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Use of Recycled Asphalt Pavement in Rubberized Hot Mix Asphalt—Gap Graded

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Use of Recycled Asphalt Pavement in Rubberized Hot Mix Asphalt–Gap-Graded

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(DRISI Task 3198)

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16. ABSTRACT

Current Caltrans Standard Specifications for rubberized hot mix asphalt–gap-graded (RHMA-G) do not allow the inclusion of reclaimed asphalt pavement (RAP). This report summarizes the research conducted by the UCPRC in support of the Caltrans-industry initiative "10% RAP in RHMA-G," whose goal is to evaluate the use of up to 10% RAP (by aggregate replacement) in RHMA-G mixes, provided that the research does not identify significant potential problems for durability. Five pilot projects were built by Caltrans as part the initiative. In each of the pilots, a control RHMA-G (without RAP) and an RHMA-G with 10% RAP were placed. The mixes were sampled during production and tested using performance-related tests at the UCPRC laboratory. The results of the testing of the mixes—including stiffness, four-point bending fatigue resistance, and rutting resistance—indicate that the addition of 10% RAP had minor effects on the mechanical properties of the RHMA-G. With just a few exceptions related to changes in the total binder content of the mix, the effect of the RAP addition was negligible compared with project-to-project differences. Modeling with *CalME* software based on four-point bending testing results indicated that the impact of the RAP addition on the cracking performance of the pavement was either negligible or comparable to project-to-project differences. From the constructability point of view, the addition of the RAP did not create any problems. The life cycle assessment presented in this report indicates that the addition of 10% RAP to the RHMA-G can reduce the greenhouse gasses emissions associated with the RHMA-G production (cradle-to-gate) by up to 5%.

17. KEYWORDS
asphalt overlay, rubberized hot mix asphalt–gap-graded (RHMA-G), crumb rubber modifier, reclaimed asphalt pavement (RAP)

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7. PROPOSALS FOR IMPLEMENTATION

It is recommended that Caltrans move forward with inclusion of 10% RAP in RHMA-G mixes in more projects, that the five pilot projects be supplemented with several projects in the Inland Valley climate region, and that all projects be monitored for performance for several years after construction.

8. RELATED DOCUMENTS

9. VERSION UPDATES

10. LABORATORY ACCREDITATION

The UCPRC laboratory is accredited by AASHTO resource and CCRL for the laboratory testing discussed in this report

AASHTO ACCREDITED

CCRL Cement and Concrete Reference Laboratory

11. SIGNATURES

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PROJECT OBJECTIVES

The objective of Partnered Pavement Research Center (PPRC) Project 4.76, New RHMA Materials with RAP/RAS; Part A: for Structural Layers in Flexible Pavements, is to develop guidance on the use of RHMA (gap and other gradation) mixes containing RAP, RAS, or RAP with RAS in pavement structures. This will be achieved through the following tasks:

Task 1: Literature review.

Task 2: Running of initial *CalME* simulations in various structural layer applications in flexible pavements using properties for RHMA with RAP, RAS, or RAP with RAS, based on already completed research.

Task 3: Laboratory testing of RHMA mixes with fine and coarse RAP, RAS, or RAP with RAS.

Task 4: Running of refined *CalME* simulations using RHMA with RAP, RAS, or RAP with RAS, in various structural layer applications in flexible pavements.

Task 5: If results from the first four tasks warrant, conduct pilot studies and/or HVS testing to verify simulations.

The research summarized in this report completes the work of Task 5 by presenting the results of the pilot implementation in the field of RHMA-G mixes with 10% RAP.

EXECUTIVE SUMMARY

This report summarizes the research completed by the UCPRC on five pilot projects in support of the Caltrans-industry initiative “10% RAP in RHMA-G.” The goal of this initiative is to allow up to 10% reclaimed asphalt pavement (RAP), by aggregate replacement, in rubberized hot mix asphalt–gap-graded (RHMA-G) mixes. Current Caltrans Standard Specifications do not allow any RAP in RHMA-G.

To evaluate the impact of the RAP addition on the RHMA-G properties with regard to expected material properties, simulated performance, and environmental impact, five pilot projects were built by Caltrans between 2022 and 2023. All the projects included an RHMA-G surface, 0.15 to 0.20 ft. (46 to 61 mm) thick, placed in a mill and fill operation. In each of the pilots, two RHMA-G surfaces were placed: a control RHMA-G without RAP and an RHMA-G with 10% RAP. Overall, the collection of RHMA-G mixes used in the five pilots can be regarded as a good representative sample of the RHMA-G mixes currently used by Caltrans.

In each of the five pilots, the two mixes were sampled during production and tested at the UCPRC laboratory. The testing included the following main mechanical properties that can potentially be impacted by the RAP addition:

- Fatigue resistance, tested by following ASTM D8237-21 (four-point bending fatigue resistance).
- Stiffness at different temperatures and loading times, tested by following ASTM D8237-21 (flexural complex modulus in four-point bending) and AASHTO T 378-22 (axial complex modulus in the asphalt mixture performance tester [AMPT]).
- Rutting resistance, tested by following AASHTO T 378-22 (repeated load testing in the AMPT).
- Rutting and moisture resistance, tested by following AASHTO T 324-22 (Hamburg Wheel-Track test).
- Fracture cracking resistance, tested by following ASTM D8225-19 (IDEAL cracking test [IDEAL-CT]).

The expected field cracking performance of the mixes with and without RAP was modeled with *CalME*, which can model the cracking performance on an asphalt pavement, based on the flexural stiffness and fatigue resistance of the mix measured in the four-point flexural bending test.

A cradle-to-gate life cycle assessment (LCA) using *eLCAP*, the Caltrans environmental life cycle assessment tool for pavements, was conducted. The goal of the assessment was to determine how the global warming potential (GWP) and primary energy demand (PED) of the RHMA-G fabrication change due to the addition of 10% RAP. The cradle-to-gate analysis considered impacts from the extraction of raw materials, their transport to the manufacturing plants, and product manufacturing.

The following conclusions were extracted from the results of the laboratory testing of the asphalt mixes, the *CalME* modeling, and the LCA. The conclusions have been grouped around the four questions that this research study intended to answer.

1. How do the mechanical properties of the RHMA-G change due to the addition of 10% RAP?
    - The addition of 10% RAP had minor effects on the mechanical properties of the RHMA-G. With just a few exceptions related to changes in the total binder content, the effect of the RAP addition was negligible compared with project-to-project differences.
    - Overall, the stiffness slightly increased (up to 20%) and the fatigue resistance at very high strain levels (at or above 1000 με) slightly decreased. At the strain levels that take place in a highway pavement, up to few hundred microstrain (με), the fatigue resistance of the RHMA-G remained essentially unchanged or improved after the addition of RAP.
    - From the constructability point of view, the addition of the RAP did not create any problems. In particular, the field densities achieved for each of the mixes with RAP were within specifications and similar to the densities achieved for the corresponding control mixes.
2. What is the expected field fatigue and reflective cracking performance of the RHMA-G with 10% RAP compared with the RHMA-G without RAP when used as a surface layer?
    - The impact of the 10% RAP addition on the cracking performance of the pavement, based on *CalME* modeling, was either negligible or comparable to project-to-project differences.
    - For one of the pilots, VEN-1, the addition of RAP resulted in worse cracking performance in some modeling scenarios based on *CalME*. Still, the cracking performance of the VEN-1 mix with RAP was comparable to the cracking performance of the statewide median RHMA-G. The statewide median RHMA-G provides median performance across all RHMA-G mixes included in the *CalME* standard materials library.
    - For one of the pilots, SLO-41 pilot, the addition of RAP resulted in better cracking performance in all modeling scenarios based on *CalME*.
3. What adjustments to RHMA-G design, fabrication, and construction are recommended when adding 10% RAP?
    - The positive outcomes from the five pilot projects support the steps that all contractors followed to add the 10% RAP:
        - Adjust the proportions of the different virgin aggregate bins to match the gradation of the control mix (without RAP).
        - Reduce the design number of gyrations to meet the 4.0% design Va (air voids in the mix).
        - Maintain mixing and compaction temperatures, type of virgin asphalt rubber binder, and, where used, the warm mix asphalt or antistripping additive unchanged.

   - Based on the laboratory testing, the *CalME* modeling, and the field compaction results, no reason was found why the RAP binder should not be considered as part of the total binder content to meet the minimum 7.5% total binder requirement. In other words, the results indicate that the RAP binder can be considered to contribute to the minimum 7.5%.

4. How do cradle-to-gate GWP and PED of the RHMA-G fabrication change due to the addition of 10% RAP?
   - The addition of 10% RAP to the RHMA-G, assuming the RAP binder contributes to the total binder content minimum of 7.5%, resulted in GWP reductions of 5% and PED savings of 6%.
   - The main reason for GWP and PED reductions was the reduction in virgin asphalt binder associated with the 10% RAP addition when the RAP binder was accounted for in meeting the 7.5% minimum asphalt content required by Caltrans for RHMA-G mixes.
   - Smaller reductions (1% GWP and 0% PED) are expected when the RAP binder is not counted as contributing to the 7.5% minimum asphalt content requirement.

It is recommended that Caltrans move forward with inclusion of 10% RAP in more projects based on the predicted performance presented in this report. It is recommended, as the next step, that the five pilot projects and subsequent projects be monitored for several years after construction to validate the predicted performance presented in this report and that forensic investigations be done if any problems associated with the use of RAP are detected.

While the collection of pilots covers most of the climate conditions where RHMA-G is currently used in California, a project in the Inland Valley is missing. It is recommended that several projects be built as soon as possible in the Inland Valley climate region.

It is recommended that research continue about the possibility of using RAP contents above 10% in the RHMA-G, which most likely would require changes in the combined (virgin plus RAP) aggregate gradation curve.

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LIST OF ABBREVIATIONS

AASHTO	American Association of State Highway and Transportation Officials
AC	Asphalt concrete
AMPT	Asphalt mixture performance tester
ASTM	American Society for Testing and Materials
CalME	California Mechanistic-Empirical Design Software
CalRecycle	California Department of Resources Recycling and Recovery
Caltrans	California Department of Transportation
CRM	Crumb rubber modifier
EA	Expenditure Authorization
FWD	Falling weight deflectometer
HMA	Hot mix asphalt
HWT	Hamburg Wheel-Track
JMF	Job mix formula
LCA	Life cycle assessment
MTOA	Medium-term oven aging
NMAS	Nominal maximum aggregate size
PCC	Portland cement concrete
PG	Performance grade
PGH	High performance grade
PGI	Intermediate performance grade
PGL	Low performance grade
PMPC	Pavement & Materials Partnering Committee
RAP	Reclaimed asphalt pavement
RAS	Recycled asphalt shingles
RHMA-G	Rubberized hot mix asphalt–gap-graded
RLT	Repeated load triaxial
SAMI	Stress-absorbing membrane interface
SWM	Statewide median
TWM	Total weight of mix
UCPRC	University of California Pavement Research Center

LIST OF TEST METHODS AND SPECIFICATIONS

AASHTO M 320-21	Standard Specification for Performance-Graded Asphalt Binder
AASHTO PP 3	Standard Practice for Preparing Hot Mix Asphalt (HMA) Specimens by Means of the Rolling Wheel Compactor
AASHTO T 30-19	Standard Method of Test for Mechanical Analysis of Extracted Aggregate
AASHTO T 275-17	Standard Method of Test for Bulk Specific Gravity (Gmb) of Compacted Asphalt Mixtures Using Paraffin-Coated Specimens
AASHTO T 308-22	Standard Method of Test for Determining the Asphalt Binder Content of Hot Mix-Asphalt (HMA) by the Ignition Method
AASHTO T 312-22	Standard Method of Test for Preparing and Determining the Density of Asphalt Mix Specimens by Means of the Superpave Gyratory Compactor
AASHTO T 324-22	Standard Method of Test for Hamburg Wheel-Track Testing of Compacted Asphalt Mixtures
AASHTO T 378-22	Standard Method of Test for Determining the Dynamic Modulus and Flow Number for Asphalt Mixtures Using the Asphalt Mixture Performance Tester (AMPT)
ASTM D 1856-21	Standard Test Method for Recovery of Asphalt From Solution by Abson Method
ASTM D 8159-19	Standard Test Method for Automated Extraction of Asphalt Binder from Asphalt Mixtures
ASTM D 8225-19	Standard Test Method for Determination of Cracking Tolerance Index of Asphalt Mixture Using the Indirect Tensile Cracking Test at Intermediate Temperature
ASTM D 8237-21	Standard Test Method for Determining Fatigue Failure of Asphalt-Aggregate Mixtures with the Four-Point Beam Fatigue Device
CT 384	California Method of Test to Determine Combined Gradations for Hot Mix Asphalt (HMA) using up to 25% Reclaimed Asphalt Pavement (RAP)

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

The California Department of Transportation (Caltrans) Standard Specifications (Std. Specs.) Section 39, "Asphalt Concrete," includes rubberized hot mix asphalt–gap-graded (RHMA-G). This mix type has a gap gradation with only a small fraction, around 15%, of aggregates between sieves #200 and #8 (0.075 to 2.36 mm). Figure 1.1 shows the gradation of RHMA-G mixes with 1/2 in. and 3/4 in. nominal maximum aggregate size (NMAS) together with the continuous gradation of dense graded hot mix asphalt (HMA) with the same NMAS. The gap gradation leaves a minimum of 18% voids in the mineral aggregate and allows the use of a relatively high content of asphalt rubber binder with a relatively high content of crumb rubber modifier (CRM). Caltrans Std. Specs. Section 39 specifies a minimum of 7.5% asphalt rubber binder content by total weight of mix (TWM) for the RHMA-G and 18% to 22% CRM content for the asphalt rubber binder. The rubber is introduced in the mix by a process referred to as "wet process–high viscosity," where CRM particles from used tires passing the #8 sieve (2.36 mm) are blended with the plain binder at 375°F to 425°F (191°C to 218°C) for a minimum of 45 minutes, resulting in partial digestion of the particles.

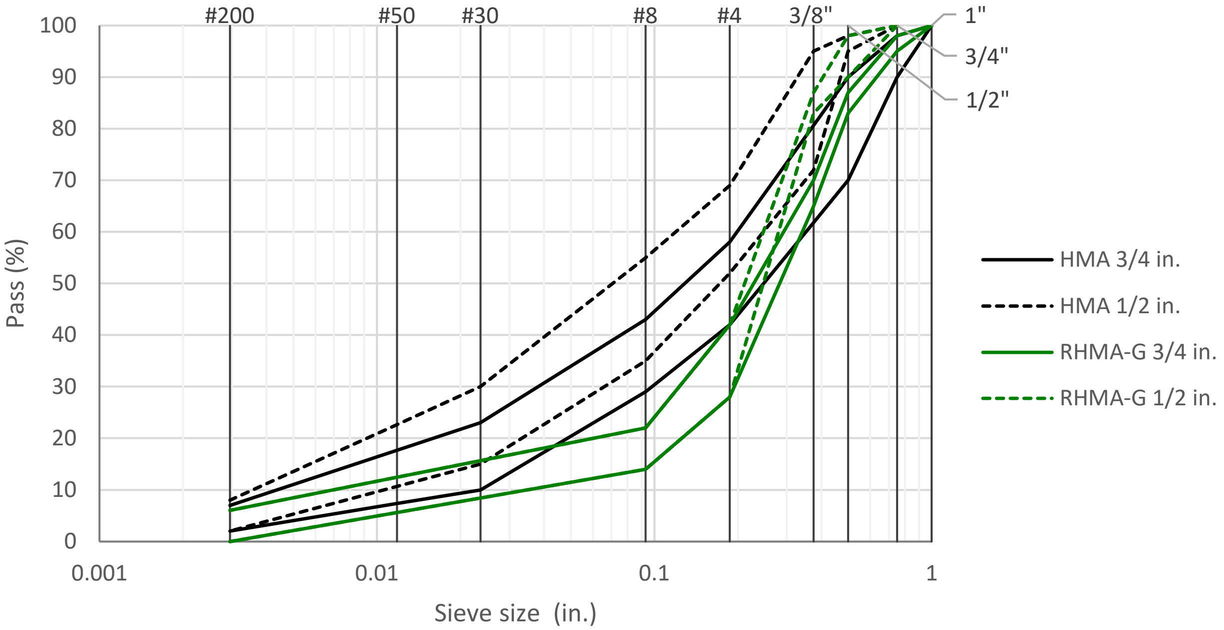


Figure 1.1: Comparison of gap (RMHA-G) versus dense gradations (HMA).

RHMA-G is the Caltrans surface mixture of preference at elevations below 3,000 feet for several reasons. The first reason is the high reflective cracking resistance of RHMA-G when used in thin overlays over cracked asphalt pavement, which makes it ideal for use for asphalt overlays and surface layers in general. RHMA-G has generally been shown through numerous studies, including a large number of University of California Pavement Research Center (UCPRC) studies, to have good resistance to top-down, fatigue, reflective, low-temperature, and age-related cracking, which are the primary performance challenges for asphalt overlays. The second reason is that RHMA-G consumes used tires. California legislation mandating the use of CRM in asphalt mixes is included in California Public Resources Code Section 42703: "The Department of Transportation shall use, on an annual average, not less than 11.58 pounds of CRM per metric ton of the total amount of asphalt paving materials used." In 2020, 41% of the asphalt concrete tonnage placed by Caltrans was RHMA-G *(1)*.

Current Caltrans Standard Specifications for RHMA-G, included in Caltrans Std. Specs. Section 39, do not allow the use of any reclaimed asphalt pavement (RAP) in RHMA-G. The use of RAP in RHMA-G has been proposed because of the following potential environmental and economic benefits:

- Reduction of virgin aggregate production because of the aggregate in the RAP and the consequent preservation of California natural resources and reduction of energy consumption required for mix fabrication.
- Reclaiming of the binder in the RAP and the consequent reduction of virgin binder use.
- Reduction of RAP in landfills.
- Reduction of RHMA-G production costs, due to the replacement of virgin aggregates by RAP aggregates and the replacement of virgin binder by RAP binder.

While the environmental and economic benefits are evident, the risk exists that the addition of RAP may negatively impact some properties of RHMA-G, in particular its cracking resistance. Depending on the magnitude of the potential negative impact, the initial environmental and economic gains may not counteract the losses associated with the performance drop.

Current knowledge regarding the RAP impact on RHMA-G performance is very limited. Research conducted in 2016 at the UCPRC for the California Department of Resources Recycling and Recovery (CalRecycle) on this specific topic concluded that "adding RAP to gap-graded asphalt rubber mixes used in overlays will potentially have some improvement in overall rutting performance, but a potentially overall negative effect on fatigue cracking performance." The research also concluded that "more comprehensive testing should be carried out before any changes to current practice are considered" as only one mix was evaluated *(2)*. However, research completed in 2023 at the UCPRC for Caltrans and CalRecycle concluded that the addition of small amounts of RAP in terms of binder replacement, around 3%, did not have a noticeable impact on the fatigue resistance of RHMA-G *(3)*.

The Caltrans Pavement & Materials Partnering Committee (PMPC) Asphalt Task Group convened a team to study the use of RAP in RHMA-G in 2020. The team released the corresponding scoping document, which includes a problem statement, goal, and work plan *(4)*. The goal stated in the scoping document is to revise Caltrans Std. Specs. Section 39 to allow up to 10% RAP in RHMA-G, where the 10% refers to the aggregate replacement (i.e. 10% of the aggregates come from RAP). The work plan includes the development of a Non-Standard Special Provision (nSSP) and the implementation in five to ten pilot projects. This PMPC initiative is referred as "10% RAP in RHMA-G."

Five pilot projects have been built as part of the “10% RAP in RHMA-G” initiative: SON-1 (Sonoma County, Route 1), SON-101 (Sonoma County, Route 101), VEN-1 (Ventura County, Route 1), IMP-186 (Imperial County, Route 186), and SLO-41 (San Luis Obispo County, Route 41). In each of the five pilots, two RHMA-G mixes were placed as surface layer: a standard RHMA-G (without RAP), referred to as “control,” and an RHMA-G with 10% RAP, referred to as “test.” In each of the five pilots, the two mixes were sampled and then tested at the UCPRC laboratory. This report summarizes the results of the laboratory testing of the mixes as well as a study of the expected performance based on simulations using the Caltrans mechanistic-empirical software for asphalt pavement design, *CalME (5,6)*.

1.2 Problem Statements

The following problems were identified to be addressed by this research:

- Current Caltrans Standard Specifications for RHMA-G do not allow the use of any RAP.
- The addition of RAP to the RHMA-G would reduce the environmental impacts, costs, and virgin resource use of RHMA-G production, but it may negatively impact its field performance, especially in terms of cracking.
- Current knowledge regarding RAP impact on RHMA-G properties and field performance is very limited.

1.3 Goal and Questions to Answer

The goal of this research study is to evaluate how the addition of 10% RAP, by aggregate replacement, impacts the properties and expected field performance of the RHMA-G. The study was designed to address the following questions:

1. How do the mechanical properties of the RHMA-G change due to the addition of 10% RAP?
2. What is the expected field fatigue and reflective cracking performance of the RHMA-G with 10% RAP compared with the RHMA-G without RAP when used as a surface layer?
3. What adjustments to RHMA-G design, fabrication, and construction are recommended when adding 10% RAP?
4. How do cradle-to-gate global warming potential (GWP) and primary energy demand (PED) of the RHMA-G fabrication change due to the addition of 10% RAP?

1.4 Experimental Approach

The experimental data for this study come from five pilot projects built by Caltrans between 2022 and 2023. The locations and extents of the pilots are summarized in Table 1.1. In each pilot, a “test section” was selected for placing the RHMA-G with 10% RAP. The location of the test section is shown in Table 1.1. Apart from the test sections, the mix used in the pilots is standard RHMA-G (no RAP). In the five pilots, both standard RHMA-G and RHMA-G with RAP were placed as surface layers in a mill and fill operation. Details of each of the pilots are presented in Chapter 2.

