	9743.0	11.1	169.2	9513.4	1.07E-04
20.0	5.00	5978.7	17.4	5.0	6142.4	1.38E-04
29.8	5.01	3015.3	27.6	0.2	2981.9	2.33E-05
9.9	10.00	10412.3	12.3	337.8	10085.8	1.91E-04
29.8	10.00	3591.8	27.1	0.3	3551.2	2.44E-05
20.0	10.01	6669.3	18.1	9.9	6831.9	1.09E-04
9.9	15.15	10722.2	13.6	518.5	10420.5	1.54E-04
20.0	15.16	7065.9	19.0	15.0	7247.7	1.22E-04
29.7	15.16	3912.8	27.3	0.5	3937.8	7.66E-06

Note: Mix ID format = Type (Plant or Lab)-Mix # (NMAS, RAP %/ID, Binder Grade).

Table B.21: Repeated Load Triaxial Test Results (Unconfined)

Mix ID	Confining Stress (kPa)	Flow Number (cycles)	Perm. Axial Strain at Flow Number (%)	Total Cycles Applied (cycles)	Flow Number (Std Dev)	Perm. Axial Strain at Flow Number (Std Dev)	Flow Number (COV) ^a	Perm. Axial Strain at Flow Number (COV)
Plant-Mix A (1/2", 0% RAP, 64-16)	0	11,224	2.5	20,000	3,811	0.10	0.34	0.04
Plant-Mix B (3/4", 0% RAP, 64-16)	0	2,027	3.4	3,646	852	0.39	0.42	0.11
Plant-Mix C (1/2", 10% 1/2" RAP #1, 64-16)	0	1,203	2.9	2,674	320	0.39	0.27	0.14
Plant-Mix D (3/4", 10% 1/2" RAP #1, 64-16)	0	636	2.7	1,516	297	0.40	0.47	0.15
Lab-Mix10B (1/2", 0% RAP, 64-16)	0	13,155	1.17	20,000	5,547	0.56	0.42	0.48
Lab-Mix 02B (1/2", 10% 1/2" RAP #1, 64-16)	0	11,489	1.17	20,000	3,276	0.26	0.29	0.22
Lab-Mix 04 (1/2", 10% 1/2" RAP #2, 64-16)	0	16,182	1.32	20,000	4,227	0.22	0.26	0.17
Lab-Mix 11 (1/2", 0% RAP, 70-10)	0	13,483	1.28	20,000	6,580	0.54	0.49	0.42
Lab-Mix 03 (1/2", 10% 1/2" RAP #1, 70-10)	0	16,038	1.29	20,000	1,995	0.13	0.12	0.10
Lab-Mix 05 (1/2", 10% 1/2" RAP #2, 70-10)	0	13,936	1.23	20,000	2,629	0.24	0.19	0.20

^a COV: coefficient of variance

Notes: Mix ID format = Type (Plant or Lab)-Mix # (NMAS, RAP %/ID, Binder Grade); contact stress = 30 kPa (4.4 psi); deviator stress = 483 kPa (70 psi); test temperature = 50°C (122°F), unconfined

Table B.22: Repeated Load Triaxial Test Results (Confined)

Mix ID	Confining Stress (kPa)	Flow Number (cycles)	Perm. Axial Strain at Flow Number (%)	Total Cycles Applied (cycles)	Flow Number (Std Dev)	Perm. Axial Strain at Flow Number (Std Dev)	Flow Number (COV) ^a	Perm. Axial Strain at Flow Number (COV)
Plant-Mix A (1/2", 0% RAP, 64-16)	35	17,255	1.7	19,999	2,030	0.25	0.12	0.14
Plant-Mix B (3/4", 0% RAP, 64-16)	35	15,478	2.4	20,000	4,297	0.36	0.28	0.15
Plant-Mix C (1/2", 10% 1/2" RAP #1, 64-16)	35	11,718	2.6	15,520	6,793	0.60	0.58	0.23
Plant-Mix D (3/4", 10% 1/2" RAP #1, 64-16)	35	18,252	1.9	20,000	1,762	0.14	0.10	0.08
Lab-Mix 10B (1/2", 0% RAP, 64-16)	35	15,015	0.7	20,000	7,092	0.13	0.47	0.19
Lab-Mix 02B (1/2", 10% 1/2" RAP #1, 64-16)	35	13,930	0.8	20,000	4,871	0.13	0.35	0.17
Lab-Mix04 (1/2", 10% 1/2" RAP #2, 64-16)	35	9,799	0.6	20,000	6,084	0.13	0.62	0.21
Lab-Mix11 (1/2", 0% RAP, 70-10)	35	18,441	0.9	20,000	1,292	0.06	0.07	0.06
Lab-Mix 03 (1/2", 10% 1/2" RAP #1, 70-10)	35	17,687	0.8	20,000	1,583	0.23	0.09	0.30
Lab-Mix 05 (1/2", 10% 1/2" RAP #2, 70-10)	35	11,212	0.6	20,000	5,452	0.27	0.49	0.44

^a COV: coefficient of variance

Notes: Mix ID format = Type (Plant or Lab)-Mix # (NMAS, RAP %/ID, Binder Grade); Contact Stress = 30 kPa (4.4 psi); Deviator Stress = 483 kPa (70 psi); Test Temperature = 50°C (122°F); Confined = 35 kPa (5.1 psi).