Table 1.1: Location and Extent of Pilot Projects

Pilot ID	District	Route	County	PM Range	Project Lanes[a]	Test Section Lane & PM Range[b]
SON-1	4	1	Sonoma	7.100–9.100 & 16.100–19.700	N1 & S1	N1 (7.100–7.500)
SON-101	4	101	Sonoma	R54.200–R56.200	N1, N2, & N3	N2 (R55.800–R56.200)
VEN-1	7	1	Ventura	4.400–9.700	N1 & S1	S1 (9.300–9.700)
IMP-186	11	186	Imperial	0.000–2.1000	N1 & S1	N1 & S1 (1.000–1.600)
SLO-41	5	41	San Luis Obispo	0.000–11.500	N1 & S1	N1 & S1 (3.200–3.600)

[a] Lane identification includes direction (N is north, S is south) and lane number (1 is the innermost lane).

[b] The test section is where the RHMA-G with 10% RAP is placed; the RHMA-G with 10% RAP is referred to as the "test mix" while the standard RHMA-G (no RAP) is referred to as the "control mix."

In addition to the sampling and testing of the RHMA-G mixes presented in this report, the performance of the pilots will be monitored during the next five years. The monitoring will be mainly based on the Automated Pavement Condition Survey (APCS) conducted by Caltrans yearly, complemented by manual field inspections to be conducted by the UCPRC after each pilot's one and five years in service. The cracking performance of the test section (RHMA-G with RAP) will be compared with the rest of the project (RHMA-G without RAP). The outcome of the monitoring will be included in a future report.

A falling weight deflectometer (FWD) evaluation was conducted for each of the pilot projects before and after the RHMA-G overlay. The goals of the FWD evaluation are as follows:

1. Verify that the structural condition of the test section (RHMA-G with RAP) is similar to the rest of the project (RHMA-G without RAP) so that a direct and unbiased comparison can be made of the cracking performance of the test section versus the rest of the project.
2. Serve as a reference for future evaluation of the structural condition of the test section and the rest of the project. The pilots will be evaluated again with the FWD after five years in service.

From the mix design point of view, the addition of the 10% RAP was conducted by adjusting the proportions of the different aggregate bins so that the new gradation matched the gradation of the control mix without RAP. In other words, the control RHMA-G and the RHMA-G with RAP had the same (or very similar) aggregate gradation. While all five contractors followed this approach, each of them introduced several design adjustments to be able to add the 10% RAP. The design adjustments are shown for each of the pilots in Chapter 2.

The two mixes used in each of the pilots were sampled from hot drops following sample splitting procedures during production. Then the mixes were shipped to the UCPRC laboratory for mechanical characterization. The characterization included the following main mechanical properties that can potentially be impacted by the RAP addition:

- Fatigue resistance, tested by following ASTM D8237-21 (four-point bending fatigue resistance).
- Stiffness at different temperatures and loading times, tested by following ASTM D8237-21 (flexural complex modulus in four-point bending) and AASHTO T 378-22 (axial complex modulus in the AMPT).
- Rutting resistance, tested by following AASHTO T 378-22 (repeated load testing in the AMPT).
- Rutting and moisture resistance, tested by following AASHTO T 324-22 (Hamburg Wheel-Track test).
- Fracture cracking resistance, tested by following ASTM D8225-19 (IDEAL cracking test [IDEAL-CT]).

The comparison of the mechanical properties of the mixes with RAP versus the corresponding control mixes (without RAP) is presented in Chapter 3. The comparison is the basis for addressing the first question that was formulated in this study: *How do the mechanical properties of the RHMA-G change due to the addition of 10% RAP?*

The expected field cracking performance of the mixes with and without RAP was modeled with *CalME,* which can model the cracking performance on an asphalt pavement based on the flexural stiffness and fatigue resistance of the mix measured in the four-point flexural bending test. The four-point bending test results are used to calibrate material models that are used by *CalME* for predicting cracking performance. Several sections were modeled in *CalME,* including new pavements and asphalt overlays for rehabilitation, in different climatic zones and under different truck traffic conditions, with a 0.20 ft. (61 mm) RHMA-G surface and a newly placed HMA intermediate layer in all cases. The intermediate layer HMA thickness required to support the design traffic was determined through iteration using *CalME,* as is done in practice. Then the thickness required for the mixes with 10% RAP was compared versus the thickness required for the control mixes. The comparison, shown in Chapter 4, is the basis for addressing the second question that was formulated in this study: *What is the expected field fatigue and reflective performance of the RHMA-G with 10% RAP compared with the RHMA-G without RAP when used as a surface layer?* This question is answered in terms of the differences in overlay thickness needed to achieve the same simulated design life.

The third question formulated in this study was the following: *What adjustments to RHMA-G design, fabrication, and construction are recommended when adding 10% RAP?*" This questions was addressed by considering the RAP impact on the RHMA-G mechanical properties (shown in Chapter 3), the expected impact on field performance (shown in Chapter 4) in terms of difference in structural thickness required to produce the same *CalME* simulated design life, and the field compaction level measured from cores extracted after the construction (shown in Chapter 2).

The fourth question that was formulated in this study was the following: *How do cradle-to-gate global warming potential (GWP) and primary energy demand (PED) of the RHMA-G fabrication change due to the addition of 10% RAP?* This question was addressed by conducting a cradle-to-gate life cycle assessment (LCA) using *eLCAP*, the Caltrans environmental life cycle assessment tool for pavements *(7)*. The cradle-to-gate analysis, presented in Chapter 5, considers impacts from the extraction of raw materials, their transport to the manufacturing plants, and product manufacturing per declared unit of material—in this case per metric tonne of RHMA-G. A comparative LCA was performed to determine benefits and/or disbenefits of adding RAP to the RHMA-G.

Each of the four questions that were formulated in this study is summarized in Chapter 6.

1.5 Scope of the Report

This study focuses on RHMA-G mixes used as a surface layer. The RAP used in the pilots is fractionated RAP with a nominal maximum aggregate size (NMAS) of either 1/2 in. or 3/8 in. Except for IMP-186, the RAP had a relatively high content of fines (at least 50% passing #4 [<4.75 mm]), with binder contents around 4.5% to 5.0% by TWM. The IMP-186 RAP had a lower content of fines (around 30% passing #4) and lower binder content, 3.1% by TWM. Details are presented in Chapter 2.

The 10% RAP referred in this report refers to aggregate replacement, which means that 10% of the aggregates come from RAP. The binder replacement was around 6% for all pilots except for IMP-186, where it was around 4%. Details are presented in Chapter 2.

In this study, the performance modeling with *CalME* focuses on fatigue and reflective cracking where there is aggregate base or cracked asphalt pavement, respectively. Rutting could not be modeled with *CalME* as such modeling would have required repeated simple shear testing of the mixes, which was not conducted in this study due to time and resources limitations, and because RAP addition is expected to nearly always improve rutting performance.

This study is based on the results of the laboratory testing of the mixes used for the pilot projects construction and *CalME* simulations. No field performance data are included in this study. The performance of the pilots during the next five years will be included in a future report.

1.6 Measurement Units

In this report, both US and metric units (provided in parentheses after the US units) are provided in general discussion. One exception is that the performance grade of the asphalt binder is reported in metric units (°C) following AASHTO M 320-21. A conversion table (US versus metric) is provided on page xv.

2 PILOT IMPLEMENTATION IN FIELD PROJECTS

2.1 Pilot Projects Description

2.1.1 SON-1 (Sonoma County, Route 1)

The SON-1 pilot includes the rehabilitation of a secondary highway, one lane per direction, in Sonoma County (Caltrans Expenditure Authorization [EA] number 04-1W890). The boundaries of the rehabilitation, by lane, are shown in Table 2.1. The project includes two separate sections, with the first part from PM 7.100 to PM 9.100 and the second part from PM 16.100 to PM 19.700. The project layout is shown in Figure 2.1. The test section was paved on September 26, 2022.

Table 2.1: Location and Extent of SON-1 Pilot

Segment			Begin			End			2023 AADTT	Length (mi.)
ID	Direction	Lane[a]	County	PM	Odom	County	PM	Odom		
A-N1	North	1/1	SON	7.100	486.569	SON	9.100	488.569	182	2.000
A-S1	South	1/1	SON	7.100	486.526	SON	9.100	488.526	182	2.000
B-N1	North	1/1	SON	16.100	495.569	SON	19.700	499.169	44	3.600
B-S1	South	1/1	SON	16.100	495.526	SON	19.700	499.126	44	3.600
Test Section	**North**	**1/1**	**SON**	**7.100**	**486.569**	**SON**	**7.500**	**486.969**	**182**	**0.400**

[a] Lane number (1 is the innermost lane)/Number of lanes in the same direction.

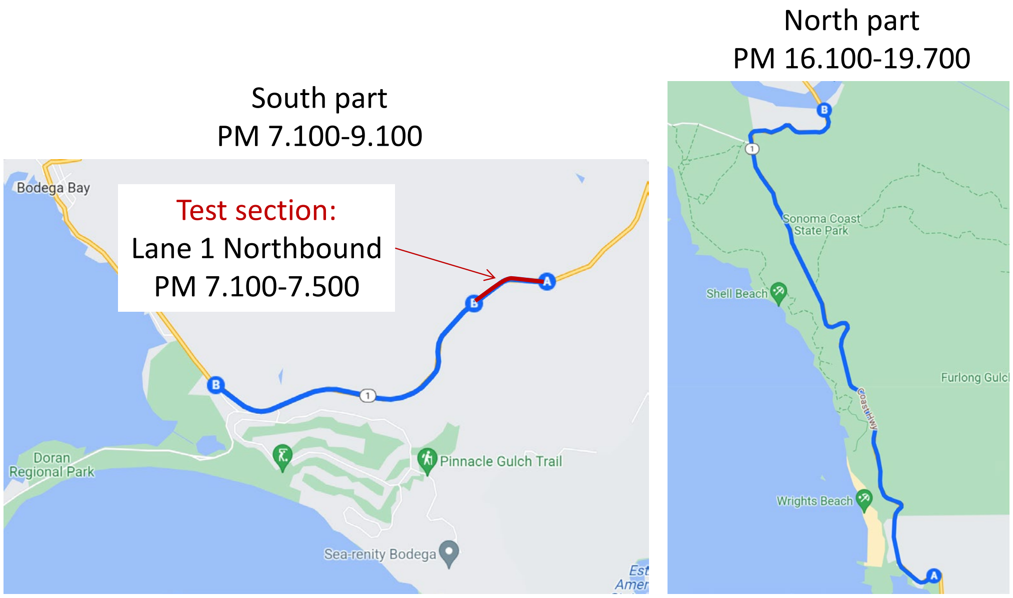

North part
PM 16.100-19.700
South part
PM 7.100-9.100
Test section:
Lane 1 Northbound
PM 7.100-7.500

Figure 2.1: SON-1 pilot layout.

The rehabilitation includes localized areas of full-depth repairs (up to 0.35 ft. [107 mm]) followed by a mill and fill operation consisting of 0.15 ft. (45 mm) cold plane and 0.15 ft. RHMA-G overlay

(Figure 2.2). The underlying HMA varies between the north and south parts of the project, shown in the figure.

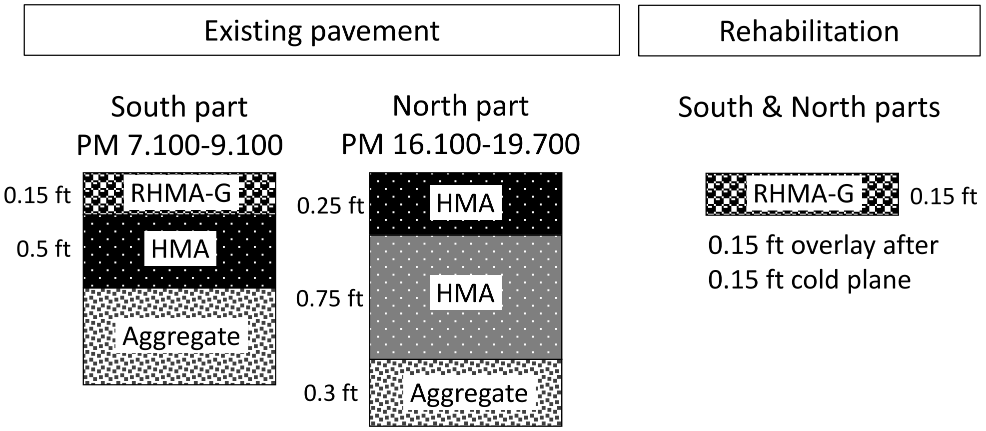


Figure 2.2: SON-1 pilot rehabilitation.

2.1.2 SON-101 (Sonoma County, Route 101)

The SON-101 pilot includes the rehabilitation of a freeway, up to three lanes per direction, in Sonoma County (Caltrans Expenditure Authorization [EA] number 04-1W880). The boundaries of the rehabilitation, by lane, are shown in Table 2.2. The project includes the three lanes of Route 101 in the northbound direction. The project layout is shown in Figure 2.3. The test section was paved on September 13, 2022

Table 2.2: Location and Extent of SON-101 Pilot

Segment			Begin			End			2023 AADTT	Length (mi.)
ID	**Direction**	**Lane[a]**	**County**	**PM**	**Odom**	**County**	**PM**	**Odom**		
N1	North	1/3	SON	R54.200	522.048	SON	R56.200	524.048	122	2.000
N2	North	2/3	SON	R54.200	522.048	SON	R56.200	524.048	478	2.000
N3	North	3/3	SON	R54.578	522.426	SON	R55.240	523.088	571	0.662
Test Section	**North**	**2/3**	**SON**	**R55.800**	**523.648**	**SON**	**R56.200**	**524.048**	**478**	**0.400**

[a] Lane number (1 is the innermost lane)/Number of lanes in the same direction.

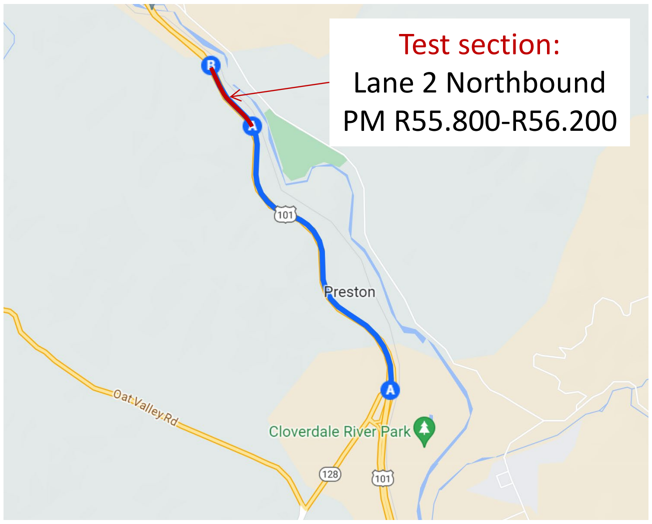


Figure 2.3: SON-101 pilot layout.

The rehabilitation includes localized areas of full-depth repairs (up to 0.50 ft. [152 mm]) followed by a mill and fill operation consisting of 0.20 ft. (60 mm) cold plane and 0.20 ft. RHMA-G overlay (Figure 2.4). The underlying pavement consists of HMA on asphalt treated permeable base (ATPB) on aggregate base.

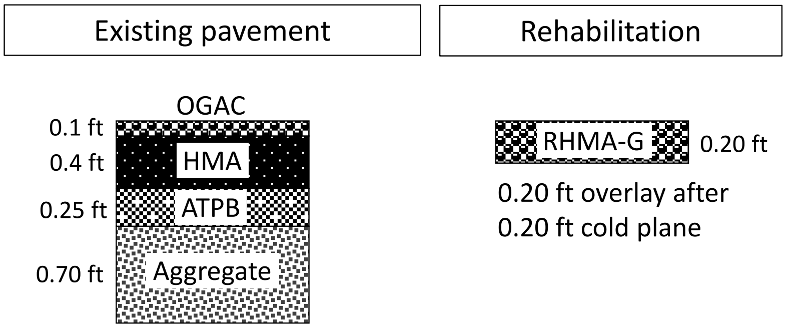


Figure 2.4: SON-101 pilot rehabilitation.

2.1.3 VEN-1 (Ventura County, Route 1)

The VEN-1 pilot includes the rehabilitation of a highway, one lane per direction, in Ventura County (Caltrans Expenditure Authorization [EA] number 07-0W140). The boundaries of the rehabilitation, by lane, are shown in Table 2.3. The project layout is shown in Figure 2.5. The test section was paved on April 24, 2023.

Table 2.3: Location and Extent of VEN-1 Pilot

Segment			Begin			End			2023 AADTT	Length (mi.)
ID	Direction	Lane[a]	County	PM	Odom	County	PM	Odom		
N1	North	1/1	VEN	4.400	92.423	VEN	9.700	97.723	360	5.300
S1	South	1/1	VEN	4.400	92.357	VEN	9.700	97.657	360	5.300
Test Section	**South**	**1/1**	**VEN**	**9.300**	**97.257**	**VEN**	**9.700**	**97.657**	**360**	**0.400**

[a] Lane number (1 is the innermost lane)/Number of lanes in the same direction.

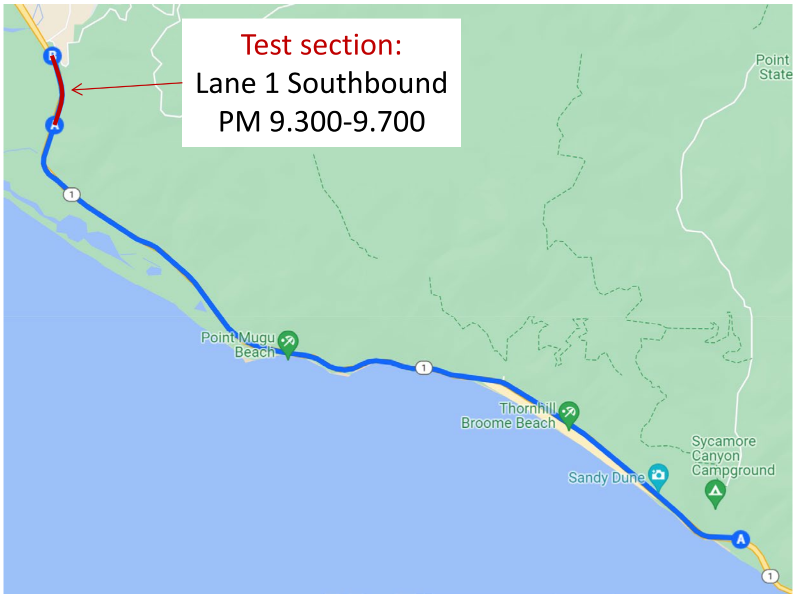


Figure 2.5: VEN-1 pilot layout.

The rehabilitation includes a mill and fill operation consisting of 0.15 ft. (45 mm) cold plane and 0.15 ft. RHMA-G overlay (Figure 2.6). There is no information available about the underlying pavement other than the existing HMA layer with varying thickness.

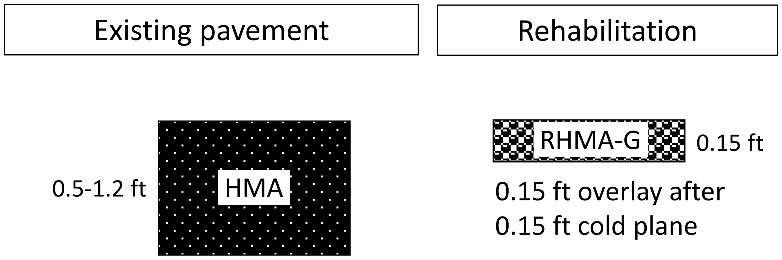


Figure 2.6: VEN-1 pilot rehabilitation.

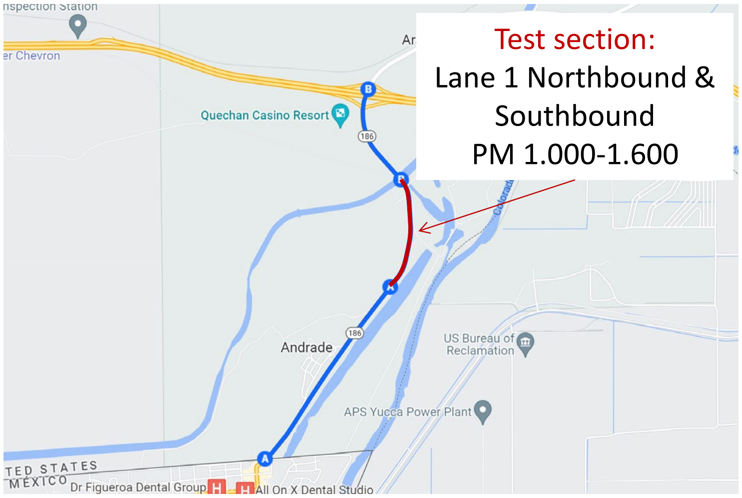
2.1.4 IMP-186 (Imperial County, Route 186)

The IMP-186 pilot includes the rehabilitation of a highway, one lane per direction, in Imperial County (Caltrans Expenditure Authorization [EA] number 11-2N116). The boundaries of the rehabilitation, by lane, are shown in Table 2.4. The project layout is shown in Figure 2.7. The test section was paved on June 6, 2023.

Table 2.4: Location and Extent of IMP-186 Pilot

Segment			Begin			End			2023 AADTT	Length (mi.)
ID	**Direction**	**Lane**[a]	**County**	**PM**	**Odom**	**County**	**PM**	**Odom**		
N1	North	1/1	IMP	0.000	0.000	IMP	2.100	2.100	69	2.100
S1	South	1/1	IMP	0.000	0.000	IMP	2.100	2.100	69	2.100
Test Section	**North & South**	**1/1**	**IMP**	**1.000**	**1.000**	**IMP**	**1.600**	**1.600**	**69**	**0.600 × 2 = 1.200**

[a] Lane number (1 is the innermost lane)/Number of lanes in the same direction.