Table B.23: Flexural Fatigue Beam Test Results: Initial Stiffness, E50

Mix ID	Initial Stiffness, E50		
	Avg (psi)	Std Dev (psi)	COV ^a (%)
Plant-Mix A (1/2", 0% RAP, 64-16)	440,144	86,710	20
Plant-Mix B (3/4", 0% RAP, 64-16)	404,075	43,892	11
Plant-Mix C (1/2", 10% 3/4" RAP, 64-16)	357,641	55,212	15
Plant-Mix D (3/4", 10% 3/4" RAP, 64-16)	382,839	47,651	12
Lab-Mix 10B (1/2", 0% RAP, 64-16)	398,313	29,133	7
Lab-Mix 02B (1/2", 10% 1/2" RAP #1, 64-16)	490,820	32,650	7
Lab-Mix 04 (1/2", 10% 1/2" RAP #2, 64-16)	520,966	35,739	7
Lab-Mix11 (1/2", 0% RAP, 70-10)	763,413	36,720	5
Lab-Mix 03 (1/2", 10% 1/2" RAP #1, 70-10)	736,947	36,438	5
Lab-Mix 05 (1/2", 10% 1/2" RAP #2, 70-10)	878,129	31,626	4

^a COV: coefficient of variance

Note: Mix ID format = Type (Plant or Lab)-Mix # (NMAS, RAP %/ID, Binder Grade).

Table B.24: Flexural Fatigue Beam Test Results, Wöhler Curve for Fitted Fatigue Life

Mix ID	Fitted Fatigue Life (Nf x SR)					
	Slope (#)	Intercept (#)	200 (μE)	400 (μE)	600 (μE)	800 (μE)
Plant-Mix A (1/2", 0% RAP, 64-16)	-6.34	1.22E+24	3,179,198,653	39,317,351	3,010,452	486,240
Plant-Mix B (3/4", 0% RAP, 64-16)	-7.38	2.87E+26	2,962,295,455	17,762,469	890,520	106,507
Plant-Mix C (1/2", 10% 3/4" RAP, 64-16)	-5.78	2.01E+22	1,018,626,195	18,558,787	1,782,492	338,131
Plant-Mix D (3/4", 10% 3/4" RAP, 64-16)	-7.60	1.74E+27	5,688,141,971	29,337,363	1,346,761	151,311
Lab-Mix 10B (1/2", 0% RAP, 64-16)	-5.52	3.91E+21	760,496,494	16,528,304	1,759,999	359,219
Lab-Mix 02B (1/2", 10% 1/2" RAP #1, 64-16)	-5.19	2.31E+20	262,708,397	7,194,651	877,055	197,036
Lab-Mix 04 (1/2", 10% 1/2" RAP #2, 64-16)	-7.30	3.62E+26	5,619,811,292	35,539,814	1,838,141	224,755
Lab-Mix 11 (1/2", 0% RAP, 70-10)	-7.82	1.37E+27	1,389,463,018	6,150,763	258,211	27,228
Lab-Mix 03 (1/2", 10% 1/2" RAP #1, 70-10)	-7.80	1.03E+27	1,166,716,839	5,241,791	221,967	23,550
Lab-Mix 05 (1/2", 10% 1/2" RAP #2, 70-10)	-7.62	1.64E+26	479,837,451	2,439,397	111,042	12,401

Note: Mix ID format = Type (Plant or Lab)-Mix # (NMAS, RAP %/ID, Binder Grade).

Table B.25: Flexural Fatigue Beam Test Results

Mix ID	E0 (MPa)	E50 (MPa)	Nf40 (#)	Nf50 (#)	NfnxSR (#)	Microstrain ($\mu\epsilon$)
Lab-Mix 02B (1/2", 10% 1/2" RAP #1, 64-16)	4095	3536	232053	42877	902500	650
	3728	3534	194279	70427	302500	757
	4258	3819	196854	86012	237500	620
	4096	3492	79588	20079	322500	750
	3926	3746	289256	116584	392500	659
	4002	3452	46781	13802	180000	850
	3689	3146	205663	50090	512500	750
	3662	3288	109682	29911	347500	750
	3352	3216	337923	141663	482500	659
	3455	3019	194811	49352	747500	750
	3872	3208	42990	12257	115000	850
	3952	3406	351111	62497	1265000	620
	3649	3130	475646	171787	622500	650
	4080	3432	51580	14151	117500	750
	4018	3337	28282	7851	66000	850
Lab-Mix 03 (1/2", 10% 1/2" RAP #1, 70-10)	5220	4804	124267	58877	147500	650
	5891	5410	108034	59434	107500	650
	5670	5346	232997	105659	282500	550
	5182	4718	96569	64299	87000	650
	5318	5134	718081	367674	897500	557
	5283	4956	203182	144975	172500	550
	5607	5356	1864771	1063451	1705000	450
	5274	5158	1889114	700568	2837500	450
	5223	4791	408166	222320	432500	550
	5196	4815	338261	177130	482500	550
	5447	5259	406631	140356	947500	550
	5563	5225	1733232	829775	1692500	450

Mix ID	E0 (MPa)	E50 (MPa)	Nf40 (#)	Nf50 (#)	NfnxSR (#)	Microstrain ($\mu\epsilon$)
Lab-Mix 04 (1/2", 10% 1/2" RAP #2, 64-16)	4019	3509	39369	11373	170000	850
	3966	3519	229641	52392	695000	700
	5426	4209	16324	1799	330000	850
	3908	3284	61440	21433	105000	850
	3855	3636	435875	114188	1225000	711
	4226	3749	304384	77121	627500	700
	4194	3805	1028426	270353	2432500	600
	3710	3384	1223293	330495	3515000	600
	3837	3643	234530	97229	257500	708
	4083	3546	89267	36261	162500	750
	4227	3777	367554	82005	1512500	700
	3706	3318	448768	150335	740000	600
	3732	3323	162330	58898	215000	750
	4080	3585	81874	25411	200000	750
Lab-Mix 05 (1/2", 10% 1/2" RAP #2, 70-10)	6309	5887	52524	29701	76000	650
	6350	5949	48127	24464	73000	650
	6706	6376	258346	115527	315000	550
	6598	6122	39405	26888	37000	650
	6558	5985	261044	108906	372500	550
	6360	6092	81027	49132	90000	550
	6526	6276	1558043	732770	1620000	450
	6510	6106	860407	368667	1162500	450
	6053	5741	189725	118276	192500	550
	6294	5942	437813	283588	410000	550
	6031	5667	150242	110026	137500	550
	6481	6255	1906686	1068969	1747500	450
	6573	6309	324281	248464	280000	450
Lab-Mix 10B (1/2", 0% RAP, 64-16)	3683	2859	13118	2822	140000	950
	3050	2448	73152	17617	862500	700

Mix ID	E0 (MPa)	E50 (MPa)	Nf40 (#)	Nf50 (#)	NfnxSR (#)	Microstrain (με)
	2911	2704	143455	46703	317500	858
	3292	2673	28579	6930	73000	950
	3567	3002	161945	29146	687500	700
	3494	3055	78736	21571	132500	850
	3115	2678	62360	15853	215000	950
	2909	2460	128957	32572	450000	850
	3444	2989	325180	90887	645000	700
	3251	2626	74339	19156	137500	850
	3333	2646	30703	5696	437500	850
	3454	2816	86133	16889	327500	850
Lab-Mix 11 (1/2", 0% RAP, 70-10)	6075	5688	284114	105475	432500	550
	5450	5178	34128	31828	48000	650
	5288	5028	65502	28699	102500	650
	5323	4890	104342	34150	500000	650
	6018	5717	216467	134364	187500	550
	5576	5304	248677	82408	622500	550
	5540	5387	4704390	1927933	5432500	450
	5636	5179	1035170	554471	1082500	450
	5713	5179	328295	101443	670000	550
	5954	5423	200335	85512	275000	550
	5554	5059	2482669	1220421	2580000	450
	5323	5130	732832	243507	1770000	557
Plant-Mix A (1/2",0% RAP, 64-16)	4265	3950	17650	4167	83000	899
	2790	2582	165503	53008	297500	913
	3848	3632	25953	6975	285000	900
	2516	2332	56220	21907	88000	1081
	3389	3431	17577	5217	157500	1049
	2594	2444	36437	17235	63000	1074
	3425	3031	595637	139922	1637500	650

Mix ID	E0 (MPa)	E50 (MPa)	Nf40 (#)	Nf50 (#)	NfnxSR (#)	Microstrain (με)
	3920	3576	205275	34668	1367500	650
	2976	2832	1143735	329256	3445000	659
	3474	3384	34876	11996	72000	899
	2627	2187	193091	53456	455000	900
Plant-Mix C (1/2", 10% 1/2" RAP #1, 64-16)	3152	2932	21508	5551	197500	900
	3091	3037	32094	9535	340000	900
	2997	2858	29150	8528	142500	899
	2591	2338	169223	49680	430000	700
	2770	2391	194854	46988	1565000	700
	2552	2241	202391	54845	1000000	700
	3232	2835	43138	9822	167500	800
	2249	2152	133117	60184	190000	819
	2030	1745	138672	39159	362500	800
	2305	2242	178792	67688	577500	818
	2446	2325	95215	44219	147500	808
	2917	2493	90226	26897	340000	800
Plant-Mix D (3/4", 10% 1/2" RAP #1, 64-16)	2681	2198	20352	6913	137500	850
	2866	2396	25439	8843	81000	850
	2742	2536	47865	18524	112500	858
	2722	2587	56042	28678	79000	709
	3332	2905	74665	23755	225000	700
	2384	2215	90947	29395	815000	702
	3697	3315	77582	21262	522500	600
	2941	2591	503050	112663	3907500	600
	2687	2617	527612	160772	1670000	615
	2866	2463	110411	32691	377500	700
	3289	2841	84929	25340	252500	700
	3375	3011	134536	33529	1320000	700
Plant-Mix B (3/4", 0% RAP, 64-16)	3959	3265	27804	8703	77000	900

Mix ID	E0 (MPa)	E50 (MPa)	Nf40 (#)	Nf50 (#)	NfnxSR (#)	Microstrain ($\mu\epsilon$)
	3188	2984	17281	6814	43000	899
	2984	2497	6926	4259	13000	899
	3297	2788	29511	12775	56000	750
	3232	2731	55767	17020	345000	750
	3318	2858	90234	25326	380000	750
	2636	2286	387198	98796	1277500	600
	3619	3216	124980	35694	1335000	600
	3064	2748	177483	83454	227500	600
	3665	3023	45499	12372	90000	750
	2932	2589	186993	42253	342500	750
	2838	2446	203295	55218	430000	750

Note: Mix ID format = Type (Plant or Lab)-Mix # (NMAS, RAP %/ID, Binder Grade).