Test section:
Lane 1 Northbound & Southbound
PM 1.000-1.600

Figure 2.7: IMP-186 pilot layout.

The rehabilitation includes a mill and fill operation consisting of 0.18 ft. (55 mm) cold plane followed by 0.03 ft. (10 mm) stress-absorbing membrane interface (SAMI) and 0.15 ft. (45 mm) RHMA-G overlay (Figure 2.8).

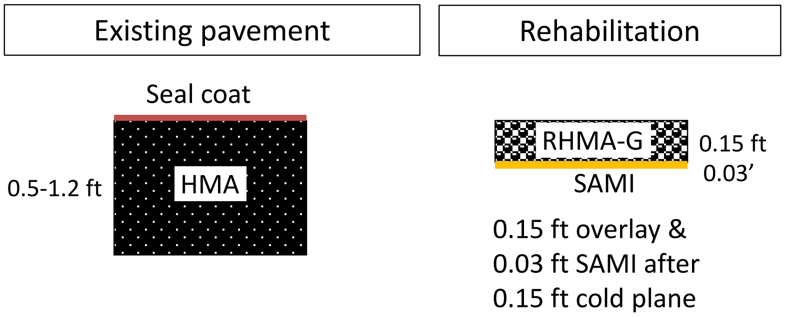


Figure 2.8: IMP-186 pilot rehabilitation.

2.1.5 SLO-41 (San Luis Obispo County, Route 41)

The SLO-41 pilot includes the rehabilitation of a highway, one lane per direction, in San Luis Obispo County (Caltrans Expenditure Authorization [EA] number 05-1P160). The boundaries of the rehabilitation, by lane, are shown in Table 2.5. The project layout is shown in Figure 2.9. The test section was paved on July 25, 2023.

Table 2.5: Location and Extent of SLO-41 Pilot

Segment			Begin			Ends			2023 AADTT	Length (mi.)
ID	**Direction**	**Lane**[a]	**County**	**PM**	**Odom**	**County**	**PM**	**Odom**		
N1	North	1/1	SLO	0.000	0.000	SLO	11.500	11.500	107	11.500
S1	South	1/1	SLO	0.000	0.000	SLO	11.500	11.500	107	11.500
Test Section	**North & South**	**1/1**	**SLO**	**3.200**	**3.200**	**SLO**	**3.600**	**3.600**	**107**	**0.400 × 2 = 0.800**

[a] Lane number (1 is the innermost lane)/Number of lanes in the same direction.

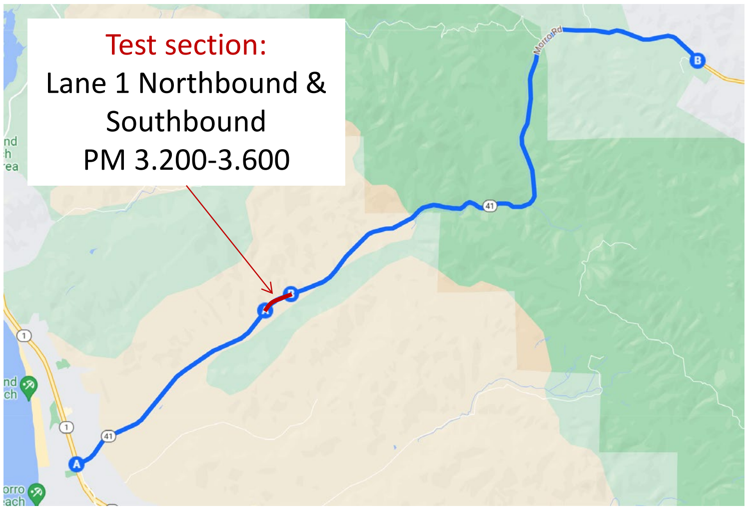


Figure 2.9: SLO-41 pilot layout.

The rehabilitation includes a mill and fill operation consisting of 0.20 ft. (60 mm) cold plane followed by 0.20 ft. RHMA-G overlay (Figure 2.10). The existing structure consisting of HMA on aggregate base is shown in the figure.

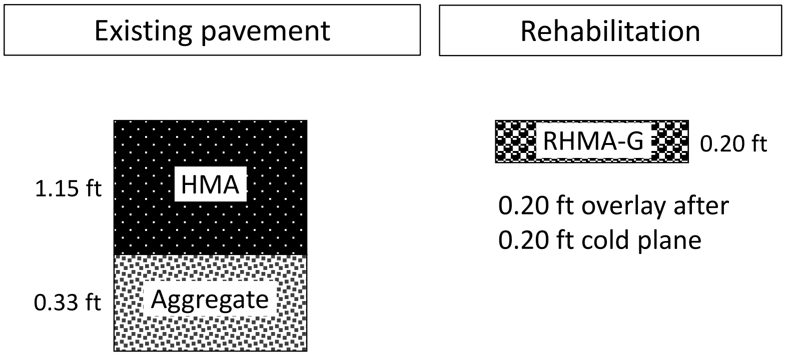


Figure 2.10: SLO-41 pilot rehabilitation.

2.2 Falling Weight Deflectometer and Existing Cracking Evaluation of the Pilots

The deflections measured under the FWD plate with 9 kips (40 kN) loading are summarized in Figure 2.11 to Figure 2.15, one figure per pilot project. In each figure, the deflections measured in the test section (striped boxes) can be compared with the deflections measured in the total project (solid boxes). The box limits correspond to the first quartile, second quartile (i.e., the median), and third quartile of the deflection distribution. Asphalt surface temperature ranges during each of the FWD evaluations are indicated in the figures.

Based on the SON-1 pilot data shown in Figure 2.11, the deflections measured in the test section are comparable to the deflections measured in the overall project. This means that the structural condition of the test section is comparable to the structural condition of the rest of the project. The same conclusion for SON-1 pilot can be extended to the other four pilots. In all cases, the deflections indicate that the structural condition of the test section is comparable to the structural condition of the rest of the project with regard to structural support. As expected, the deflections change little due to the mill and fill treatment because of the relatively small thickness of the milling and the subsequent RHMA-G overlay (compare Pre-Construction versus Post-Construction deflections in Figure 2.11 to Figure 2.15).

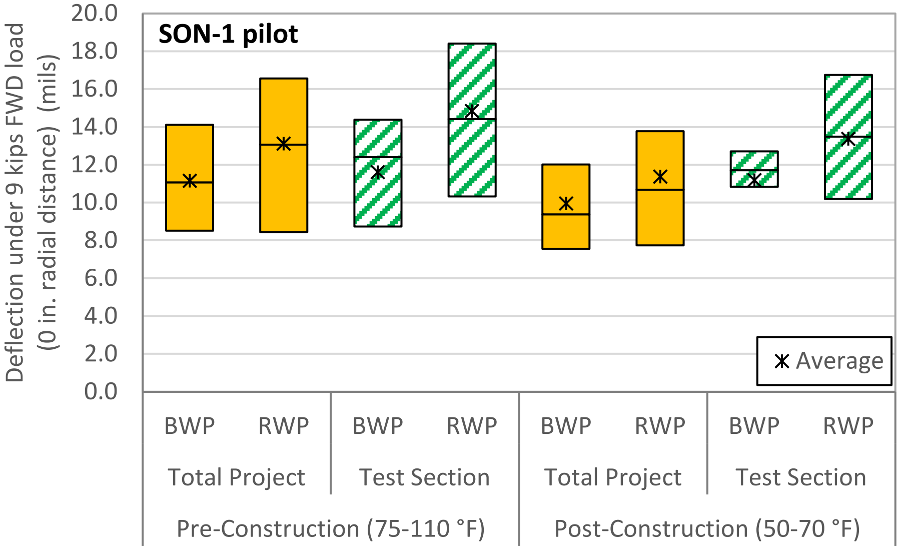


Figure 2.11: FWD evaluation of SON-1 pilot.

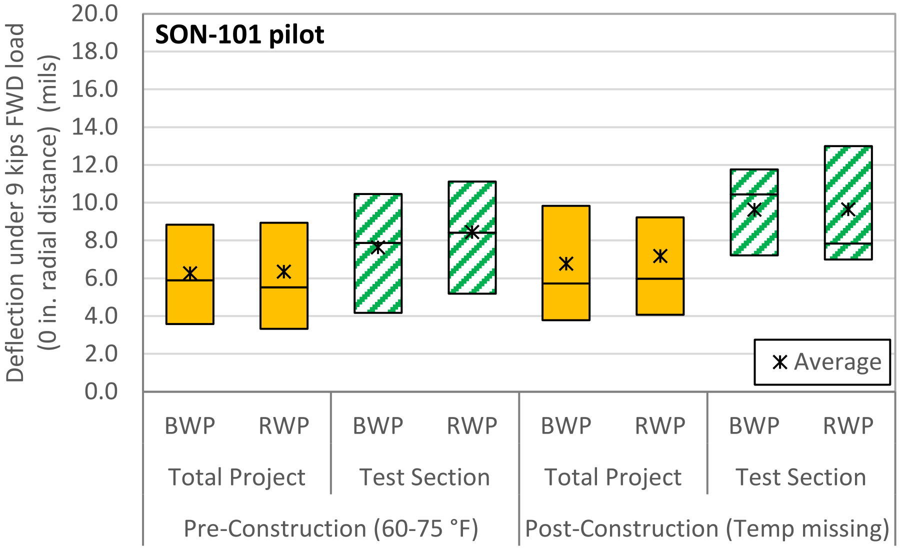


Figure 2.12: FWD evaluation of SON-101 pilot.

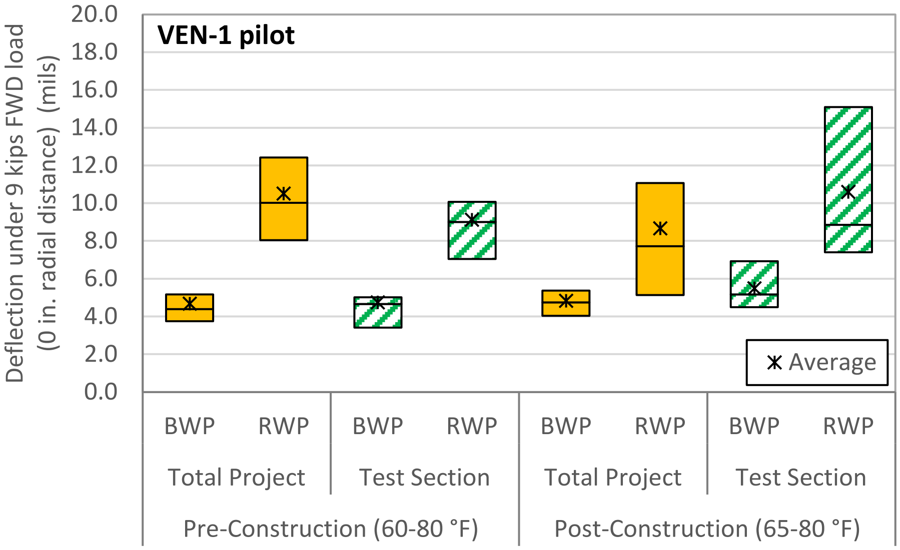


Figure 2.13: FWD evaluation of VEN-1 pilot.

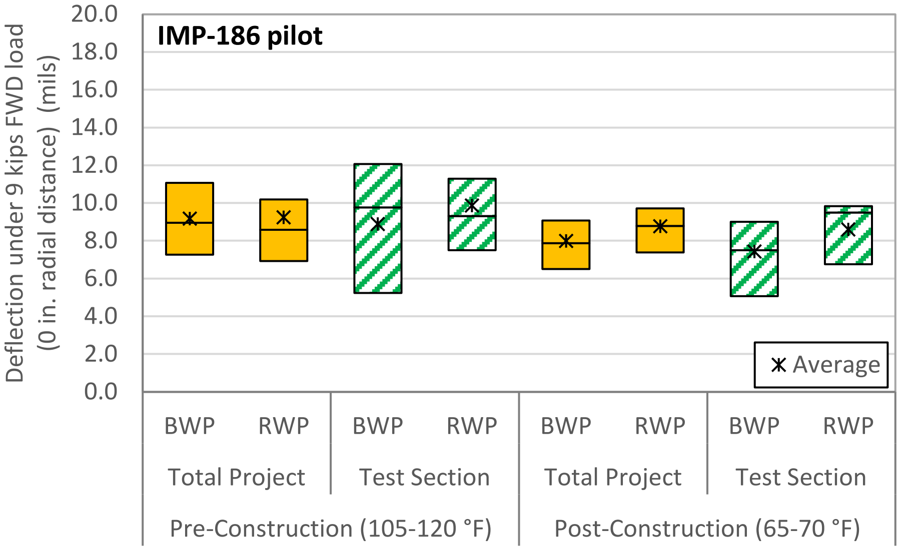


Figure 2.14: FWD evaluation of IMP-186 pilot.

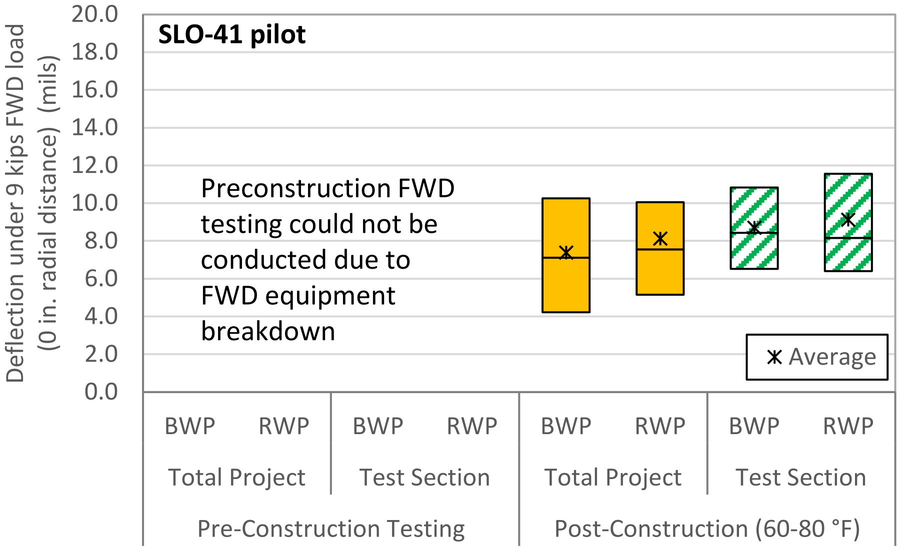


Figure 2.15: FWD evaluation of SLO-41 pilot.

The cracking condition of the different projects is summarized in Table 2.6. The cracking presented in the table is based on the 2021 APCS data. The table does not include specific cracking data for each pilot test section since the visual inspection conducted by UCPRC staff confirmed, for each of the five pilots, that the cracking condition of the test section was similar to the rest of the project. The cracking is presented as the percentage of the total project with cracking type A (single crack) and type B (multiple interconnected cracks).

Table 2.6: Cracking Measured (APCS, 2021) in the Pilot Projects

Pilot ID	Lanes	Cracking A (% length)	Cracking B (% length)	Cracking A+B (% length)
SON-1 (PM 7.100-9.100)[a]	N1 and S1	18	12	30
SON-101[b]	N2	10	22	32
VEN-1[a]	N1 and S1	6	1	7
IMP-186[a]	N1 and S1	5	0	5
SLO-41[a]	N1 and S1	21	1	22

[a] This project has one lane per direction.
[b] This project has three lanes, the three in the north direction; cracking data correspond exclusively to lane 2, which is where the test section is located.

2.3 Climate and Materials Coverage of the Pilots

2.3.1 Climate Coverage

Caltrans has nine climate regions for pavement design and management purposes: North Coast, Central Coast, South Coast, Inland Valley, Low Mountain, South Mountain, High Mountain, Desert, and High Desert *(8)*. The five pilots cover the North Coast, Central Coast, South Coast, Low Mountain, and Desert climate regions (Figure 2.16). Therefore, the collection of pilots is missing the following climate regions:

- South Mountain: This is not considered to be an important limitation of the study as this climate falls between the coastal, desert, and low mountain climate regions, which are all represented in the collection of pilots.
- High Desert and High Mountain: This is not considered to be an important limitation of the study as these regions are mostly above the 3,000 ft. elevation where the Caltrans *Highway Design Manual* (Chapter 630) does not allow the use of RHMA-G.
- Inland Valley: This is considered to be an important limitation because of the large percentage of Caltrans lane-miles in this climate region and its climate characteristics, in particular the high temperatures during summer.

Overall, other than the lack of a project in the Inland Valley region, the pilots cover most of the climate conditions where RHMA-G is currently used in California.

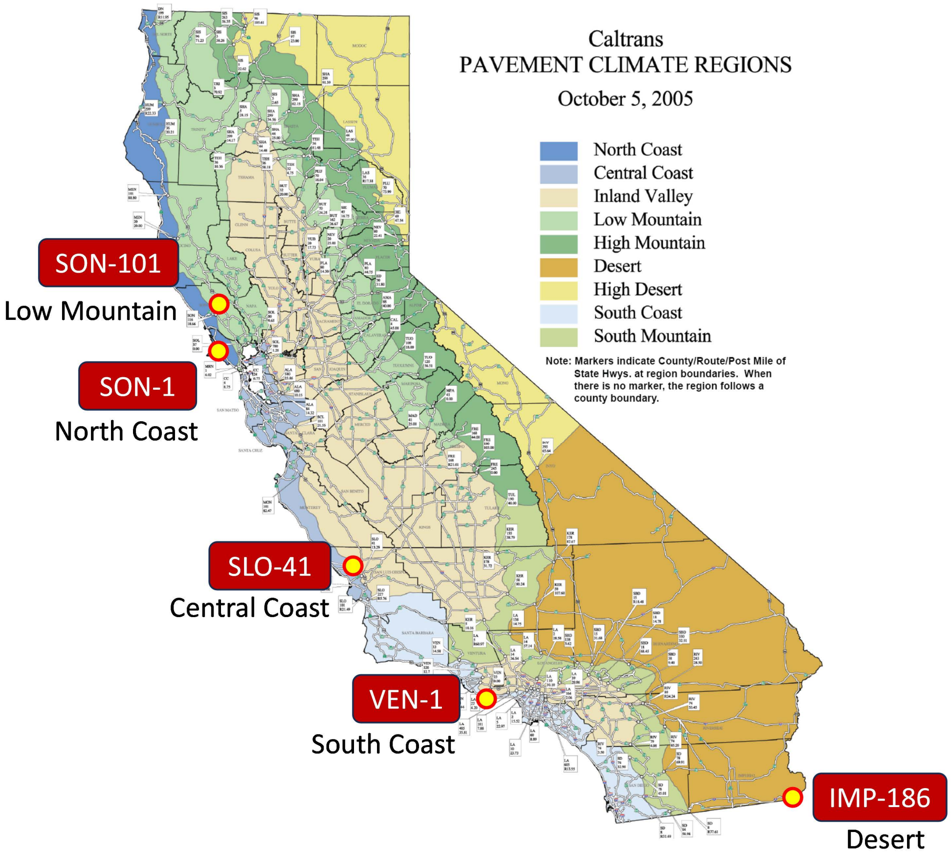


Figure 2.16: Distribution of the pilot projects in California.

2.3.2 Materials Coverage

Table 2.7 shows the main design features of the RMHA-G mixes used in each of the five pilots. The collection of mixes covers the two NMAS that Caltrans Std. Specs. Section 39 considers for RHMA-G, which are 1/2 in. and 3/4 in., and two out of the three base binder PG grades that the Caltrans *Highway Design Manual* (Section 630) allows for RMHA-G (PG 64-16 and 70-10; missing PG 58-22). The collection of mixes also includes three suppliers for the PG 64-16 binder grade, which is important as the properties of the base binders used for rubberized asphalt binder vary considerably—within the same grade—from supplier to supplier in California.

The PG 58-22 base binder missing is not considered to be a critical limitation as this PG is only used in the High Desert and High Mountain climate regions, which are mostly above the 3,000 ft. elevation where the Caltrans *Highway Design Manual* (Chapter 630) does not allow the use of RHMA-G.

The most common geologic types for aggregate sources in California are alluvial, granite, and basalt. Based on UCPRC sampling and evaluation of around 100 asphalt concrete mixes (HMA and RHMA-G) during the last 10 years, around 65% of the mixes contain alluvial aggregates, around 20% contain granitic aggregates, and around 10% contain basaltic aggregates (Figure 2.17). The alluvial source is well represented in the collection of pilot projects as it is used in four of them. One pilot includes basaltic aggregates, and no granite sources are used in any of the pilots. This is not considered to be a critical limitation as the aggregate mineralogy is not believed to have a significant effect on the effects of the RAP addition to RHMA-G.

Overall, the collection of RHMA-G mixes used in the pilots are considered to be a good representation of the RHMA-G mixes currently used in the Caltrans road network.

Table 2.7: Mix Design Features of the RHMA-G

Pilot	NMAS	PG Base Binder	Base Binder Supplier	Aggregate Source
SON-1	1/2 in.	64-16	Valero, Benicia	Blend of marine sedimentary and volcanic (basalt)
SON-101	3/4 in.	64-16	Valero, Benicia	Marine and non-marine sedimentary (alluvial)
VEN-1	1/2 in.	64-16	Valero, Wilmington	Marine and non-marine sedimentary (alluvial)
IMP-186	1/2 in.	70-10	Valero, Wilmington	Marine and non-marine sedimentary (alluvial)
SLO-41	3/4 in.	64-16	San Joaquin Refinery	Marine and non-marine sedimentary (alluvial)

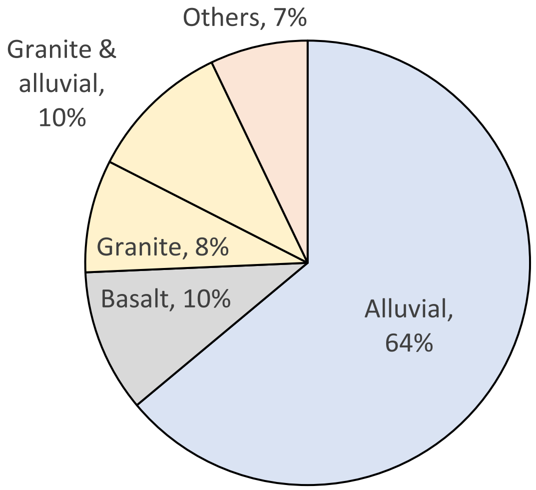


Figure 2.17: Asphalt concrete aggregate types in database of HMA mixes tested by the UCPRC.

2.4 Mix Design Adjustments

The job mix formula (JMF) proposal gradations for the control (without RAP) and test (with RAP) mixes for each of the five pilots are presented in Figure 2.18 and Figure 2.19, respectively. Overall, the gradation of each of the mixes with RAP is almost the same as the gradation of the corresponding control mix.

While all five contractors maintained the control mix gradation with their mixes containing RAP, each of them introduced a number of design adjustments to add the 10% RAP (Table 2.8). The adjustments were as follows:

- The main change that all contractors introduced was a reduction in the design number of gyrations to meet the 4.0% design Va (air voids in the mix). The number of gyrations was 85 to 130 for the control mixes and 50 to 100 for the mixes with RAP (Caltrans specifications range is 50 to 150).
- Two of the contractors (IMP-186 and SLO-41) adopted a design Va different from 4.0% in either the control mix or the mix with RAP. In those two cases, Va was around 1.0% higher in the control mix than in the mix with RAP.
- Based on the JMFs, three contactors (SON-101, IMP-186, and SLO-41) accounted for the RAP binder to meet the minimum 7.5% TWM binder required by Caltrans specifications. In those three pilots, the total binder content of RAP and control mixes was 7.5% TWM. For the mixes with RAP, the 7.5% corresponded approximately to 7.0% virgin asphalt rubber binder plus 0.5% RAP binder. In the other two pilots (SON-1 and VEN-1), based on the JMFs, the total binder content of the mixes with RAP was 8.0% TWM, corresponding approximately to 7.5% virgin asphalt rubber binder plus 0.5% RAP binder, while the control mix binder content remained at 7.5%.

- All the contractors used the same mixing and compaction temperatures for the control mix and the mix with RAP.
- All the contractors maintained the same type of virgin asphalt rubber binder and the same type and dosage of warm mix asphalt or antistripping additive, where applicable, for the control mix and the mix with RAP.

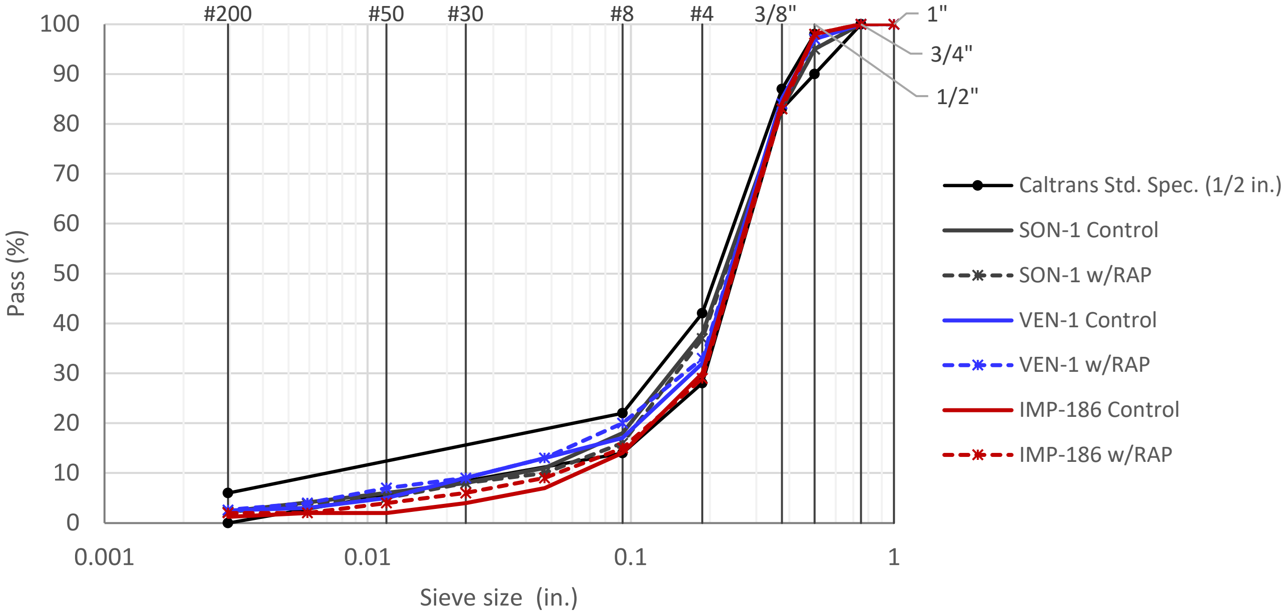


Figure 2.18: Gradation of RHMA-G mixes with 1/2 in. NMAS.

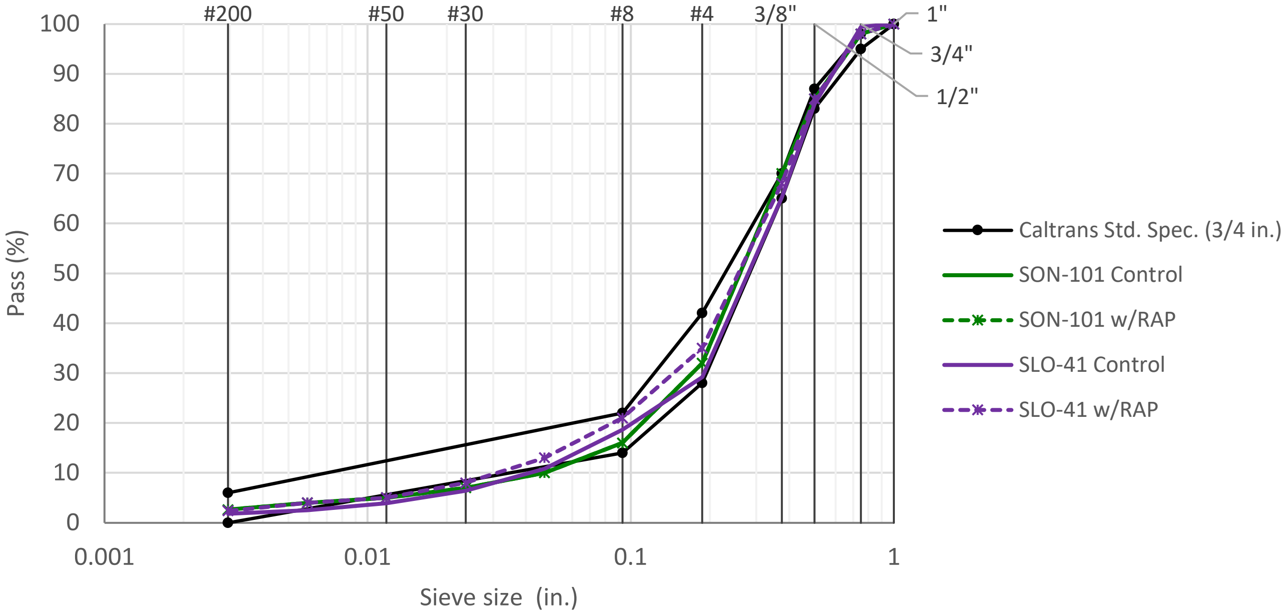


Figure 2.19: Gradation of RHMA-G mixes with 3/4 in. NMAS.

Table 2.8: Mix Design Adjustments to Add 10% RAP

	SON-1		**SON-101**		**VEN-1**		**IMP-186**		**SLO-41**	
	Control	**w/RAP**	**Control**	**w/RAP**	**Control**	**w/RAP**	**Control**	**w/RAP**	**Control**	**w/RAP**
Design Features										
NMAS	1/2 in.	≡ [a]	3/4 in.	≡	1/2 in.	≡	1/2 in.	≡	3/4 in.	≡
PG base binder	64-16	≡	64-16	≡	64-16	≡	70-10	≡	64-16	≡
WMA/Antistrip	0.5%	≡	0.5%	≡	0.5%	≡	0.8%	≡	1.0%	0.5%
Production Temp (°F)										
Mixing (aggregates)	325	≡	320	≡	325	≡	330	≡	315-330	≡
Mixing (binder)	375-425	≡	375-425	≡	375	≡	375	≡	315-330	≡
Compaction	305	≡	300	≡	300	≡	300	≡	300	≡
Gyratory Compaction										
Ndesign	130	100	95	70	95	50	105	60	85	60
Pressure (kPa)	825	≡	800	≡	600	≡	825	≡	825	≡
Hold (minutes)	30	≡	50	≡	30	≡	45	≡	60	≡
JMF Proposal										
Pb	7.50%	8.00%	7.50%	7.50%	7.50%	8.00%	7.50%	7.50%	7.50%	7.50%
Va	4.0%	4.0%	4.1%	4.0%	4.0%	4.0%	5.1%	4.0%	4.0%	3.1%
VMA	19.7%	21.0%	20.5%	21.0%	19.0%	20.0%	20.4%	20.4%	18.7%	18.4%
P200	2.3%	2.2%	2.6%	2.6%	2.5%	2.6%	1.2%	2.0%	2.0%	2.4%
JMF Approval										
Pb[b]	7.42%	7.96%	7.33%	7.41%	7.46%	7.85%	7.52%	7.77%	7.34%	7.7%
Va	2.9%	5.0%	3.4%	3.4%	5.0%	3.9%	5.6%	3.2%	3.7%	2.8%
VMA	18.3%	20.9%	19.2%	20.5%	19.7%	19.5%	20.7%	18.6%	18.0%	19.4%
P200[b]	1.8%	2.8%	2.5%	2.7%	2.9%	3.0%	1.2%	2.3%	1.8%	2.6%
UCPRC Sampled During Construction										
Pb[c]	7.01%	7.14%	6.99%	7.13%	6.30%	6.84%	7.04%	6.35%	5.67%	6.77%
Va	2.4%	3.7%	4.3%	4.0%	7.1%	4.4%	5.4%	9.6%	4.9%	3.9%
VMA	18.7%	20.6%	21.0%	22.1%	20.7%	19.7%	22.7%	25.0%	19.2%	18.0%
P200[c]	2.9%	3.1%	3.0%	3.2%	2.9%	4.2%	2.1%	1.6%	2.7%	4.3%

[a] The symbol (≡) means the same value as the mix without RAP (i.e., the property is the same in the control and test mixes).

[b] Pb determined following AASHTO T308-22 (Ignition method) and P200 determined following California Test 384 (2023, combined virgin aggregate and RAP gradation).

[c] Pb and P200 determined following automated extraction (ASTM D8159-19).

2.5 Reclaimed Asphalt Pavement Properties

The RAP used in the pilot projects is fractionated RAP with NMAS of either 1/2 in. or 3/8 in. Each of the five RAPs was sampled and evaluated at the UCPRC. The RAP binder was extracted following ASTM D8159-19 (automated extraction). The binder was then recovered following ASTM D1856-21 (Abson method) and tested for PG, while the aggregates were graded following AASHTO T30-19.

The binder content; high, intermediate, and low PGs (PGH, PGI, and PGL); and ΔTc are shown for each of the five RAPs in Table 2.9. The gradation results are presented in Figure 2.20. The following are observations about the binder and gradation results:

- The PG of the RAP binder is consistent with the climatic region: higher PGs for IMP-186 RAP (Desert region) than for the other RAPs (North Coast, Central Coast, South Coast, and Low Mountain regions).
- The RAP binder contents (Pb, TWM) are consistent with the RAP gradations, with higher binder contents for finer gradations, and they also match typical HMA binder contents in California. The IMP-186 RAP has a binder content smaller than the other RAPs because its gradation is much coarser (Figure 2.20).
- Based on the RAP Pb, the contribution of the RAP binder to the total binder content of the RHMA-G (i.e., the binder replacement [BR]) was determined. Except for IMP-186, the binder replacement is approximately 5% to 6%. For IMP-186, the binder replacement is approximately 4%.
- Except for IMP-186, the RAP has a relatively high content of fines (at least 50% passing #4 [<4.75 mm] and at least 35% passing #8 [<2.36 mm]). On the contrary the RHMA-G gradation is scarce in those fine particle sizes. The high content of fines represents a challenge for adding RAP to RHMA-G because of the gap gradation required for RHMA-G.

Table 2.9: RAP Binder Properties

Pilot	Binder PG			Binder ΔTc	Binder Pb	RAP BR
	PGH	PGI	PGL			
SON-1	87.9	32.2	-14.3	-4.6	4.8	5.8%
SON-101	99.0	40.6	-7.3	-4.2	4.7	6.1%
VEN-1	98.9	46.4	-3.9	-5.8	4.8	5.8%
IMP-186	102.9	46.8	0.6	-10.4	3.1	3.9%
SLO-41	92.0	42.6	-7.9	-2.0	4.4	5.7%

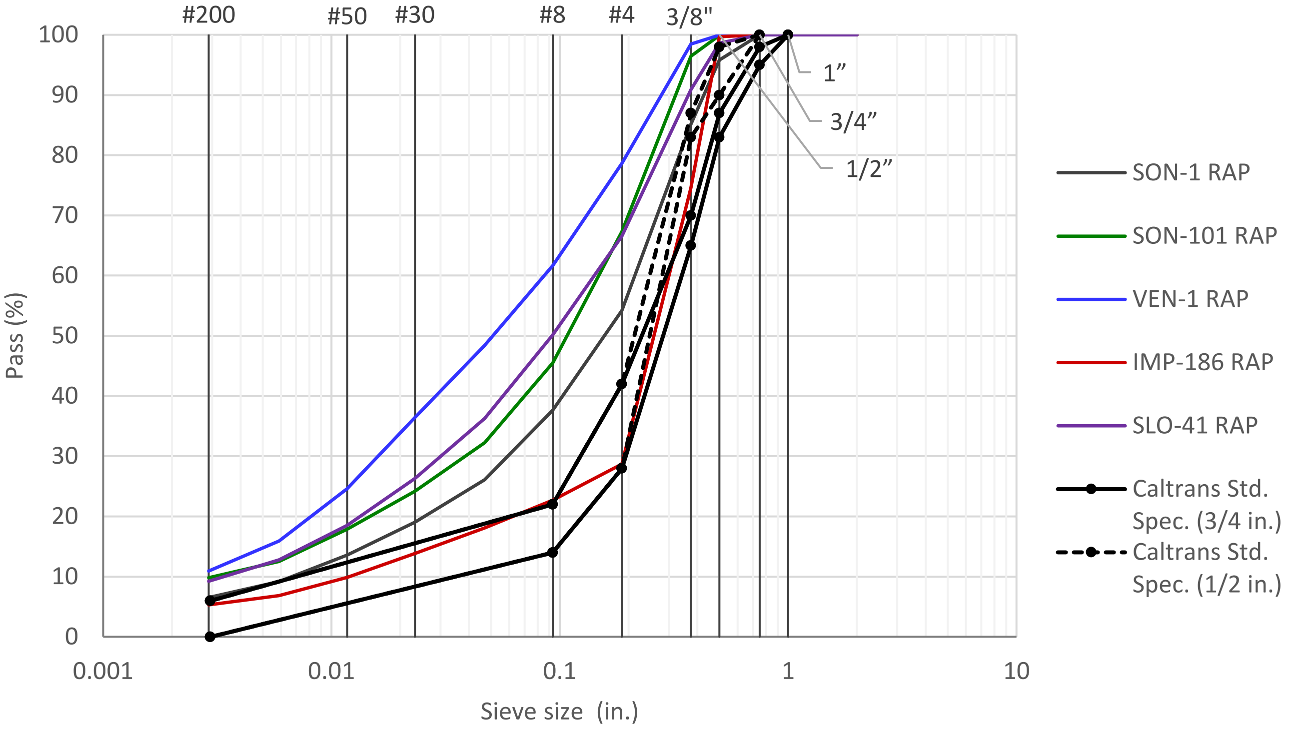


Figure 2.20: Gradation of RAP used in the RHMA-G mixes.

2.6 Field Density of the RHMA-G

The density achieved in the construction compaction of the RHMA-G mixes in the field was evaluated based on cores, following AASHTO T275-17. The core density data were provided by the resident engineer of each of the pilot projects. A summary is shown in Figure 2.21, where Va is 100% minus density. Overall, the density achieved for the mixes with RAP is comparable to the density achieved for the control mixes.

The construction crew did not report any compaction issues with any of the mixes with RAP, and in all cases the core density fell between the 91% and 97% density relative to theoretical maximum density required by Caltrans specifications.

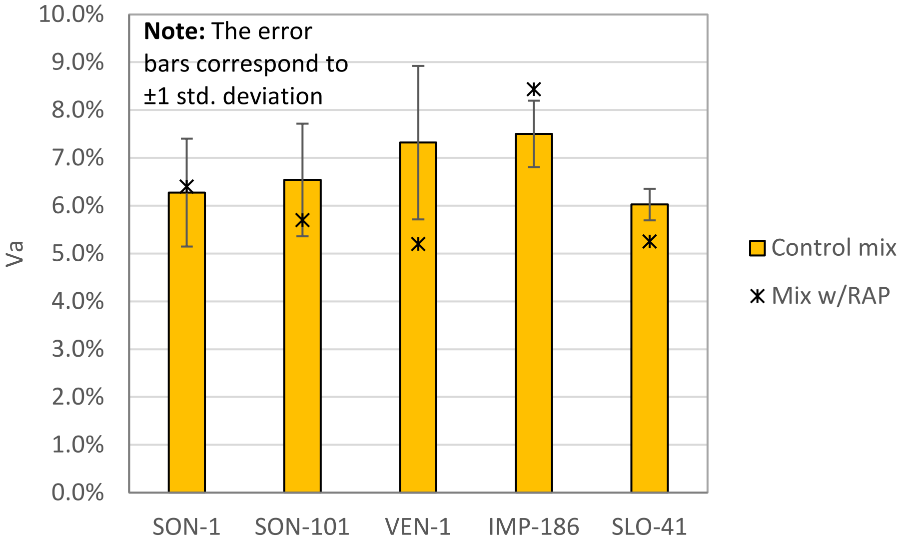


Figure 2.21: Field compaction of the RHMA-G mixes.

3 LABORATORY EVALUATION OF THE ASPHALT MIXES

3.1 Specimens Preparation

All mixes were sampled in 3.5-gallon or 5-gallon metal buckets and immediately shipped to the UCPRC laboratory. In the laboratory, the buckets were kept in a shed to prevent heating due to solar radiation and consequent aging. The specimen preparation included the following steps:

1. Heat the bucket with the lid on at 302°F (150°C) for four hours.
2. Split the bucket content into pans. Spread the mix in a 2 in. (50 mm) lift.
3. Put the pans in an oven at the compaction temperature for 1 to 2 hours.
4. Proceed with compaction with either the gyratory (AASHTO T 312-22) or the rolling wheel (AASHTO PP3).

A set of specimens for each mix was prepared using loose mix conditioned following the draft midterm oven aging (MTOA) procedure developed by Caltrans and the UCPRC. The MTOA included 20 hours at 212°F (100°C). The MTOA set was tested for cracking resistance following ASTM D8225-19 (IDEAL CT). The outcome of the testing of the MTOA mixes will be presented in a separate report on mix aging. All asphalt mix specimens were compacted to 7.0 ± 0.5% Va (air voids content).

3.2 Stiffness

3.2.1 Axial Stiffness

The axial stiffness of the asphalt mix was measured in the asphalt mixture performance tester (AMPT) following AASHTO T 378-22. The test temperatures were 39°F, 68°F, 100°F, and 129°F (4°C, 20°C, 38°C, and 54°C) and the frequency range was 0.1 to 25 Hz. The outcome of the AMPT stiffness testing is the complex modulus (dynamic modulus and phase angle) of the asphalt specimen at each combination of temperature and frequency.