Table B.26: Semicircular Bend Test Results, Flexibility Index and Peak Strength

Type	Mix ID	Flexibility Index	Standard Deviation	COV ^a (%)	Peak Strength (psi)	Standard Deviation	COV (%)
Plant	Mix A (1/2", 0% RAP, 64-16)	8.6	2.0	23	70.0	10.0	14
Plant	Mix B (3/4", 0% RAP, 64-16)	16.8	2.1	13	55.9	4.8	9
Plant	Mix C (1/2", 10% 1/2" RAP #1, 64-16)	14.0	3.2	23	60.3	5.3	9
Plant	Mix D (3/4", 10% 1/2" RAP #1, 64-16)	9.8	3.2	32	61.9	10.6	17
Lab	Mix 10B (1/2", 0% RAP, 64-16)	4.4	1.3	29	78.4	3.00	4
Lab	Mix 02B (1/2", 10% 1/2" RAP #1, 64-16)	3.5	1.3	39	91.8	3.90	4
Lab	Mix 04 (1/2", 10% 1/2" RAP #2, 64-16)	1.8	1.0	54	119.7	4.04	3
Lab	Mix 11 (1/2", 0% RAP, 70-10)	7.9	1.8	23	90.4	6.92	8
Lab	Mix 03 (1/2", 10% 1/2" RAP #1, 70-10)	4.0	1.7	44	80.6	6.72	8
Lab	Mix 05 (1/2", 10% 1/2" RAP #2, 70-10)	4.2	0.8	20	63.5	11.92	19

^a COV: coefficient of variance

Note: Mix ID format = Type (Plant or Lab)-Mix # (NMAS, RAP %/ID, Binder Grade).

Table B.27: Semicircular Bend Test Results, Fracture Energy and Post-Peak Slope

Type	Mix ID	Flexibility Index	Standard Deviation	COV ^a (%)	Peak Strength (psi)	Standard Deviation	COV (%)
Plant	Mix A (1/2", 0% RAP, 64-16)	2,425.9	207.1	9	-3.0	0.9	29
Plant	Mix C (1/2", 10% 3/4" RAP, 64-16)	2,503.5	268.9	16	-1.8	0.3	22
Plant	Mix B (3/4", 0% RAP, 64-16)	2,575.1	397.8	10	-1.6	0.4	19
Plant	Mix D (3/4", 10% 3/4" RAP, 64-16)	2,193.5	391.8	18	-2.5	1.1	44
Lab	Mix 10B (1/2", 0% RAP, 64-16)	2,334.0	95.9	4	-6.1	1.58	26
Lab	Mix 02B (1/2", 10% 3/4" RAP, 64-16)	2,509.6	174.2	7	-10.3	1.92	19
Lab	Mix 04 (1/2", 10% 1" RAP, 64-16)	2,565.5	193.0	8	-17.9	1.22	7
Lab	Mix 11 (1/2", 0% RAP, 70-10)	2,431.6	445.8	18	-3.3	2.85	86
Lab	Mix 03 (1/2", 10% 3/4" RAP, 70-10)	2,041.8	256.5	13	-5.4	7.14	132
Lab	Mix 05 (1/2", 10% 1" RAP, 70-10)	1,727.5	331.6	19	-4.6	9.94	216

^a COV: coefficient of variance

Note: Mix ID format = Type (Plant or Lab)-Mix # (NMA5, RAP %/ID, Binder Grade).

APPENDIX C STATISTICAL TESTING OF RHMA-G MIX TEST RESULTS

This section includes statistical testing of the stiffness and fatigue life of the RHMA-G mixes. The goal is to determine whether the difference in test results for different mixes are statistically significant. The data used are the initial stiffness (i.e., the stiffness at the 50th cycle, E50) from the fatigue life testing at one temperature (20°C) and one frequency (10 Hz) and not from the frequency sweeps, which are conducted at one strain level (100 microstrain) and ranges of temperature and frequency, and the fatigue life (Nf) determined using the peak nxSR criteria.

The procedure involved the following steps:

1. Develop linear regression models: $\ln(E50) = a + b \cdot \text{eps}$ and $\ln(Nf) = a + b \cdot \ln(\text{eps})$, where eps is the strain level and a and b are model parameters.
2. Select a strain level to evaluate E50 and Nf using the regression models.
3. Estimate the confidence interval for the predicted E50 and Nf.
4. Use the confidence interval to backcalculate the standard error (SE) of the predicted value, the predicted values follow Students' t-distribution.
5. Based on the predicted value, the SE, and the degrees of freedom (DF), conduct pairwise t-test for equivalency.

Note that the confidence interval is for the model prediction and not for the actual observations at the given strain level. The equation for the confidence interval is:

$$\hat{y} \pm t_{crit} \cdot SE$$

Where $\hat{y}$ is the model predictions, t_{crit} is the t-score for 95% confidence level, and

$$SE = S_{yx} \sqrt{\frac{1}{n} + \frac{(x - \bar{x})^2}{SS_x}}$$

Where S_{yx} is the standard estimate of the error, and S_x is the squared deviation of the x -values in the sample. Because the confidence intervals are typically provided by the regression software, SE can be backcalculated using the t-score for the given degree of freedom (DF), which is equal to the number of specimens minus 2 for linear regressions.