The AMPT dynamic modulus data were fit with the sigmodal master curve, shown in Equation 3.1.

$$\log(\mathrm{E}) = \delta + \frac{\alpha}{1+e^{\beta+\gamma\cdot\log(f_{\mathrm{red}})}} \tag{3.1}$$

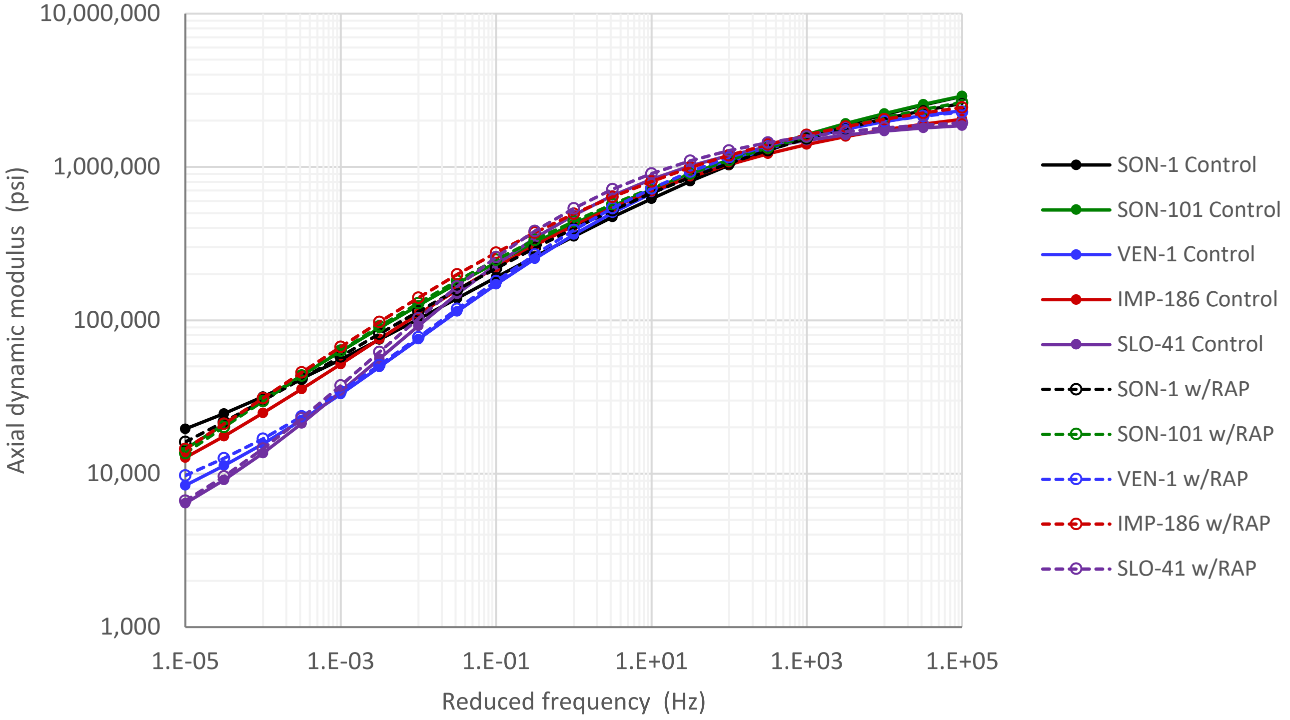
where E is the dynamic modulus; δ, α, β, and γ are fitting parameters; and f_{red} (Equation 3.2) is the reduced frequency:

$$f_{red} = f \cdot a_T \tag{3.2}$$

where f is the frequency and a_T is the time-temperature shift factor; a_T is assumed to depend on temperature as follows: $\log(a_T)=\beta_T\cdot(T-T_{Ref})$, where T is the test temperature, $T_{Ref.}$ is the master curve reference temperature, 68°F (20°C), and β_T is a fitting parameter.

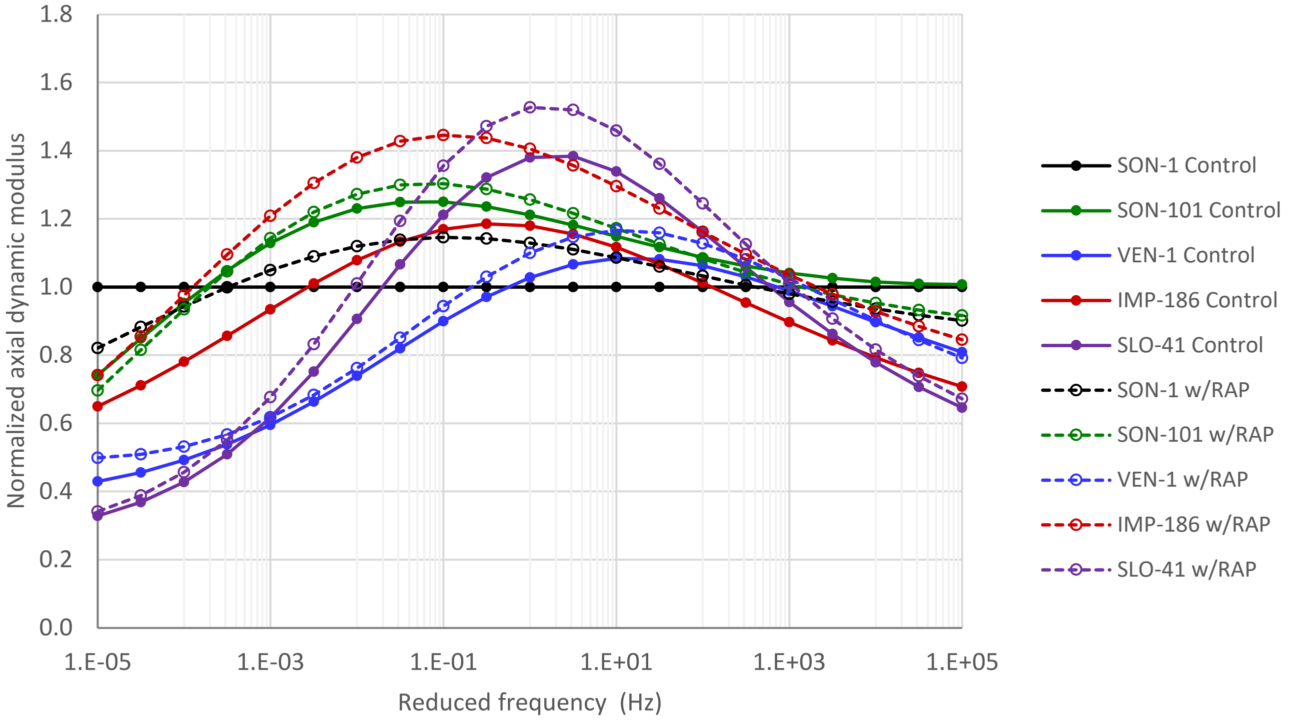
The master curves of the mixes are presented in Figure 3.1 (absolute values) and Figure 3.2 (normalized values versus SON-1 control). Figure 3.3 shows the complex modulus data in the Black space (dynamic modulus versus phase angle). Each series in these figures is the average of five AMPT specimens. The effects of the 10% RAP addition are summarized as follows:

- The effect of the RAP addition on the RHMA-G dynamic modulus is relatively small. Overall, project-to-project differences (e.g., SON-1 control versus VEN-1 control) are higher than the effect of the RAP addition. The same applies to the phase angle.
- As expected, the RAP addition results in an increase of the dynamic modulus, up to 20%. The increase depends on the reduced frequency (combination of temperature and frequency) and it varies from project to project.
- No clear link was found between dynamic modulus increase and binder replacement and RAP properties.



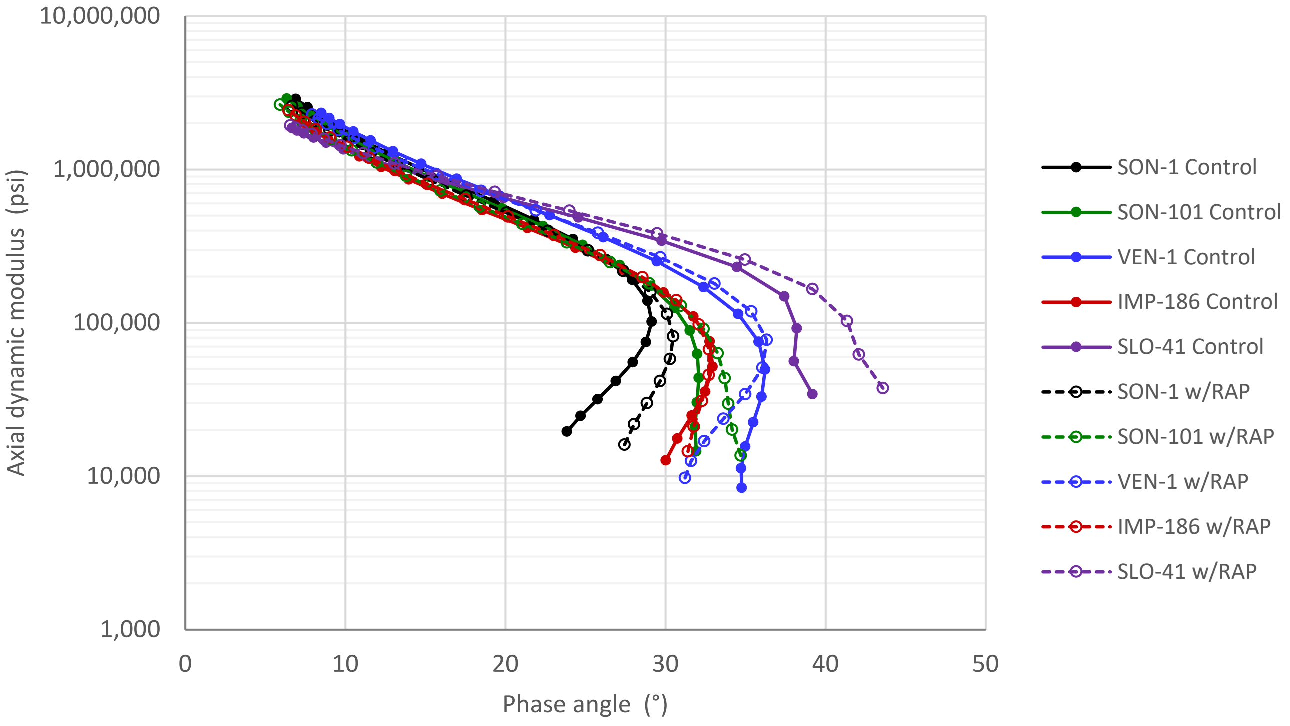
Note: The IMP-186 mixes base binder is PG 70-10; the rest are PG 64-16.

Figure 3.1: Axial dynamic modulus, 68°F (20°C) reference temperature.



Note: The IMP-186 mixes base binder is PG 70-10; the rest are PG 64-16.

Figure 3.2: Axial dynamic modulus (normalized values).



Note: The IMP-186 mixes base binder is PG 70-10; the rest are PG 64-16.

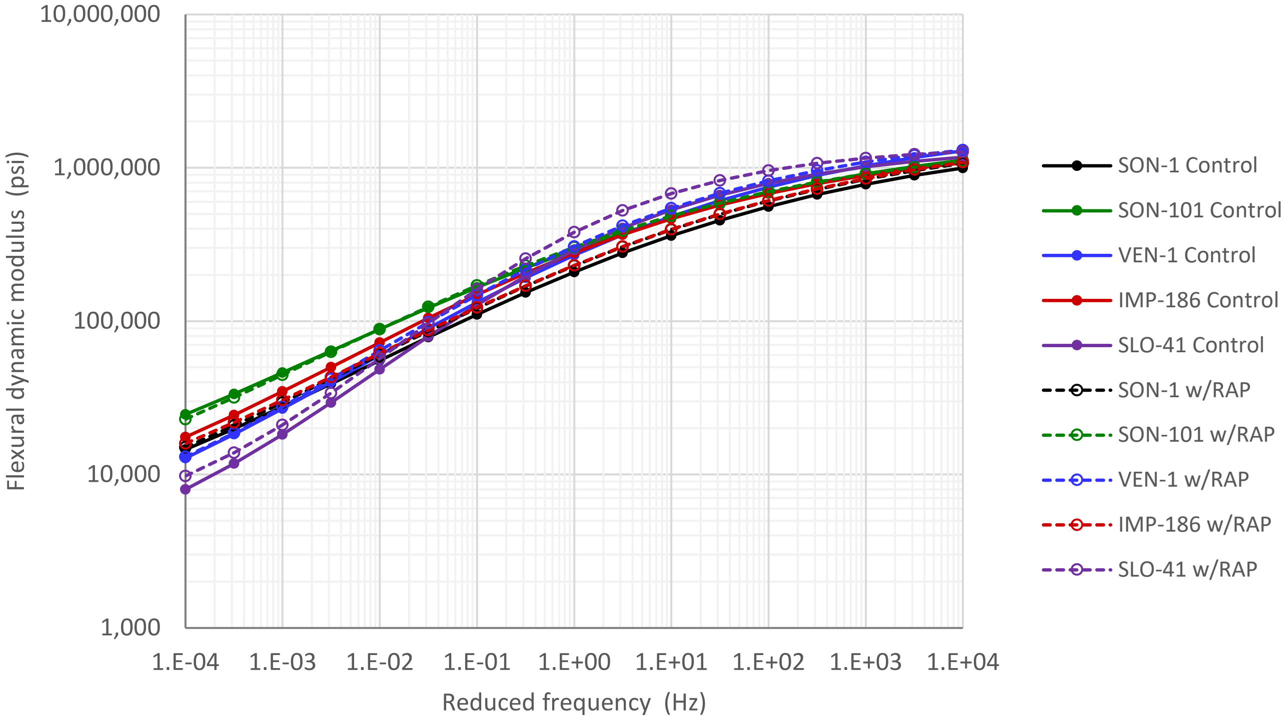
Figure 3.3: Axial complex modulus in the Black space.

3.2.2 Flexural Stiffness

The flexural stiffness of the asphalt mix was measured in the four-point bending (4PB) machine following ASTM D8237-21. The test temperatures were 50°F, 68°F, and 86°F (10°C, 20°C, and 30°C) and the frequency range was 0.01 to 15 Hz. The outcome of the 4PB stiffness testing is the complex modulus (dynamic modulus and phase angle) of the asphalt specimen at each combination of temperature and frequency. The 4PB dynamic modulus data were fit with the sigmodal master curve shown in Equation 3.1, the same used for AMPT axial dynamic modulus.

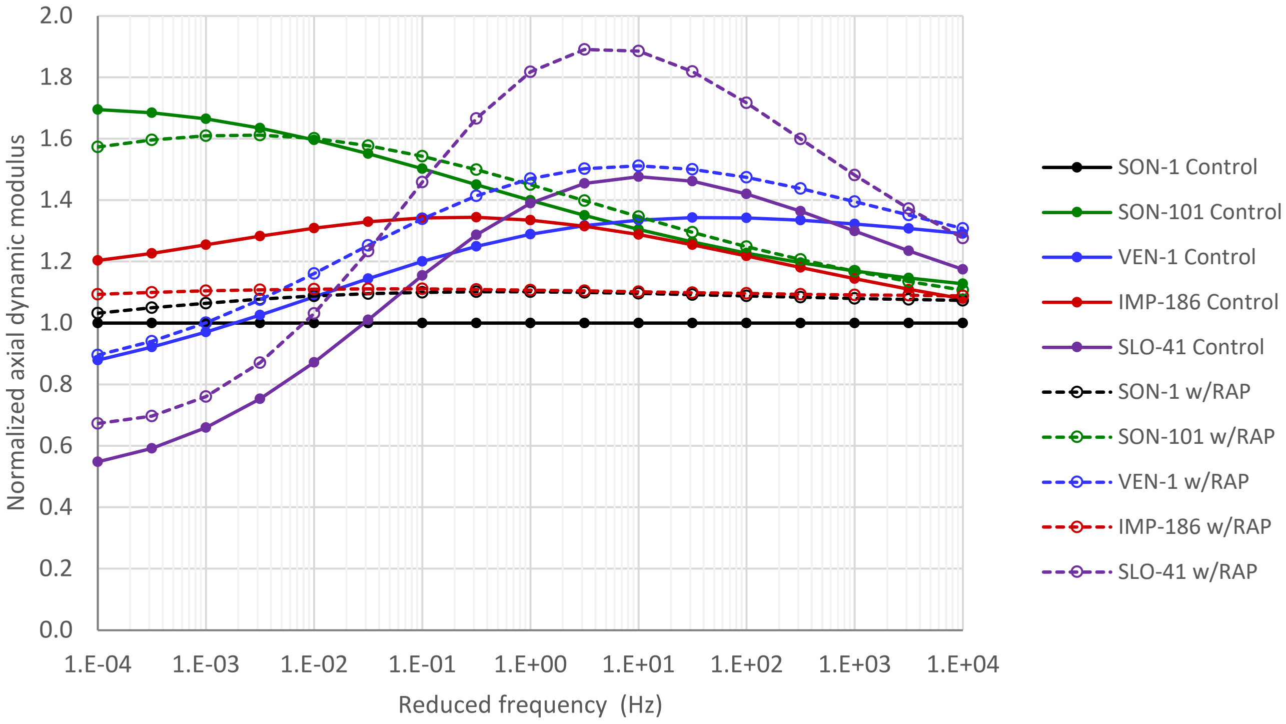
The master curves of the mixes are presented in Figure 3.4 (absolute values) and Figure 3.5 (normalized values versus SON-1 control). Figure 3.6 shows the complex modulus data in the Black space (dynamic modulus versus phase angle). Each series in these figures is the average of three beams. The effects of the 10% RAP addition are summarized as follows:

- The effect of the RAP addition on the RHMA-G dynamic modulus is relatively small. Overall, project-to-project differences (e.g., SON-1 control versus VEN-1 control) are higher than the effect of the RAP addition. The same applies to the phase angle.
- As expected, the RAP addition results in an increase of the dynamic modulus, up to 20%. The increase depends on the reduced frequency (combination of temperature and frequency) and it varies from project to project.
- No clear link was found between dynamic modulus increase and binder replacement and RAP properties.
- The IMP-186 mix shows higher modulus for the control mix than for the mix with RAP, which is not expected and was not seen in the axial modulus values. The reason is not clear.



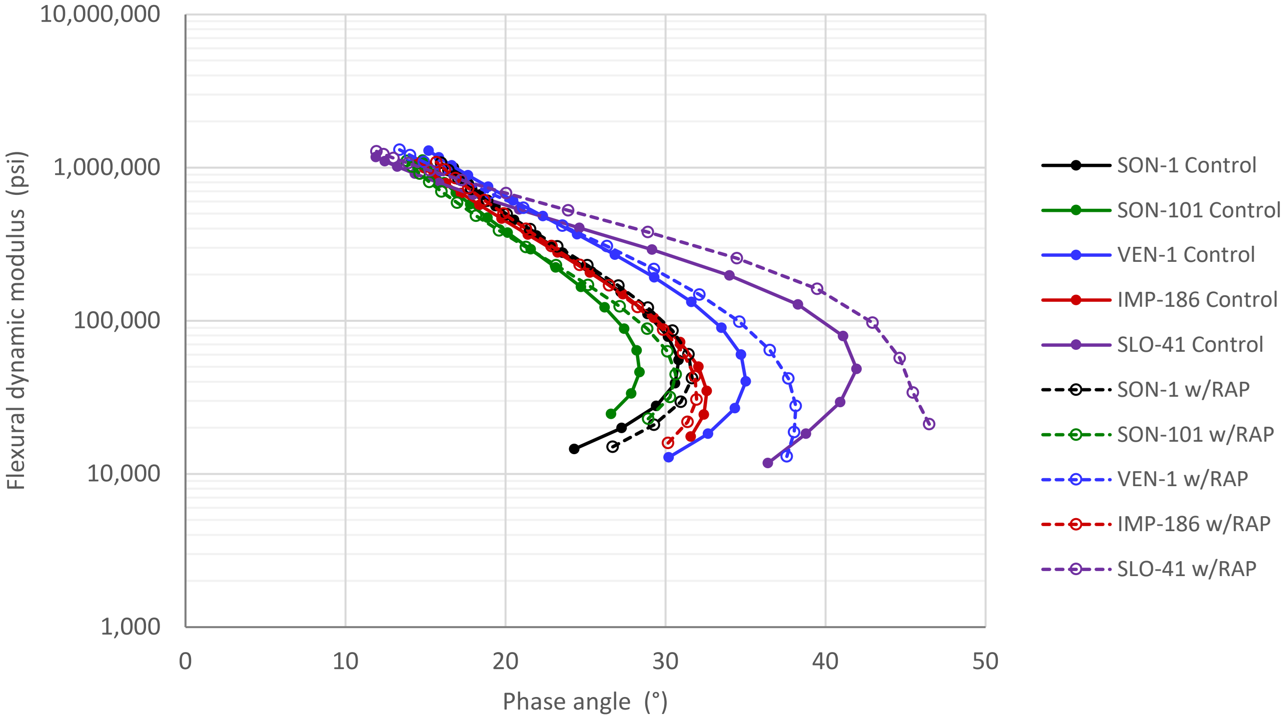
Note: The IMP-186 mixes base binder is PG 70-10; the rest are PG 64-16.

Figure 3.4: Flexural dynamic modulus, 68°F (20°C) reference temperature.



Note: The IMP-186 mixes base binder is PG 70-10; the rest are PG 64-16.

Figure 3.5: Flexural dynamic modulus (normalized values).



Note: The IMP-186 mixes base binder is PG 70-10; the rest are PG 64-16.

Figure 3.6: Flexural complex modulus in the Black space.

3.3 Fatigue Resistance

The flexural fatigue resistance of the asphalt mix was measured in the four-point bending (4PB) machine following ASTM D8237-21. The test temperature was 68°F (20°C) and the test frequency was 10 Hz. The outcome of the 4PB fatigue resistance testing is the fatigue life of the mix for different strain levels. Further, the stiffness reduction curves (dynamic modulus versus number of cycles) obtained in this test are the input for the calibration of *CalME* fatigue resistance material model, which *CalME* uses for simulating field fatigue and reflective cracking performance.

The fatigue life data were fit with the log-log equation shown in Equation 3.3. This log-log equation is typically referred as Wöhler curve.

$$\log(\mathrm{Nf}) \; = a + n \cdot \log(\varepsilon) \tag{3.3}$$

where Nf is the number of cycles to failure, ε is the applied peak-to-peak strain, and a and n are fitting parameters.