With the known SE, the pairwise statistic testing can be constructed by creating a new random variable as the difference between each pair of model predictions:

$$y_{diff} = \hat{y}_1 - \hat{y}_2$$

and testing whether y_{diff} is zero with a t-distribution. The SE for y_{diff} is calculated as the following:

$$SE_{y_{diff}} = \sqrt{SE_{\hat{y}_1}^2 + SE_{\hat{y}_2}^2}$$

The DF for y_{diff} is the sum of the DF of each regression model. The strain levels used are 400, 600 and 700 microstrain for both E50 and Nf.

The list of mixes is shown Table C.1, and these mixes are referenced in all the remaining tables in this section (Table C.2 to Table C.7).

Table C.1: List of Mixes Included in the Statistical Testing

Mix No.	Mix ID in OLTS	Mix Label in Report
1	GR-GG-0.5-V-FMLC	Plant-Mix A (1/2", 0% RAP, 64-16)
2	GR-GG-0.5-R-FMLC	Plant-Mix C (1/2", 10% 3/4" RAP, 64-16)
3	GR-GG-0.75-V-FMLC	Plant-Mix B (3/4", 0% RAP, 64-16)
4	GR-GG-0.75-R-FMLC	Plant-Mix D (3/4", 10% 3/4" RAP, 64-16)
5	CALR-MIX10B-LL	Lab-Mix 10B (1/2", 0% RAP, 64-16)
6	CALR-MIX2B-LL	Lab-Mix 02B (1/2", 10% 3/4" RAP, 64-16)
7	CALR-MIX4-LL	Lab-Mix 04 (1/2", 10% 1" RAP, 64-16)
8	CALR-MIX11-LL	Lab-Mix 11 (1/2", 0% RAP, 70-10)
9	CALR-MIX3-LL	Lab-Mix 03 (1/2", 10% 3/4" RAP, 70-10)
10	CALR-MIX5-LL	Lab-Mix 05 (1/2", 10% 1" RAP, 70-10)

Table C.2 to Table C.7 show the statistical test results for E50 and Nf at different strain levels. The tables show the model predictions, standard error (SE) in log space, and degrees of freedom (DF) for each model, along with the matrix of p-values of the pairwise t-tests. For each row, pX is the p-value of the t-test between the mix in the current row and the X-th mix in the list. Comparisons are shown within each binder group for the stiffnesses and both within each binder group and between the PG 64 and PG 70 binder groups for fatigue life. The values are that are marked indicate p-values are less than 0.05 (i.e., the difference is statistically significant at the 95% confidence level).

Table C.2: Pairwise Statistical Test Results for E50 at 400 Microstrain

Mix No.	ln_E50	Estimate E50 (MPa)	Estimate E50 (ksi)	SE	DF	p1	p2	p3	p4	p5	p6	p7	p8	p9	p10
1	8.18	3,559	516.1	0.398	9	1.000	0.201	0.488	0.864	—	—	—	—	—	—
2	7.36	1,565	226.9	0.476	10	0.201	1.000	0.354	0.176	—	—	—	—	—	—
3	7.85	2,578	373.8	0.223	10	0.488	0.354	1.000	0.457	—	—	—	—	—	—
4	8.10	3,285	476.3	0.229	10	0.864	0.176	0.457	1.000	—	—	—	—	—	—
5	7.96	2,874	416.7	0.220	10	—	—	—	—	1.000	0.367	0.483	0.012*	0.015*	0.002*
6	8.21	3,661	530.8	0.145	13	—	—	—	—	0.367	1.000	0.784	0.022*	0.030*	0.002*
7	8.15	3,462	502.0	0.141	13	—	—	—	—	0.483	0.784	1.000	0.009*	0.012*	0.000*
8	8.59	5,399	782.9	0.065	10	—	—	—	—	0.012*	0.015*	0.002*	1.000	0.821	0.072
9	8.57	5,286	766.5	0.065	10	—	—	—	—	0.022*	0.030*	0.002*	0.821	1.000	0.041*
10	8.74	6,245	905.5	0.041	11	—	—	—	—	0.009*	0.012*	0.000*	0.072	0.041*	1.000

Note: Values marked with an asterisk (*) indicate p-values <0.05.

Table C.3: Pairwise Statistical Test Results for E50 at 600 Microstrain

Mix No.	ln_E50	Estimate E50 (MPa)	Estimate E50 (ksi)	SE	DF	p1	p2	p3	p4	p5	p6	p7	p8	p9	p10
1	8.10	3,305	479.2	0.252	9	1.000	0.154	0.462	0.590	—	—	—	—	—	—
2	7.58	1,950	282.8	0.251	10	0.154	1.000	0.257	0.177	—	—	—	—	—	—
3	7.90	2,686	389.5	0.112	10	0.462	0.257	1.000	0.706	—	—	—	—	—	—
4	7.95	2,847	412.8	0.102	10	0.590	0.177	0.706	1.000	—	—	—	—	—	—
5	7.94	2,812	407.7	0.125	10	—	—	—	—	1.000	0.140	0.112	0.000*	0.000*	0.000*
6	8.16	3,485	505.3	0.064	13	—	—	—	—	0.140	1.000	0.862	0.000*	0.000*	0.000*
7	8.17	3,540	513.3	0.062	13	—	—	—	—	0.112	0.862	1.000	0.000*	0.000*	0.000*
8	8.56	5,213	755.9	0.034	10	—	—	—	—	0.000*	0.000*	0.000*	1.000	0.411	0.003*
9	8.52	5,008	726.2	0.034	10	—	—	—	—	0.000*	0.000*	0.000*	0.411	1.000	0.000*
10	8.70	5,974	866.2	0.024	11	—	—	—	—	0.000*	0.000*	0.000*	0.003*	0.000*	1.000

Note: Values marked with an asterisk (*) indicate p-values <0.05.