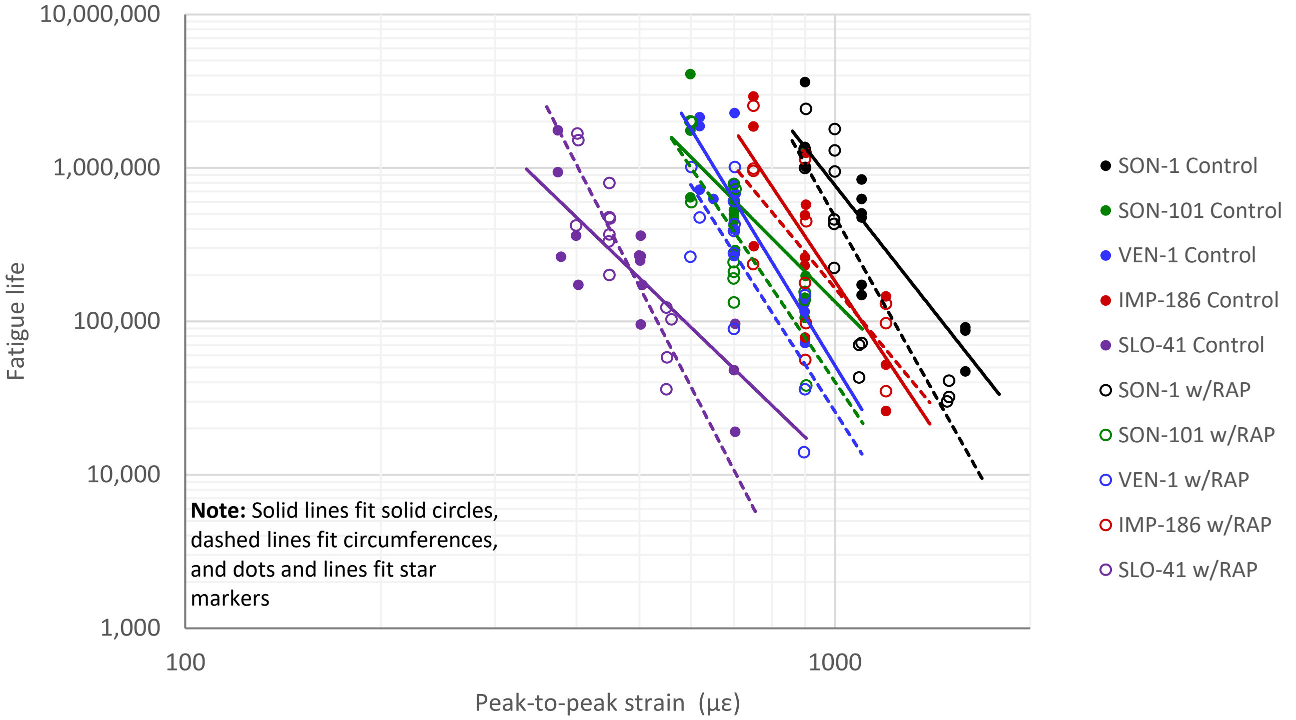
The Wöhler curves of the mixes are presented in Figure 3.7 together with the actual Nf-ε points. The effects of the 10% RAP addition are summarized as follows:

- The effect of the RAP addition on the RHMA-G fatigue resistance is relatively small. Overall, project-to-project differences (e.g. SON-1 control versus VEN-1 control) are greater than the effect of the RAP addition.

- For three of the mixes (SON-1, SON-101, and SLO-41), the RAP addition resulted in an increase of the Wöhler curve slope. In other words, at high strain levels, the RAP addition had a negative effect on the fatigue resistance, but at low strain levels, the effect was positive. The increase in the slope is the expected outcome of the RAP addition as, typically, the higher the stiffness of the mix, the higher the slope of the Wöhler curve. In thin applications, strains are greater while in thicker structures they are smaller, and the effect of RAP on pavement as opposed to mix performance will depend on the structural design context, thin or thick.

- For two of the mixes (VEN-1 and IMP-186), the RAP addition did not result in an increase of the Wöhler curve slope.
    - For the VEN-1 mix, it is likely that the Wöhler curve slope did not increase because the RAP addition was combined with an increase in the total binder content of the mix, from 7.5% to 8.0% TWM. Based on UCPRC binder content determinations, shown in Table 2.7, VEN-1 was the only project where the RAP binder was not accounted for to meet the 7.5% minimum requirement.
    - For the IMP-186 mix, it is likely that the Wöhler curve slope did not increase because of the low RAP binder replacement, which at the same time was due to the low asphalt binder content of this particular RAP (Table 2.8).

- For the VEN-1 mix, the RAP addition produced a small reduction of the fatigue resistance. For the IMP-186 mix, the RAP addition did not have an important impact on the fatigue resistance.



Notes: Solid line is control mix, dashed line is RAP mix. The IMP-186 mixes base binder is PG 70-10; the rest are PG 64-16.

Figure 3.7: Fatigue resistance (4PB).

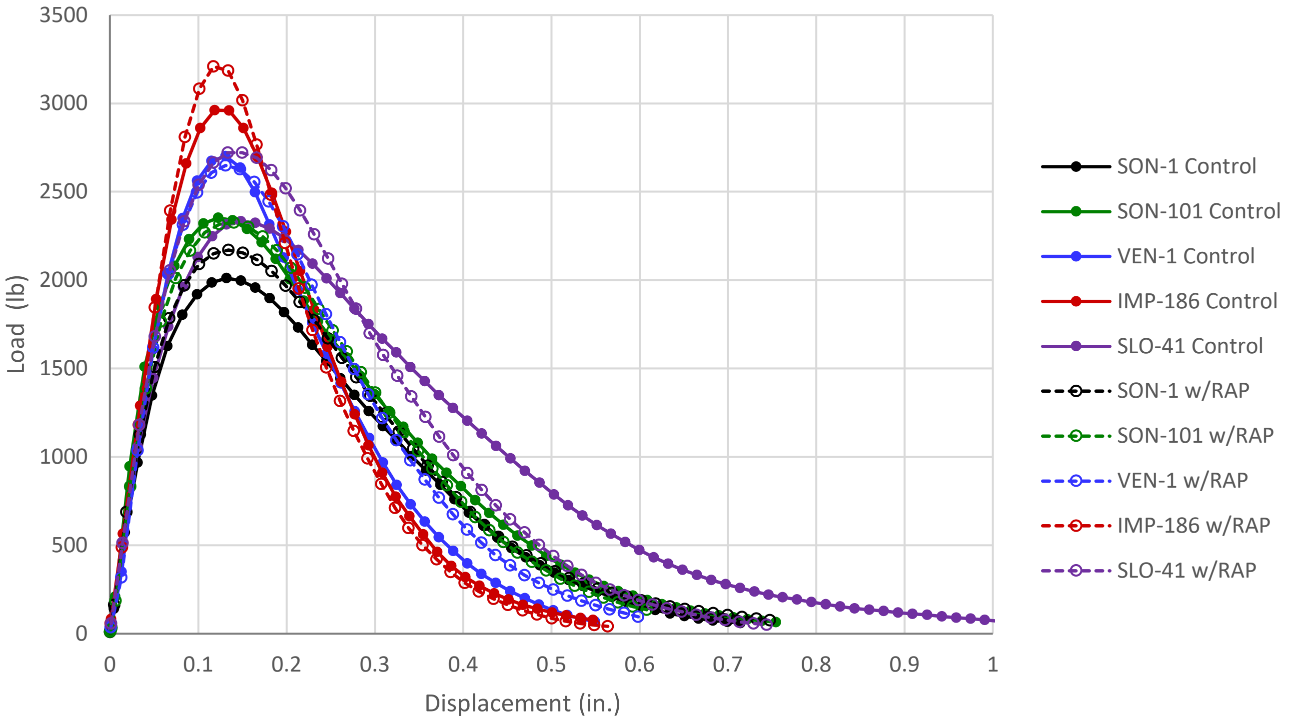
3.4 Fracture Cracking Resistance

The fracture cracking resistance of the asphalt mix was measured by IDEAL-CT following ASTM D8225-19, at 77°F (25°C). The outcome of the IDEAL-CT is a load versus displacement curve that can be used to determine several parameters that are relevant to the facture cracking resistance of the mix, including the failure energy, strength, post-peak slope, and cracking tolerance index (CT_{Index}).

The load versus displacement curves obtained for each of the mixes are shown in Figure 3.8. Each curve in this figure is the average of five specimens. The parameters CT_{Index} and strength are shown in Figure 3.9. The CT_{Index} is plotted versus strength in Figure 3.10. The effects of the 10% RAP addition are summarized as follows:

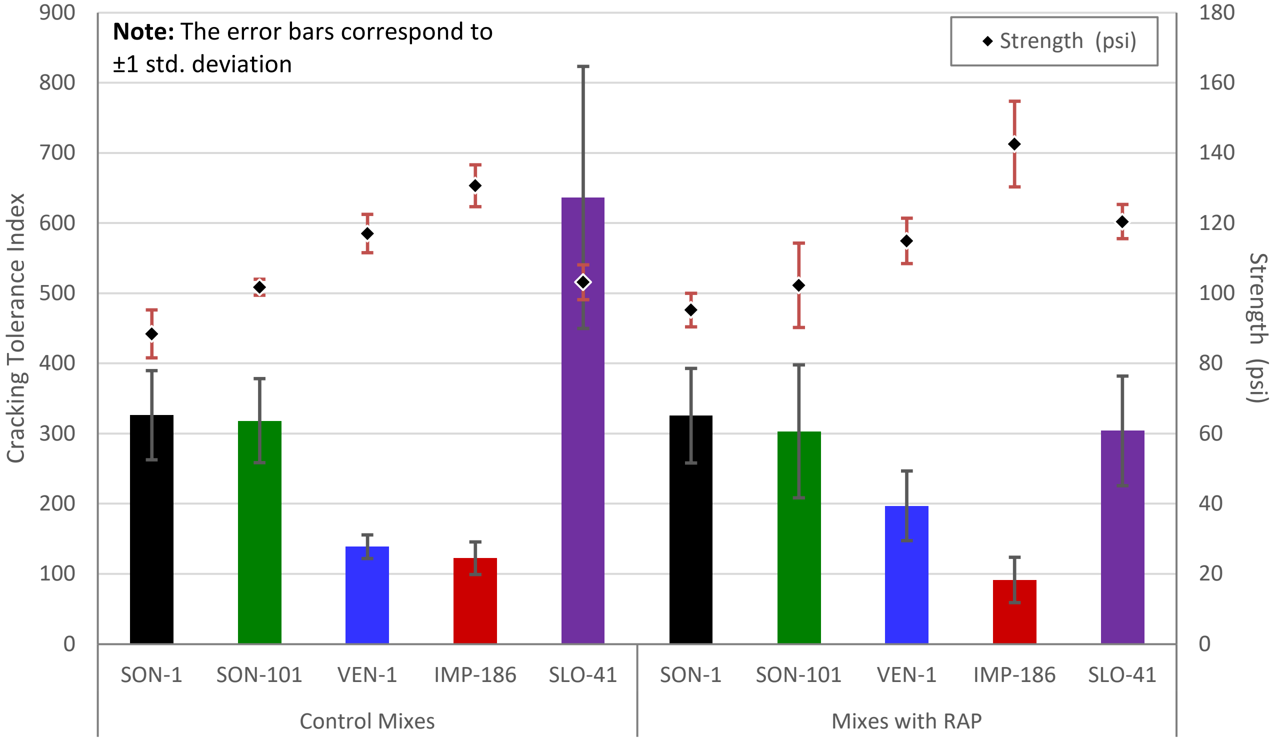
- With the exception of SLO-41 project, the effect of the RAP addition on the RHMA-G cracking resistance, as measured by the IDEAL-CT, is relatively small and project-to-project differences (e.g., SON-1 control versus VEN-1 control) are greater than the effect of the RAP addition.
- The aged binder in the RAP is expected to increase the strength and to reduce the CT_{Index} of the mix, as indicated by the "Hardening" arrow in Figure 3.10. On the contrary, an increase in the total binder content of the mix is expected to reduce the strength and to increase the CT_{Index}, as indicated by the "Softening" arrow in Figure 3.10.

- Differences were observed between the control mix and the mix with RAP for three of the projects—VEN-1, IMP-186, and SLO-41—and were not observed for the other two projects:
    - In the VEN-1 project, the RAP addition acted in the "Softening" direction (Figure 3.10). The mix with RAP had a CT_{Index} around 40% higher than the control mix. This outcome is attributed to the higher total binder content of the VEN-1 mix with RAP compared with the control mix (8.0% versus 7.5%).
    - In the IMP-186 project, the RAP addition acted in the "Hardening" direction (Figure 3.10). The mix with RAP had a CT_{Index} around 25% lower than the control mix. This outcome is attributed to the relatively low binder content of the mix with RAP, around 6.5% based on the UCPRC evaluation (Table 2.7), together with the highly aged binder of the RAP used in this project with a PGH of 102.9°C.
    - In the SLO-41 project, the RAP addition acted in the "Hardening" direction (Figure 3.10). The mix with RAP had a CT_{Index} around 50% lower than the control mix. It is not clear why the RAP produced such high impact in this particular mix.
- For the SON-1 and SON-101 mixes, the RAP addition barely produced any effect on the IDEAL-CT results.



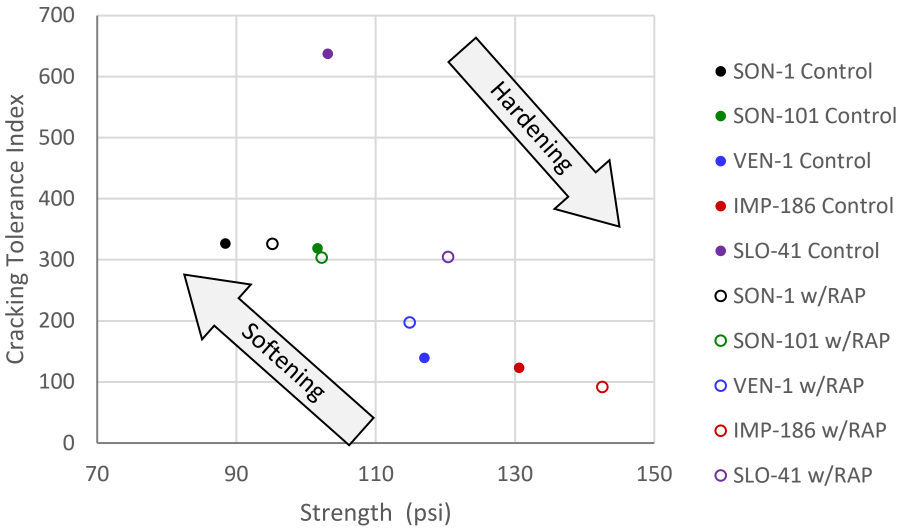
Note: The IMP-186 mixes base binder is PG 70-10; the rest are PG 64-16.

Figure 3.8: IDEAL-CT load versus displacement curves.



Note: The IMP-186 mixes base binder is PG 70-10; the rest are PG 64-16.

Figure 3.9: IDEAL-CT, CT_{Index} and Strength.



Note: The IMP-186 mixes base binder is PG 70-10; the rest are PG 64-16.

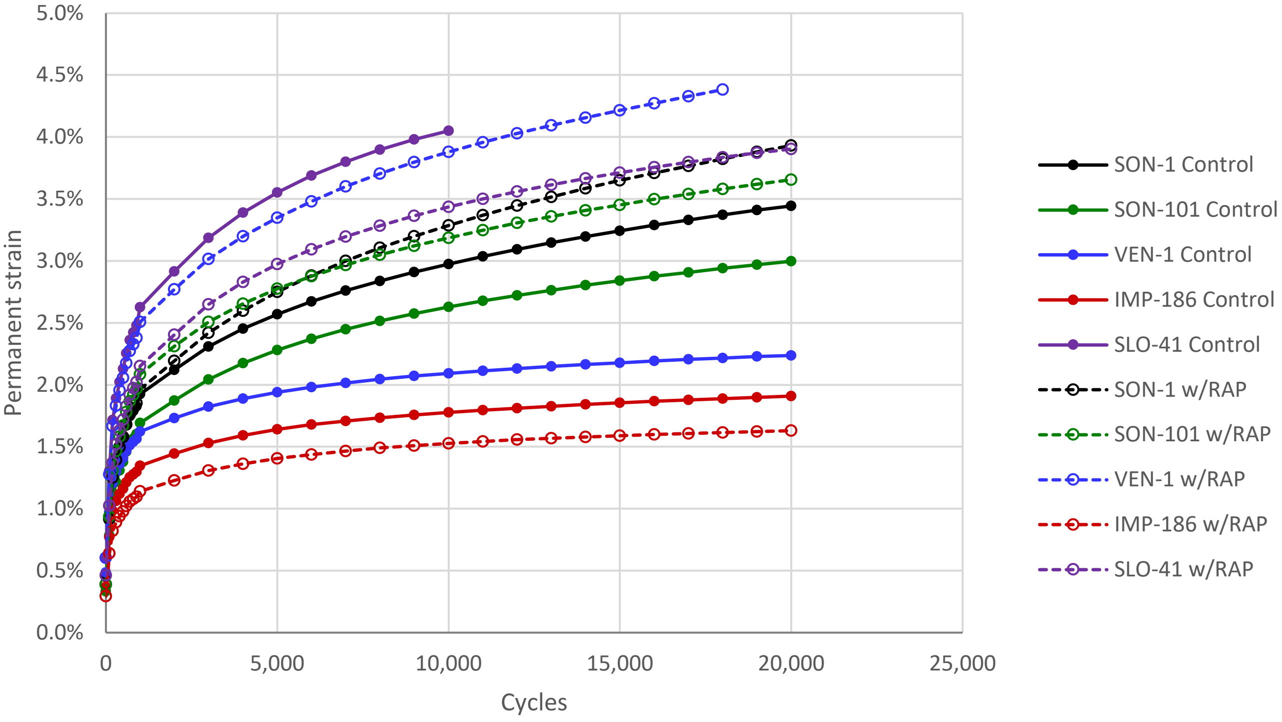
Figure 3.10: IDEAL-CT, CT_{Index} versus Strength.

3.5 Rutting Resistance

The rutting resistance of the asphalt mixes was measured in the asphalt mixture performance tester (AMPT) following AASHTO T 378-22, using the repeated load testing (RLT). The test temperatures were 113°F and 131°F (45°C and 55°C), the axial deviator stress was 70 psi (480 kPa), and the test was conducted under confined (5 psi [35 kPa]) and unconfined conditions. The outcome of the RLT is the specimen permanent deformation versus the number of cycles, a curve that can be used to determine several rutting resistance parameters like the flow number and the number of cycles to 3% deformation.

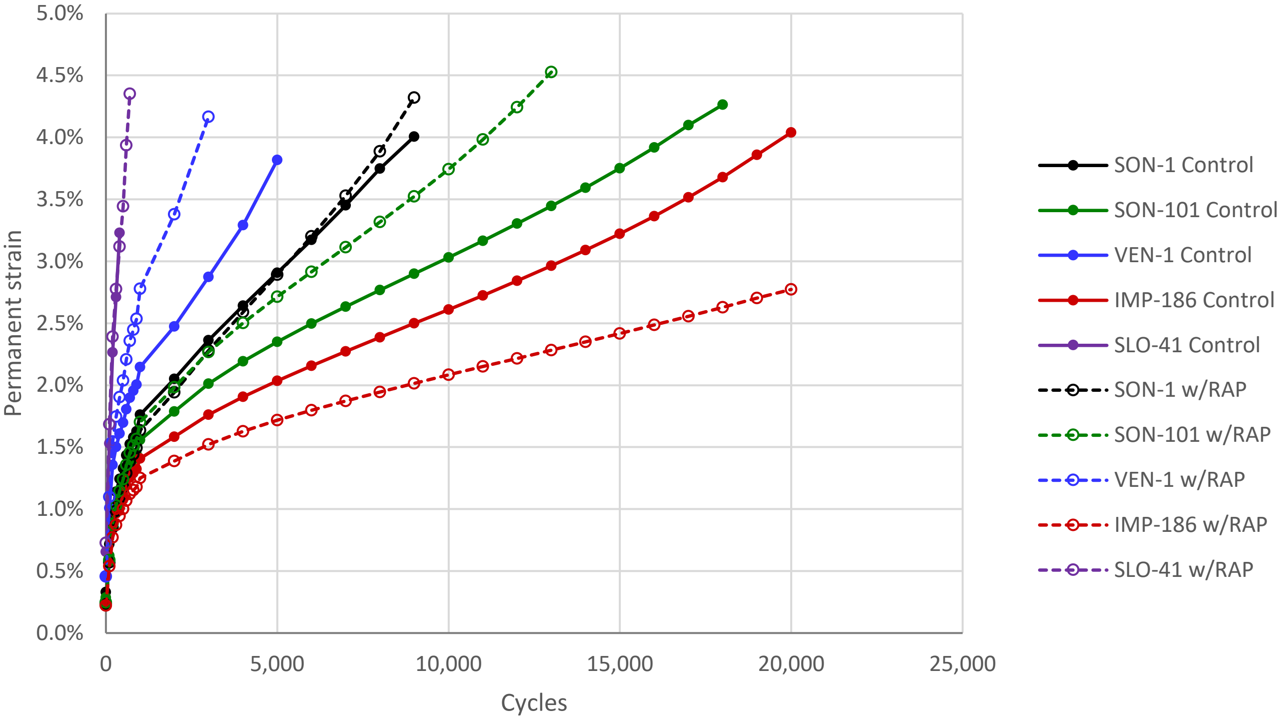
The specimen permanent deformation curves obtained for each of the mixes at 131°F (55°C) under confined conditions are shown in Figure 3.11. The curves obtained at 113°F (45°C) under unconfined conditions are shown in Figure 3.12. Each curve in this figure is the average of three specimens. The effects of the RAP addition are summarized as follows:

- Similar trends can be seen in the confined and unconfined test results.
- Except for the VEN-1 project, the effect of the RAP addition on the RHMA-G rutting resistance is relatively small. Overall, project-to-project differences (e.g., SON-1 control versus IMP-186 control) are greater than the effect of the RAP addition.
- For all the projects except IMP-186 and SLO-41, the permanent deformation resistance was somewhat lower for the mix with RAP than for the control mix, while for the VEN-1 project the difference is substantial. In general, the opposite effect is expected and the addition of RAP is expected to improve rutting resistance. A possible reason why this did not occur for the SON-1 and SON-101 projects is that the aged RAP binder may still produce less permanent deformation resistance than the rubberized binder that it is replacing in the mix. For the VEN-1 project this effect probably also occurred, but a larger contribution to the difference is attributed to the higher total binder content of the VEN-1 mix with RAP compared with the control mix (8.0% versus 7.5%).



Note: The IMP-186 mixes base binder is PG 70-10; the rest are PG 64-16.

Figure 3.11: AMPT repeated load testing (confined, 131°F [55°C]).



Note: The IMP-186 mixes base binder is PG 70-10; the rest are PG 64-16.

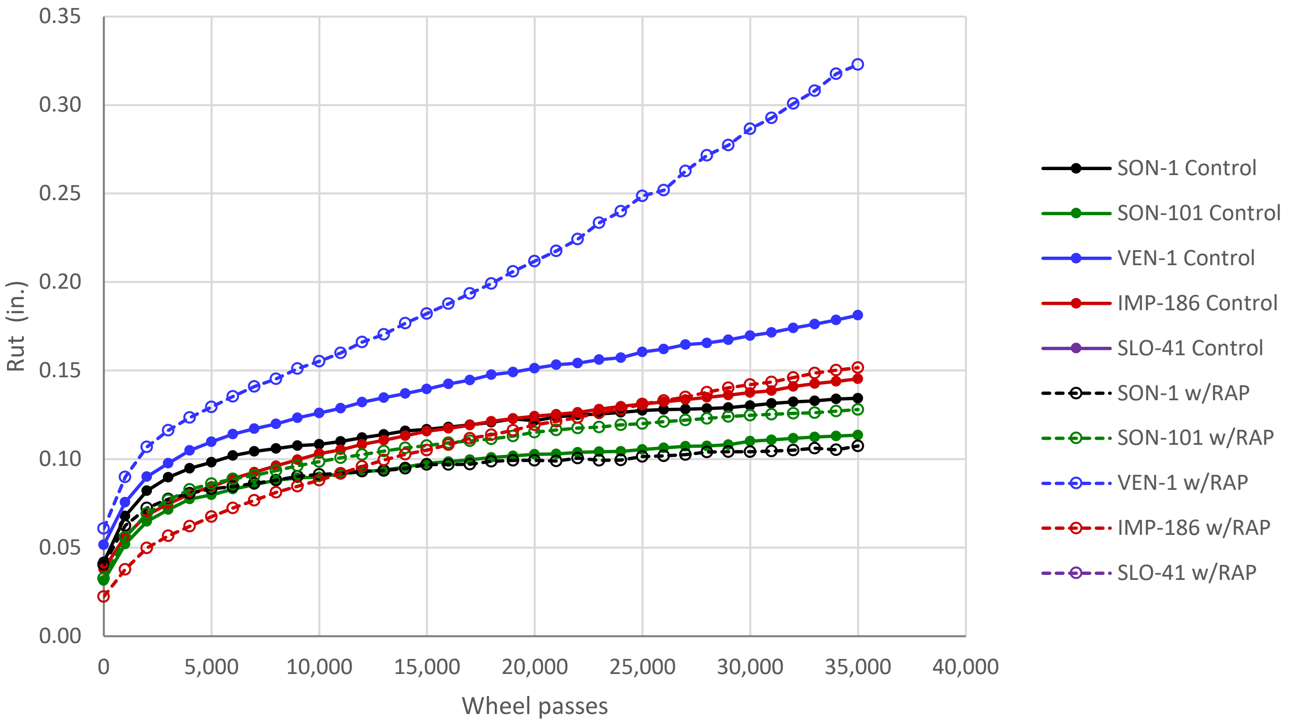
Figure 3.12: AMPT repeated load testing (unconfined, 113°F [45°C]).

3.6 Rutting and Moisture Resistance

The rutting/moisture resistance of the asphalt mix was measured in the Hamburg Wheel-Track (HWT) test following AASHTO T 324-22. The test temperature was 122°F (50°C), regardless of the base binder PG grade. The outcome of the HWT test is the rutting versus the number of cycles, a curve that can be used to determine several rutting/moisture resistance parameters such as the stripping inflection point and the number of cycles to 1/2 in. (12.5 mm) rutting.

The rutting curves obtained for each of the mixes are shown in Figure 3.13. Each curve in this figure is the average of the left and right wheels of the HWT test device. The effects of the RAP addition are summarized as follows:

- Except for the VEN-1 project, the effect of the RAP addition on the RHMA-G rutting/moisture resistance is relatively small. Overall, project-to-project differences (e.g., SON-1 control versus IMP-186 control) are higher than the effect of the RAP addition.
- The SON-101 and VEN-1 results showed less rutting resistance for the RAP mix than for the control mix, with the difference large for the VEN-1 project and small for the SON-101 project.
- For the VEN-1 project, the likely reason that the rutting/moisture resistance was lower for the mix with RAP than for the control mix is the higher total binder content of the VEN-1 mix with RAP compared with the control mix (8.0% versus 7.5%).



Note: The IMP-186 mixes base binder is PG 70-10; the rest are PG 64-16.

Figure 3.13: HWT testing (122°F [50°C]).

4 CalME MODELING OF ASPHALT MIXES PERFORMANCE

Different pavement structures have been modeled in *CalME* to evaluate how the addition of 10% RAP impacts fatigue and reflective cracking performance. All pavement structures have a 0.20 ft. (61 mm) thick RHMA-G surface and a newly placed HMA intermediate layer (layer below the RHMA-G). The thicknesses are fixed for all layers except for the newly placed HMA intermediate layer. The thickness of the intermediate layer was changed from one modeling scenario to another, and it was changed depending on the RHMA-G mix used as the surface. A MATLAB script is used to run the *CalME* engine and programmatically find the thickness of the intermediate layer that is needed to support the design traffic. It should be noted that the thickness was determined at 0.05 ft. increments in keeping with how typical designs are conducted in *CalME*.

Some of the parameters used in *CalME* simulations are the following:

- Simulation type: Monte Carlo
- Number of simulations: 30
- Design life: 40 years
- Traffic volume growth rate: 2%
- Load spectrum: Group1b

The following three structures were modeled: (1) new pavement (or reconstruction), (2) AC on AC overlay (asphalt overlay on old asphalt pavement), and (3) AC on PCC overlay (asphalt overlay on crack and seated concrete pavement). The three structures are described as follows:

- New pavement (fatigue cracking):
  - Surface: 0.20 ft (61 mm) of different RHMA-G mixes, with and without RAP
  - Intermediate layer: HMA mix with PG 64-16 binder and 15% RAP (statewide median)
  - Aggregate base: 1.0 ft. (305 mm) of 2020 Standard AB-Class 2
  - Aggregate subbase: 0.50 ft. (152 mm) of 2020 Standard AS-Class 1
  - Subgrade: 2020 Standard CH or SC (Unified Soil Classification System)
- AC on AC overlays (fatigue plus reflective cracking):
  - Surface: 0.20 ft. (61 mm) of different RHMA-G mixes, with and without RAP
  - Intermediate layer: HMA mix with PG 64-16 binder and 15% RAP (statewide median)
  - Base: 0.35 ft. (107 mm) of 2020 Standard Old HMA
  - Aggregate base: 1.0 ft. (305 mm) of 2020 Standard AB-Class 2
  - Subgrade: 2020 Standard CH or SC (Unified Soil Classification System)
- AC on PCC overlays (fatigue plus reflective cracking):
  - Surface: 0.20 ft. (61 mm) of different RHMA-G mixes, with and without RAP
  - Intermediate layer: HMA mix with PG 64-16 binder and 15% RAP (statewide median)
  - Base: 0.67 ft. (204 mm) of 2020 Standard PCC for CSOL (crack and seat and overlay)
  - Aggregate base: 1.0 ft (305 mm) of 2020 Standard AB-Class 2
  - Subgrade: 2020 Standard CH or SC (Unified Soil Classification System)

It should be noted that these structures are only meant to be reasonable so that the effects of adding RAP can be evaluated. They are not intended to be used as standard designs. The statewide median mix used as intermediate layer provides median performance across all HMA mixes with PG 64-16 binder included in CalME library. The *CalME* simulation factorial is the same for the three structures and is summarized in Table 4.1.

Table 4.1: Factorial for CalME Simulations

Variable	Number of Levels	Levels
Surface Layer Mix Type	11	SON-1 Control, SON-1 w/RAP SON-101 Control, SON-101 w/RAP VEN-1 Control, VEN-1 w/RAP IMP-186 Control, IMP-186 w/RAP SLO-41 Control, SLO-41 w/RAP Statewide median (SWM) RMHA-G[a]
Climate Region	2	Inland Valley South Coast
Subgrade Type	2	CH SC
Truck Traffic Volume	3	TI = 10.0 (2.4 mill. ESALs, AADTT ≈ 500)[b] TI = 12.3 (13.8 mill. ESALs, AADTT ≈ 3000) TI= 14.2 (46.2 mill. ESALs, AADTT ≈ 9000)

[a] The SWM provides median performance across all RHMA-G mixes included in *CalME* library. This means that roughly 50% of the RHMA-G mixes in the *CalME* library perform better than the SWM while the rest of the RHMA-G mixes perform worse than the SWM.

[b] The TI (Traffic Index) is a function of the total number of ESALS (18-kip equivalent single-axle loads) during the pavement design life.

CalME accounts for both fatigue and reflective cracking when determining the cracking performance of the pavement. The reflective cracking comes from the old HMA (AC on AC overlay) or from the cracked and sealed concrete pavement (AC on PCC overlay). The contribution from reflective cracking is not applicable to new (or reconstructed) pavements.

The outcome of the *CalME* simulations is summarized in Figure 4.1. For each RHMA-G surface, Figure 4.1 shows the total thickness (0.2 ft. RHMA-G and designed thickness for the underlying HMA) required to meet the design criteria for each of the three pavement structures (new, AC on AC, and AC on PCC) for each of the three truck traffic levels. The box limits correspond to the first quartile, second quartile (i.e., median), and third quartile of the required thickness distribution. The effect of the RAP addition can be evaluated by comparing the thickness required for each the mixes with RAP versus the corresponding control mix. The following conclusions were drawn from the results shown:

- The effect of the RAP addition on the pavement design is relatively small. Overall, project-to-project differences (e.g., SON-1 control versus IMP-186 control) are higher than the effect of the RAP addition.
- For all pilots except for the VEN-1 and SLO-41 projects, adding 10% RAP to the RHMA-G led to roughly the same pavement designs.

- For the VEN-1 pilot, adding 10% RAP to the RHMA-G led to thicker pavement designs in two scenarios: (1) new pavement under low traffic, up to 0.1 ft. thicker, and (2) AC on PCC overlay under intermediate and high traffic, up to 0.2 ft. thicker. While in the two scenarios the thickness required for the RHMA-G with RAP is greater than the thickness required for the control mix, it is still comparable to the thickness required for the SWM RHMA-G.
- For the SLO-41 pilot, adding 10% RAP to the RHMA-G led to thinner pavement designs, up to 0.4 ft. thinner. This outcome is due to the impact that the RAP produced on the fatigue resistance of this mix, shown in Figure 3.7. For the strain levels expected in the field, up to a few hundred microstrains, the fatigue resistance of the mix with RAP is higher than the fatigue resistance of the control mix.

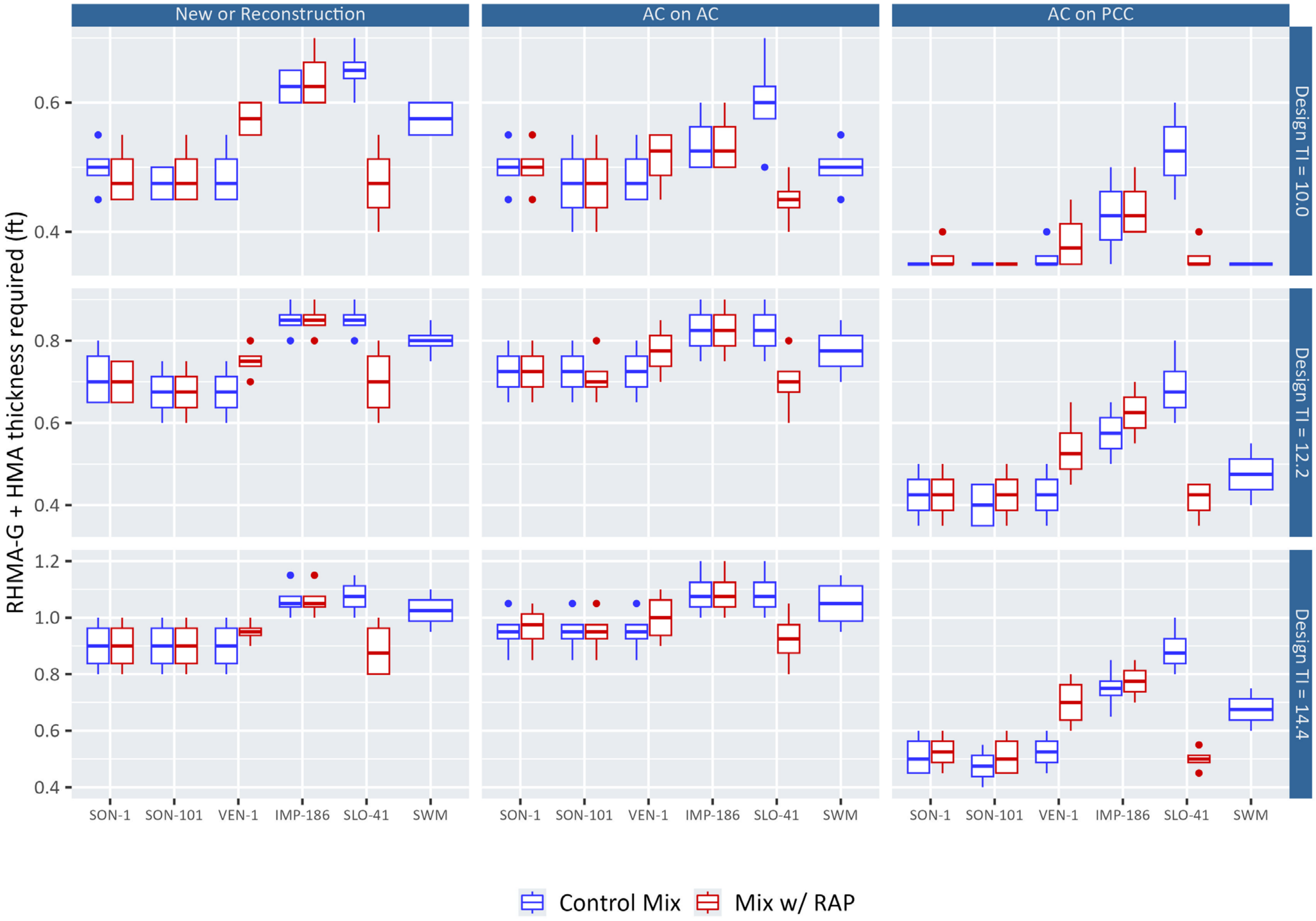


Figure 4.1: Outcome of *CalME* simulations: Required thickness of newly placed asphalt concrete.

5 LIFE CYCLE ASSESSMENT OF THE ADDITION OF RAP TO THE RHMA-G

A comparative cradle-to-gate life cycle assessment (LCA) of the RHMA-G with and without 10% RAP was performed to quantify the environmental impacts of the mixes and to determine the benefits/savings in terms of greenhouse gas emissions and primary energy demand for the manufacturing and material transportation processes, without considering any differences in performance from *CalME* simulations or laboratory testing. The declared unit for this study was defined as 1 metric ton (tonne) of asphalt mixtures. Figure 5.1 shows the system diagram for producing RHMA-G with and without RAP; this diagram shows the processes that are included in the cradle-to-gate analysis. Also, it should be noted that energy consumption, product production, emissions, and waste are calculated for each unit process shown in Figure 5.1.

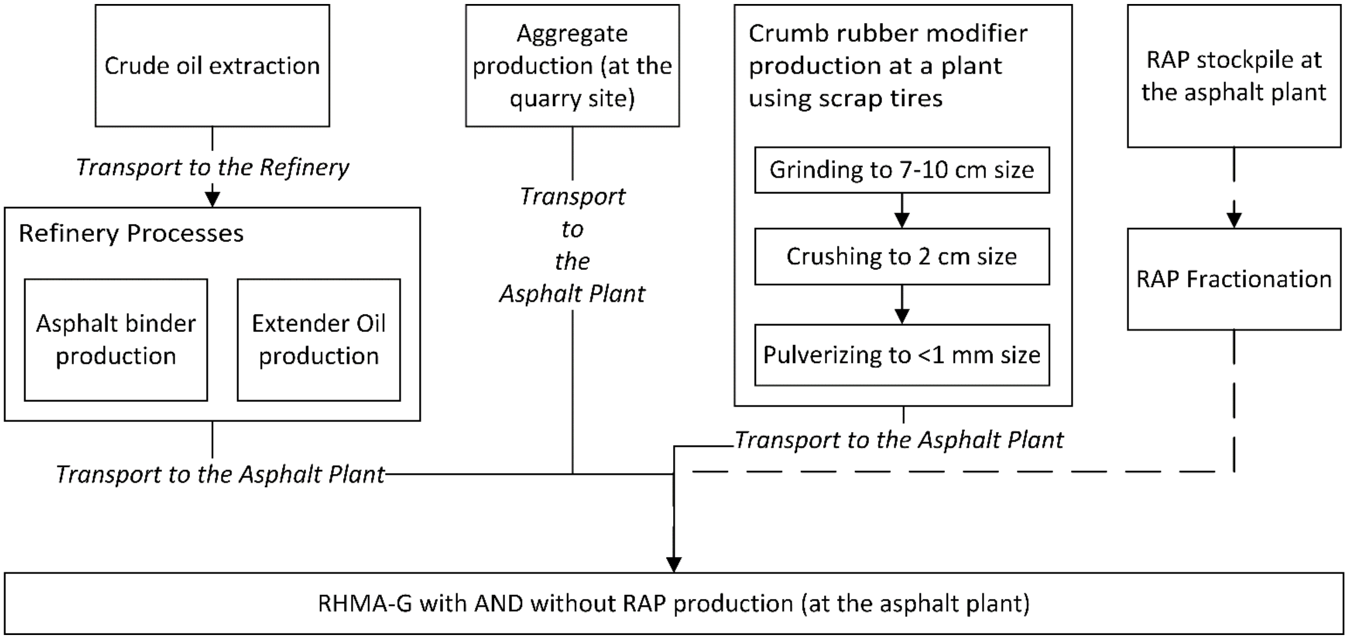


Figure 5.1: Cradle-to-gate system diagram to produce RHMA-G with and without RAP.

The cutoff method is used for the crumb rubber modifier (CRM) as well as the RAP, which means that only the processing of the two materials is considered and environmental impacts quantified. Scrap tire is considered to have zero impacts to start with (i.e., its production and use impacts are allocated to its original product manufacturing process and its original use). Grinding, crushing, and pulverizing the scrap tires to produce less than 1 mm size CRM are considered within the system boundary of this study. Similarly, production of the HMA that became RAP, demolition, and transportation of RAP to the asphalt plant are not included in the system boundary. Rather, it is assumed that the RAP stockpiles already exist at the asphalt plant where the RHMA-G with RAP is being produced. Only the fractionation of the RAP material at the plant and its related impacts are included in the analysis. It is also assumed that the asphalt plant operations to produce RHMA-G and RHMA-G with 10% RAP are the same, and no extra energy or heating is needed at the plant with the addition of RAP. No other additives or rejuvenator agents other than the extender oil (used to produce the asphalt rubber binder) are used in any of the mixes.

The Caltrans *eLCAP* software was used to quantify the environmental impacts of the control RHMA-G and the RHMA-G with 10% RAP *(7)*. *eLCAP* uses California-specific life cycle inventory data and models, considering the construction practices of Caltrans. The models for each material/process, data sources, assumptions, and calculation methods were defined as part of the *eLCAP* development *(7)*. The life cycle impact assessment (LCIA), presented in the following discussion, included global warming potential (GWP) and primary energy demand (PED).

The LCIA was conducted for the control RHMA-G and the RHMA-G with 10% RAP based on JMF properties. The outputs are summarized in Table 5.1. The outcomes of the LCIA of the control RHMA-G do not change from project-to-project as the design variables that contribute to the LCIA are the same in the five pilot projects. This is the reason why only one "Control RHMA-G" is included in Table 5.1. Regarding the RHMA-G with 10% RAP, only the outcomes for the SON-101 and VEN-1 pilot projects are presented in Table 5.1. The SON-101 pilot represents the scenario where the RAP binder is accounted for to meet the 7.5% minimum requirement set by Caltrans (Pb is 7.5% for both the control RHMA-G and the RHMA-G with 10% RAP). The VEN-1 pilot represents the scenario where the RAP binder is not accounted for to meet the 7.5% minimum requirement set by Caltrans (Pb is 7.5% for the control RHMA-G and 8.0% for the RHMA-G with 10% RAP).

Table 5.1: LCIA for One Metric Tonne of RHMA-G With and Without 10% RAP

	GWP Excluding Biogenic Carbon (kg CO2-e)			**PED from Renewable and Nonrenewable Resources (net calorific value in MJ)**		
	Control RHMA-G	**RHMA-G with 10% RAP (SON-101), 0.5% reduction of virgin binder content**	**RHMA-G with 10% RAP (VEN-1), no reduction of virgin binder content**	**Control RHMA-G**	**RHMA-G with 10% RAP (SON-101), 0.5% reduction of virgin binder content**	**RHMA-G with 10% RAP (VEN-1) , no reduction of virgin binder content**
HMA Production, Cradle-Gate	77.9	74.2 (95.3% of Control RHMA-G)	77.0 (98.8% of Control RHMA-G)	3839	3620 (94.3% of Control RHMA-G)	3838 (100% of Control RHMA-G)
Aggregate Production	2.6	2.4	2.3	58	52	52
Virgin Asphalt Binder Production	27.1	25.5	27.3	3001	2817	3016
RAP Fractionation	—	0.005	0.005	—	0.111	0.111
Only Asphalt Plant Operations	23.8	23.8	23.8	402.6	402.6	402.6
Extender Oil Production	4.4	4.1	4.4	129	120	129
Material Transport (Cradle-Gate)	20.1	18.5	19.2	248	228	237

Based on the cradle-to-gate results presented in Table 5.1, the addition of 10% RAP to the RHMA-G resulted in GWP savings between 1% and 5% and PED savings between 0% and 6%. The upper limit of the impact reductions (5% GWP and 6% PED) are expected when the RAP binder is accounted for to meet the 7.5% minimum asphalt content requirement set by Caltrans (SON-1 scenario). On the contrary, the GWP and PED savings are very small when the RAP binder is not accounted for to meet the 7.5% minimum requirement (VEN-1 scenario) and the virgin binder content is not reduced.