Table C.4: Pairwise Statistical Test Results for E50 at 700 Microstrain

Mix No.	ln_E50	Estimate E50 (MPa)	Estimate E50 (ksi)	SE	DF	p1	p2	p3	p4	p5	p6	p7	p8	p9	p10
1	8.07	3,185	461.8	0.187	9	1.000	0.125	0.465	0.364	—	—	—	—	—	—
2	7.69	2,176	315.5	0.146	10	0.125	1.000	0.170	0.229	—	—	—	—	—	—
3	7.92	2,742	397.6	0.072	10	0.465	0.170	1.000	0.723	—	—	—	—	—	—
4	7.88	2,650	384.3	0.063	10	0.364	0.229	0.723	1.000	—	—	—	—	—	—
5	7.93	2,781	403.2	0.081	10	—	—	—	—	1.000	0.033*	0.009*	0.000*	0.000*	0.000*
6	8.13	3,400	493.0	0.036	13	—	—	—	—	0.033*	1.000	0.315	0.000*	0.000*	0.000*
7	8.18	3,580	519.1	0.036	13	—	—	—	—	0.009*	0.315	1.000	0.000*	0.000*	0.000*
8	8.54	5,122	742.7	0.065	10	—	—	—	—	0.000*	0.000*	0.000*	1.000	0.593	0.108
9	8.49	4,874	706.7	0.064	10	—	—	—	—	0.000*	0.000*	0.000*	0.593	1.000	0.031*
10	8.67	5,843	847.2	0.044	11	—	—	—	—	0.000*	0.000*	0.000*	0.108	0.031*	1.000

Note: Values marked with an asterisk (*) indicate p-values <0.05.

Table C.5: Pairwise Statistical Test Results for Nf at 400 Microstrain

Mix No.	ln_Nf	Estimated Nf	SE	DF	p1	p2	p3	p4	p5	p6	p7	p8	p9	p10
1	17.5	39,317,351	1.74	9	1.000	0.811	0.786	0.922	—	—	—	—	—	—
2	16.7	18,558,787	2.56	10	0.811	1.000	0.990	0.897	—	—	—	—	—	—
3	16.7	17,762,469	2.30	10	0.786	0.990	1.000	0.881	—	—	—	—	—	—
4	17.2	29,337,363	2.37	10	0.922	0.897	0.881	1.000	—	—	—	—	—	—
5	16.6	16,528,304	1.83	10	—	—	—	—	1.000	0.746	0.764	0.664	0.570	0.353
6	15.8	7,194,651	1.75	13	—	—	—	—	0.746	1.000	0.526	0.943	0.870	0.583
7	17.4	35,936,637	1.78	13	—	—	—	—	0.764	0.526	1.000	0.431	0.332	0.184
8	15.6	6,150,763	1.30	10	—	—	—	—	0.664	0.943	0.431	1.000	0.917	0.555
9	15.5	5,241,791	0.77	10	—	—	—	—	0.570	0.870	0.332	0.917	1.000	0.509
10	14.7	2,439,397	0.84	11	—	—	—	—	0.353	0.583	0.184	0.555	0.509	1.000

Table C.6: Pairwise Statistical Test Results for Nf at 600 Microstrain

Mix No.	ln_Nf	Estimated Nf	SE	DF	p1	p2	p3	p4	p5	p6	p7	p8	p9	p10
1	14.9	3,010,450	0.90	9	1.000	0.717	0.358	0.521	—	—	—	—	—	—
2	14.4	1,782,487	1.11	10	0.717	1.000	0.636	0.842	—	—	—	—	—	—
3	13.7	890,519	0.93	10	0.358	0.636	1.000	0.745	—	—	—	—	—	—
4	14.1	1,346,757	0.84	10	0.521	0.842	0.745	1.000	—	—	—	—	—	—
5	14.4	1,759,992	0.85	10	—	—	—	—	1.000	0.518	0.962	0.084	0.038*	0.009*
6	13.7	877,051	0.63	13	—	—	—	—	0.518	1.000	0.409	0.179	0.072	0.013*
7	14.4	1,853,229	0.63	13	—	—	—	—	0.962	0.409	1.000	0.036*	0.008*	0.001*
8	12.5	258,210	0.62	10	—	—	—	—	0.084	0.179	0.036*	1.000	0.836	0.282
9	12.3	221,966	0.37	10	—	—	—	—	0.038*	0.072*	0.008*	0.836	1.000	0.247
10	11.6	111,043	0.45	11	—	—	—	—	0.009*	0.013*	0.001*	0.282	0.247	1.000

Note: Values marked with an asterisk (*) indicate p-values <0.05.

Table C.7: Pairwise Statistical Test Results for Nf at 700 Microstrain

Mix No.	ln_Nf	Estimated Nf	SE	DF	p1	p2	p3	p4	p5	p6	p7	p8	p9	p10
1	13.9	1,133,352	0.617	9	1.000	0.614	0.115	0.223	—	—	—	—	—	—
2	13.5	731,447	0.590	10	0.614	1.000	0.262	0.476	—	—	—	—	—	—
3	12.6	285,404	0.561	10	0.115	0.262	1.000	0.618	—	—	—	—	—	—
4	12.9	417,404	0.497	10	0.223	0.476	0.618	1.000	—	—	—	—	—	—
5	13.5	751,112	0.508	10	—	—	—	—	1.000	0.298	0.719	0.071	0.008*	0.003*
6	12.9	394,045	0.328	13	—	—	—	—	0.298	1.000	0.385	0.162	0.022*	0.007*
7	13.3	600,351	0.345	13	—	—	—	—	0.719	0.385	1.000	0.083	0.006*	0.002*
8	11.3	77,354	1.078	10	—	—	—	—	0.071	0.162	0.083	1.000	0.907	0.545
9	11.1	66,715	0.642	10	—	—	—	—	0.008*	0.022*	0.006*	0.907	1.000	0.513
10	10.4	34,305	0.767	11	—	—	—	—	0.003*	0.007*	0.002*	0.545	0.513	1.000

Note: Values marked with an asterisk (*) indicate p-values <0.05.

The following findings are based on the statistical testing results:

- Initial stiffness (E50) at 20°C and 10 Hz:
 - + There is no statistically significant difference between the four plant mixes. It should be noted that the largest differences seen in the frequency sweep results were at higher temperatures and slower frequencies than 20°C and 10 Hz.
 - + There is no statistically significant difference between laboratory mixes with PG 64-16 base binder at 400 and 600 microstrain, but there are statistically significant differences at the 95% confidence level between the virgin mix and the RAP mixes at 700 microstrain, with higher stiffness for the RAP mixes.
 - + There are statistically significant differences at the 95% confidence level between laboratory mixes with PG 70-10 base binder at 400, 600 and 700 microstrain. The mixes with 1" RAP are always stiffer than the ones without RAP and the one with 3/4 in. RAP. The mix without RAP is stiffer than the one with 10% 3/4 in. RAP only at 600 microstrain.
 - + There are statistically significant differences at the 95% confidence level between the mixes with PG 64 and PG 70 base binder,s with higher stiffnesses for PG 70 mixes.
- Regarding fatigue Life (Nf):
 - + There is no statistically significant difference between any pair of mixes studied in the report at 400 microstrain.
 - + There are no statistically significant differences in fatigue between control mixes with no RAP and mixes with 10% RAP and the same binder type as the control mix at the 600 and 700 microstrain levels.
 - + There are some statistically significant differences at 600 and 700 microstrain between the laboratory mixes with different control binders, with longer fatigue life for mixes for the PG 64 base binder mixes than for the ones with PG 70 base binder.

APPENDIX D ADDITIONAL CalME SIMULATIONS TO EVALUATE EFFECTS OF INCREASING RHMA-G THICKNESS ON PAVEMENT PERFORMANCE

Simulation Factorial

The following is a summary of the *CalME* simulations which were performed using the four plant mixes and HMA materials in *CalME*:

- Types of structure evaluated: new construction, asphalt concrete (AC) on AC overlay, and AC on PCC overlay.
- The total AC thickness of new RHMA-G and HMA depends on the structure type:
 - + New construction: 0.70 ft., 0.90 ft., or 1.10 ft.
 - + AC on AC overlay: 0.40 ft. to 0.70 ft. in 0.10 ft. increments
 - + AC on PCC overlay: 0.50 ft. or 0.70 ft.
- The range of RHMA-G thickness evaluated within the total AC thickness ranges shown above is between 0.10 ft. and 0.50 ft. at 0.10 ft. increments.
- The HMA thickness is determined by the total AC thickness minus RHMA-G thickness. It can be as low as 0 ft. (i.e., all RHMA-G and no HMA underneath).
- The assumed layer type below the new AC depends on the structure type:
 - + New construction: 0.50 ft. of AB-Class 2
 - + AC on AC overlay: 0.35 ft. of old HMA over 0.50 ft. of AB-Class 2
 - + AC on PCC overlay: 0.75 ft. of old PCC over 0.50 ft. of AB-Class 2
- There is no subbase; the subgrade is CL.
- The traffic depends on the total AC thickness and structure. It is determined through a trial-and-error process with the goal of achieving failure for all designs at 20 years. The resulting failure traffic volumes were between 0.8 and 70 million ESALs (between 8 and 15 in the traffic index).
- Two representative climate zones were used: Inland Valley and South Coast.
- All materials used in addition to the RHMA-G and HMA were statewide median from the Standard Materials Library included in *CalME*. The HMA mix has PG 64-16 binder.
- Distresses accounted for include cracking and rutting. The type of cracking depends on the structure type:
 - + New construction: fatigue cracking
 - + AC on AC overlay: fatigue and reflective cracking (16% to 25% existing cracks)

- + AC on PCC overlay: fatigue and reflective cracking
- Other analysis inputs:
 - + Analysis type: Monte Carlo simulation
 - + Number of simulations: 50
 - + Traffic growth rate: 0%

Results

The effect of RHMA-G thickness on pavement life is shown in Figure D.12. The percent of the wheelpath with rutting failure at the end of pavement life for the cases evaluated is shown in Figure D.13.