6 RESULTS AND DISCUSSION

The results of the testing of the asphalt mixes, the *CalME* modeling, and the LCA are reviewed in the following discussion, which is organized around the different questions that this research study was expected to answer (Section 1.3).

6.1 How Do the Mechanical Properties of the RHMA-G Change Due to the Addition of 10% RAP?

The addition of 10% RAP had minor effects on the mechanical properties of the RHMA-G. With just a few exceptions, reviewed in the following discussion, the effect of the RAP addition was negligible compared with project-to-project differences. Overall, the stiffness increased somewhat (maximum 20%) and the fatigue resistance at very high strain levels (at or above 1000 με) slightly decreased. At the strain levels that take place in the road, which are generally less than 400 με for thin overlays or pavements and smaller as thickness increases, the fatigue resistance of the RHMA-G remained essentially unchanged or improved after the addition of RAP. These conclusions are supported by the data shown in Chapter 3 and the summary plots in Figure 6.1 (ε_6, which is peak-to-peak strain that produces 10^6 repetitions fatigue life), Figure 6.2 (axial dynamic modulus at 10^{-4}, 1, and 10^{+4} Hz reduced frequency, which correspond to high, intermediate, and low temperatures), and Figure 6.3 (HWT test, rut after 15,000 passes).

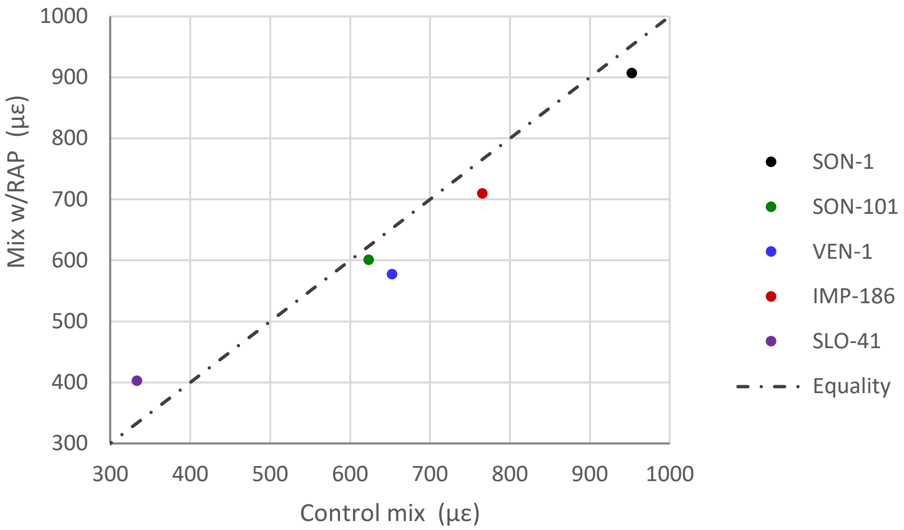
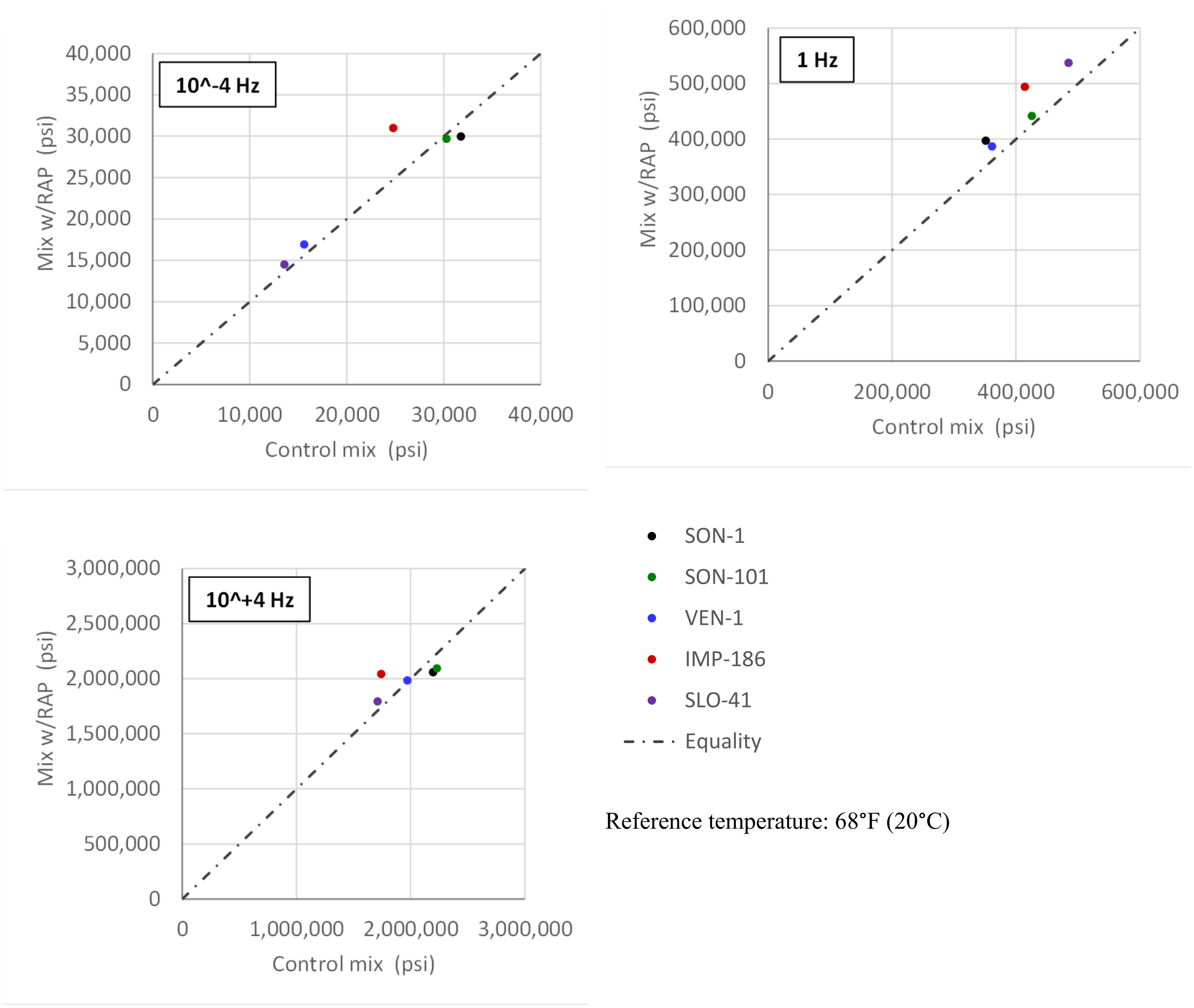


Figure 6.1: RAP effect on ε_6 (strain corresponding to 1 million repetitions to failure).



Reference temperature: 68°F (20°C)

Figure 6.2: RAP effect on stiffness (AMPT axial dynamic modulus).

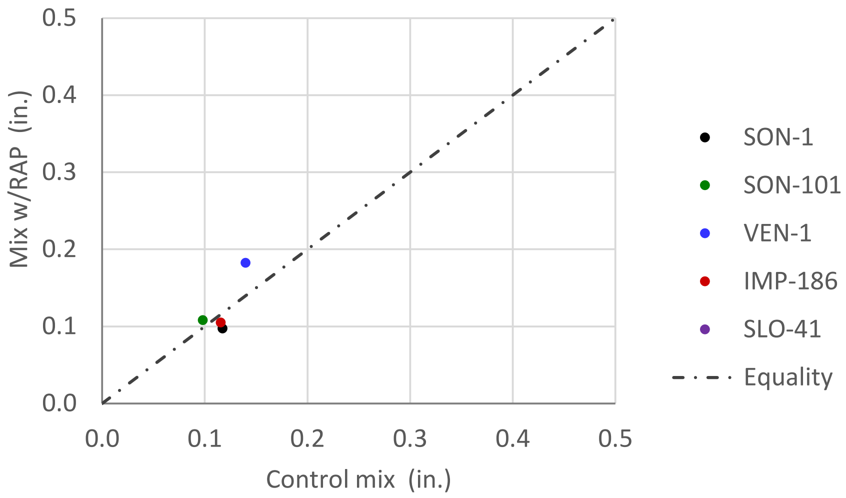


Figure 6.3: RAP effect on rutting/moisture resistance (HWT test, 122°F [50°C], rut after 15,000 passes).

In two of the projects, VEN-1 and IMP-186, some differences between the mechanical properties of the RHMA-G with RAP and the corresponding control mix were observed. But the differences were related to the binder content rather than to the RAP addition. In the VEN-1 project, the mix with RAP had 0.5% total binder content above the control mix, based on UCPRC binder content determination (Table 2.7). This outcome likely resulted in the mix with RAP being softer than the control mix, which resulted in slightly lower strength, higher CT_{Index}, and worse rutting performance. In the IMP-186 project, the mix with RAP had 0.7% total binder content less than that of the control mix, based on UCPRC binder content determination. This outcome likely resulted in the mix with RAP being stiffer than the control mix, which resulted in slightly higher strength, lower CT_{Index}, and better rutting performance.

6.2 What Is the Expected Field Fatigue and Reflective Cracking Performance of the RHMA-G with 10% RAP Compared with the RHMA-G Without RAP When Used as a Surface Layer?

Except for the VEN-1 pilot project, the addition of 10% RAP did not have negative effects on the expected fatigue and reflective cracking performance based on *CalME* modeling simulations. Even considering the VEN-1 pilot, project-to-project differences were greater than the effect of the RAP addition.

For the VEN-1 pilot, the addition of RAP resulted in worse simulated fatigue or reflective cracking performance in two scenarios: new pavement under low traffic and AC on PCC overlay under intermediate and high traffic. Because of the relatively poor performance of the mix with RAP, the thickness of the intermediate layer had to be increased up to 0.2 ft. compared with the pavement structures with control RHMA-G surface. Still, the cracking performance of the VEN-1 mix with RAP was comparable to the cracking performance of the statewide median RHMA-G. The statewide median RHMA-G provides median performance across all RHMA-G mixes included in *CalME* library.

In summary, the impact of the 10% RAP addition on the cracking performance of the pavement was either negligible or comparable the differences expected between typical RHMA-G mixes without RAP.

6.3 What Adjustments to RHMA-G Design, Fabrication, and Construction Are Recommended When Adding 10% RAP?

The third question that was formulated in this study can be answered by addressing the three following questions?

1. What is the approach that the different contractors followed in the pilot projects (in order to add 10% RAP)?
2. How did the approaches work in the different pilot projects?
3. What is the recommended approach?

6.3.1 What Is the Approach That the Different Contractors Followed in the Pilot Projects?

The approach for adding 10% RAP in the five pilot projects included the following two steps:

- Step 1: Adjusting the proportions of the different virgin aggregate bins to match the gradation of the control mix (without RAP).

- Step 2: Reducing the design number of gyrations to meet the 4.0% design Va (air voids in the mix), with one exception. In the SLO-41 pilot, the reduction of the number of gyrations was accompanied by a reduction in design Va from 4.0% to 3.0%.

Caltrans specifications require a minimum of 7.5% total binder content in the RHMA-G. Based on the JMFs, two approaches were followed by the contractors regarding consideration of the RAP binder:

- Approach 1 (SON-101, IMP-186, and SLO-41): Consider that the RAP binder contributes to the minimum 7.5%. Based on this approach, the total binder content of the mix with RAP is 7.5%, roughly corresponding to 7.0% virgin asphalt rubber binder plus 0.5% RAP binder.
- Approach 2 (SON-1 and VEN-1): Consider that the RAP binder does not contribute to the minimum 7.5%. Based on this approach, the total binder content of the mix with RAP is 8.0%, roughly corresponding to 7.5% virgin asphalt rubber binder plus 0.5% RAP binder.

It should be noted that based on UCPRC binder content determinations from plant mix extractions, shown in Table 2.7, Approach 2 was actually followed only on the VEN-1 pilot during construction. For the SON-1 project, the JMF test results showed the use of Approach 2, but the sample taken during construction showed nearly the same binder content for both the control and RAP mixes. The difference between the JMF and construction is probably related to the ability of the producer to control binder content during production of the small amount of RAP mix used for the test section.

Other than the mix design adjustments stated above, the contractors did not include any other changes to add the 10% RAP. In particular, all of the contractors maintained the mixing and compaction temperatures unchanged (i.e., the temperatures were the same in each of the mixes with RAP than in the corresponding control mix) and all the contractors maintained the type of virgin asphalt rubber binder and the warm mix asphalt or antistripping additive unchanged.

6.3.2 How Did the Approaches Work in the Different Pilot Projects?

The main conclusion that can be extracted from the laboratory testing presented in Chapter 3 and the *CalME* modeling presented in Chapter 4 is that the effect of the 10% RAP addition is relatively small. In particular, the effect of the 10% RAP addition is smaller than project-to-project differences.

From the constructability point of view, the addition of the RAP did not create any problems. In particular, the field densities achieved for the mixes with RAP were in the range of 92% to 95% (5% to 8% constructed air voids) based on cores. In each of the pilots, the density achieved for the mix with RAP was similar to the density achieved for the control mix.

6.3.3 What Is the Recommended Approach?

The positive outcomes summarized in the previous discussion in Section 6.3.2 validate the two steps (see Step 1 and Step 2 above) that all contractors followed to add the 10% RAP.

Regarding the approach for considering the RAP binder, the laboratory testing results, the *CalME* modeling, and the field compaction results support the adoption of Approach 1 (consider that the RAP binder contributes to the minimum 7.5%). On the contrary, the adoption of Approach 2 (consider that the RAP binder does not contribute to the minimum 7.5%) in the VEN-1 pilot resulted in worse rutting resistance of the mix with RAP compared with the control mix. Further, VEN-1 is the only case where the *CalME* modeling resulted in thicker sections for the pavement structures that included the RHMA-G with RAP compared with the pavement structures that included the control RHMA-G.

Approach 1 is also supported by results from a recent study on HMA with high RAP content (up to 50%) conducted by the UCPRC for Caltrans *(9)*. The study's conclusion states that "based on the comparison of mix test results, for which full blending is unknown, versus binder test results for which full bending is guaranteed, it appears that the RAP and RAS binders fully blended or nearly fully blended with the virgin binder." Further, the higher production temperatures of the RHMA-G compared with the HMA will aid RAP binder dispersion within the virgin binder.

The 10% RAP addition is equivalent to using a base binder with PGH 2.5°C higher than the virgin base binder. This calculation assumes the PG 64-16 base binder, a RAP binder with PGH of 100°C, and 6% binder replacement (see pilot projects binder replacements in Table 2.8) and also assumes 20% crumb rubber in the asphalt rubber binder, (i.e., PGH = 64 + 2.5 = 66.5°C).

6.4 How Do Cradle-to-Gate Global Warming Potential and Primary Energy Demand of the RHMA-G Fabrication Change Due to the Addition of 10% RAP?

Based on the LCA presented in Chapter 5, a net reduction was found in the range of 1% to 5% for GWP and 0% to 6% for PED by using 10% RAP in the RHMA-G mixes.

As discussed in Section 6.1 and Section 6.2, the RAP addition resulted on little to no effect in performance, and even improvement in some cases. Therefore, these savings could be favorable. However, to determine the real benefits, a full LCA needs to be performed (including construction stage and maintenance cycles) with approximately a 50-year analysis period to better determine if RHMA-G with 10% RAP will have lower environmental impacts compared with RHMA-G without RAP.

It should also to be noted that the impact reductions obtained in this analysis were directly tied to the use of less virgin asphalt binder, defined as Approach 1 in the previous section. The impact reductions are less if the RAP binder is not used to replace virgin binder.

Processing (fractionation) of RAP is not an energy intensive process. Therefore, its impacts are relatively small. If the asphalt plant has no or low RAP stock at the plant and it is transporting RAP from far distances, the reductions will be either lower or even turn into increases in impacts due to consumption/combustion of fossil fuels by trucks transporting RAP.

7 SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

7.1 Summary

This report summarizes the research completed by the UCPRC on five pilot projects in support of the PMPC Initiative "10% RAP in RHMA-G." The goal of this initiative is to allow up to 10% RAP (by aggregate replacement) in RHMA-G mixes. Current Caltrans Standard Specifications do not allow any RAP in RHMA-G.

To evaluate the impact of the RAP addition on the RHMA-G properties with regard to expected material properties, simulated performance, and environmental impact, five pilot projects were built by Caltrans between 2022 and 2023. All the projects included an RHMA-G surface, 0.15 to 0.20 ft. (46 to 61 mm) thick, placed in a mill and fill operation. In each of the pilots, two RHMA-G surfaces were placed: a control RHMA-G without RAP and an RHMA-G with 10% RAP. Overall, the collection of RHMA-G mixes used in the five pilots can be regarded as a good representative sample of the RHMA-G mixes currently used by Caltrans.

In each of the five pilots, the two mixes were sampled during production and tested at the UCPRC laboratory. The testing included axial and flexural stiffness, four-point bending fatigue resistance, fracture cracking resistance from the IDEAL-CT, rutting resistance from AMPT repeated load triaxial testing (RLT), and rutting/moisture resistance from the Hamburg Wheel-Track (HWT) test. The flexural stiffness and the four-point bending test results were used to calibrate the material models in *CalME*, which is Caltrans' mechanistic-empirical software for asphalt pavement design.

Also, a cradle-to-gate life cycle assessment (LCA) was conducted with *eLCAP*, which is Caltrans' environmental LCA tool for pavements. The goal of the LCA was to quantify the expected reduction of global warming potential (GWP) and primary energy demand (PED) in the fabrication of RHMA-G due to the addition of 10% RAP.

7.2 Conclusions

The following conclusions are based on the results of the laboratory testing of the asphalt mixes, the *CalME* modeling, and the LCA. The conclusions have been grouped around the four questions that this research study intended to answer.

1. How do the mechanical properties of the RHMA-G change due to the addition of 10% RAP?
    - The addition of 10% RAP had minor effects on the mechanical properties of the RHMA-G. With just a few exceptions related to changes in the total binder content, the effect of the RAP addition was negligible compared with project-to-project differences.
    - Overall, the stiffness slightly increased (up to 20%) and the fatigue resistance at very high strain levels (at or above 1000 με) slightly decreased. At the strain levels that take place in a highway pavement, up to few hundred microstrain (με), the fatigue resistance of the RHMA-G remained essentially unchanged or improved after the addition of RAP.

- From the constructability point of view, the addition of the RAP did not create any problems. In particular, the field densities achieved for each of the mixes with RAP were within specifications and similar to the densities achieved for the corresponding control mixes.

2. What is the expected field fatigue and reflective cracking performance of the RHMA-G with 10% RAP compared with the RHMA-G without RAP when used as a surface layer?
   - The impact of the 10% RAP addition on the cracking performance of the pavement, based on *CalME* modeling, was either negligible or comparable to project-to-project differences.
   - For one of the pilots, VEN-1, the addition of RAP resulted in worse cracking performance in some modeling scenarios based on *CalME*. Still, the cracking performance of the VEN-1 mix with RAP was comparable to the cracking performance of the statewide median RHMA-G. The statewide median RHMA-G provides median performance across all RHMA-G mixes included in the *CalME* standard materials library.
   - For one of the pilots, SLO-41 pilot, the addition of RAP resulted in better cracking performance in all modeling scenarios based on *CalME*.
3. What adjustments to RHMA-G design, fabrication, and construction are recommended when adding 10% RAP?
   - The positive outcomes from the five pilot projects support the steps that all contractors followed to add the 10% RAP:
     - Adjust the proportions of the different virgin aggregate bins to match the gradation of the control mix (without RAP).
     - Reduce the design number of gyrations to meet the 4.0% design Va (air voids in the mix).
     - Maintain mixing and compaction temperatures, type of virgin asphalt rubber binder, and, where used, the warm mix asphalt or antistripping additive unchanged.
   - Based on the laboratory testing, the *CalME* modeling, and the field compaction results, no reason was found why the RAP binder should not be considered as part of the total binder content to meet the minimum 7.5% total binder requirement. In other words, the results indicate that the RAP binder can be considered to contribute to the minimum 7.5%.
4. How do cradle-to-gate GWP and PED of the RHMA-G fabrication change due to the addition of 10% RAP?
   - The addition of 10% RAP to the RHMA-G, assuming the RAP binder contributes to the total binder content minimum of 7.5%, resulted in GWP reductions of 5% and PED savings of 6%.
   - The main reason for GWP and PED reductions was the reduction in virgin asphalt binder associated with the 10% RAP addition when the RAP binder was accounted for in meeting the 7.5% minimum asphalt content required by Caltrans for RHMA-G mixes.

- Smaller reductions (1% GWP and 0% PED) are expected when the RAP binder is not counted as contributing to the 7.5% minimum asphalt content requirement.

7.3 Recommendations

It is recommended that Caltrans move forward with inclusion of 10% RAP in more projects based on the predicted performance presented in this report. It is recommended, as the next step, that the five pilot projects and subsequent projects be monitored for several years after construction to validate the predicted performance presented in this report and that forensic investigations be done if any problems associated with the use of RAP are detected.

While the collection of pilots covers most of the climate conditions where RHMA-G is currently used in California, a project in the Inland Valley is missing. It is recommended that several projects be built as soon as possible in the Inland Valley climate region.

It is recommended that research continue about the possibility of using RAP contents above 10% in the RHMA-G, which most likely would require changes in the combined (virgin plus RAP) aggregate gradation curve.

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