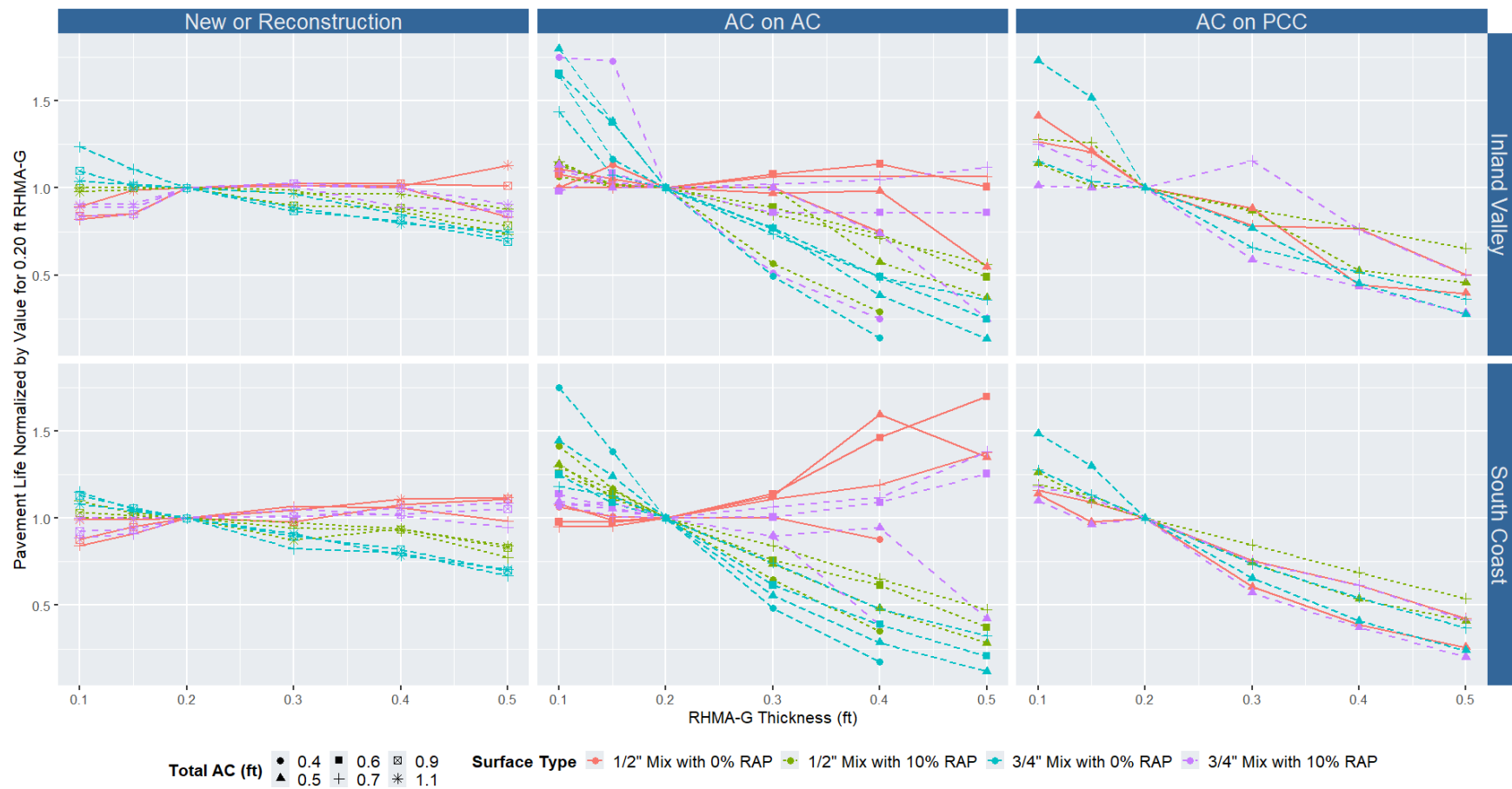


Figure D.12: Effect of RHMA-G thickness on pavement performance normalized by the value for 0.20 ft. of RHMA-G.



Figure D.13: Percent wheelpath with rutting failure at the end of pavement life.

Figure D.12 indicates that in general increasing RHMA-G thickness reduces pavement life, although in some cases increasing RHMA-G thickness can increase pavement life as well. The amount and direction of change depends on the structure and mix type. Figure D.13 indicates that some pavements failed by rutting rather than cracking. Specifically, rutting was the failure mode for the new or reconstruction or AC on AC overlay with the following two types of RHMA-G mix as the surface: the 1/2" mix with 0% RAP and the 3/4" mix with 10% RAP.

The simulations show that the effect of increasing RHMA-G thickness depends on structure and mix type. An increase of RHMA-G thickness from 0.20 ft. to 0.30 ft. causes relatively small increases or decreases in performance for new construction, small increases to significant decreases in performance for overlay on old AC, and small to significant decreases in overlay on old PCC. A larger increase from 0.20 ft. to 0.50 ft. causes small increases to modest decreases in performance for new construction, significant increases or decreases in performance for overlays on old AC, and moderate to significant decreases in performance for overlay over old PCC.

The simulations also show that increasing RHMA-G thickness causes no increased risk of rutting failure. For cases failed by rutting, the rutting life in general increases with increasing RHMA-G thickness. For cases failed by cracking, the rutting life decreases with increasing RHMA-G thickness but not to the extent of affecting pavement performance.