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Mateos, Angel
Harvey, John T
Buscheck, Jeffrey
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RESEARCH REPORT

Field Implementation of Rubberized Hot Mix Asphalt–Dense-Graded (RHMA-D) on the Levee Road Project in Davis, California

AUTHORS

Angel Mateos, John T. Harvey, Jeffrey Buscheck, Stephanus Louw, Ali A. Butt, Rongzong Wu, Mohammad Rahman, Melanie Preciado, Michael Bowman, Justin Yu, Tanoogna Mallarapu, Changmo Kim, and Yuzhao Han

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16. ABSTRACT

Rubberized hot mix asphalt–dense-graded (RHMA-D) is a dense-graded hot mix asphalt (HMA) that incorporates recycled tire rubber (RTR). This research report documents the pilot implementation of RHMA-D in an asphalt rehabilitation and reconstruction project carried out on Levee Road at the University of California, Davis campus in summer 2025. The project consisted of a 1.7-mile pavement rehabilitation and reconstruction segment. One lane was surfaced with a conventional dense-graded HMA with plain binder (Control HMA), while the adjacent lane was surfaced with five RHMA-D alternatives: two incorporating terminal blend (TB) binders, two incorporating crumb rubber modifier (CRM) added through the advanced wet process, and one incorporating engineered crumb rubber modifier (ECRM) added through the dry process. Construction of the pilot project was closely monitored, and all mixes were sampled at the plant and evaluated using a comprehensive suite of laboratory performance tests. All RHMA-D mixes were successfully produced in an asphalt mixing plant and successfully placed following standard paving and compaction procedures. Laboratory results indicate that incorporating RTR into dense-graded HMA may substantially reduce temperature susceptibility and improve cracking resistance while maintaining acceptable rutting and moisture damage resistance. The initial agency cost and global warming potential (GWP) of the RHMA-D mixes used in the Levee Road pilot project were only slightly higher than those of the Control HMA produced with plain binder. Despite these modest increases, the use of RHMA-D resulted in substantial life cycle cost savings and GWP reductions compared to the Control HMA in two case studies presented in this report, driven by improved performance and the associated reduction in future maintenance and rehabilitation needs.

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A. Mateos **FIRST AUTHOR**	J.T. Harvey **TECHNICAL REVIEW**	M. Homstad **EDITOR**	J.T. Harvey **PRINCIPAL INVESTIGATOR**	R. Garcia **CALTRANS TECHNICAL LEAD(S)** M. Botan M. Weiss **CALRECYCLE TECHNICAL LEADS**	S. Mafi **CALTRANS CONTRACT MANAGER** M. Botan M. Weiss **CALRECYCLE CONTRACT MANAGERS**

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PROJECT OBJECTIVES

The objective of Partnered Pavement Research Center (PPRC) Contract 65A1056 Project TO-21 "Evaluation of Fine Dry Rubberized Asphalt Mixes and Inclusion in Performance-Related Specifications" is to develop recommendations for using recycled tire rubber (RTR) in dense-graded hot mix asphalt (HMA), including suggested specification language for implementation in balanced mix design, where same or better life cycle cost and same or better environmental impact can be achieved. This will be achieved through the following tasks:

- Task 1: Laboratory Testing of HMA with Rubber. The goal of this task is the evaluation of existing technologies for adding RTR to HMA.
- Task 2: Develop Improved HMA Designs with Rubber. The goal of this task is the development of new HMA designs that maximize the performance benefits of RTR.
- Task 3: Pilot Implementation in the Field. The goal of this task is the validation of the constructability and benefits of the most promising technologies for adding RTR to HMA, based on a pilot project.

The research summarized in this report completes the work of tasks 2 and 3, and combines the deliverables listed as "Task 2 Research report" and "Task 3 Research report" in the contract deliverables table. The research includes testing existing technologies for adding RTR to HMA, developing optimized HMA designs with rubber, and implementing the optimized mix designs in a pilot asphalt rehabilitation project accomplished in Davis, California, in 2025.

The research presented in this report is also part of Agreement DRR22066 between the University and CalRecycle, whose objective is to investigate the use of RTR in dense-graded HMA, as well as the use of reclaimed asphalt pavement (RAP) in rubberized hot mix asphalt–gap-graded (RHMA-G) mixes. Agreement DRR22066 also provided funding for the construction of the Levee Road pilot project. This report completes the work of tasks 2 and 3 of the agreement, and corresponds to the deliverable listed as "Task 2 & 3 Report" in the contract deliverables table.

EXECUTIVE SUMMARY

Recycled tire rubber (RTR) has been used successfully in California for decades in rubberized hot mix asphalt–gap-graded (RHMA-G) and rubberized hot mix asphalt–open-graded (RHMA-O) mixes. These materials provide excellent resistance to reflective cracking, fatigue cracking, and age-related cracking while also diverting waste tires from landfills. However, the use of RTR in dense-graded hot mix asphalt (HMA) remains limited, even though dense-graded HMA accounts for the majority of asphalt paving tonnage placed in California. Recent advances in tire rubber processing technologies, including terminal blend (TB) binders, engineered crumb rubber modifier (ECRM), and fine crumb rubber modifier (CRM) used through advanced wet process, have created new opportunities for incorporating RTR into dense-graded HMA.

Rubberized hot mix asphalt–dense-graded (RHMA-D) is a dense-graded HMA that incorporates RTR while maintaining aggregate gradation and construction practices like conventional dense-graded HMA. The potential advantages of RHMA-D include improved cracking resistance, increased use of RTR, and reduced life cycle costs and environmental impacts compared to conventional dense-graded HMA. However, questions remain regarding mix design procedures, constructability, mechanical performance, and long-term benefits.

The goal of this research was to evaluate the feasibility of incorporating RTR into dense-graded HMA and to validate the constructability and performance of RHMA-D through a full-scale field pilot project. The study was designed to answer the following questions:

(1) What is the appropriate approach for conducting RHMA-D mix designs?

(2) Do the fabrication and placement of RHMA-D mixes present any major challenges?

(3) Are there significant differences between plant-produced and laboratory-produced RHMA-D?

(4) What are the performance-related properties of the RHMA-D compared to conventional dense-graded HMA with plain binder?

(5) What are the life cycle cost and environmental impacts of RHMA-D use compared to conventional dense-graded HMA with plain binder?

To answer these questions, a pilot implementation was conducted during rehabilitation and reconstruction of Levee Road on the University of California, Davis campus in spring and summer 2025. The project included approximately 1.7 miles of pavement rehabilitation and reconstruction. One lane was surfaced with a conventional dense-graded HMA fabricated with plain binder (Control HMA), while the adjacent lane was surfaced with five RHMA-D alternatives. The RHMA-D mixes included two terminal blend binder technologies (TB1 and TB2), two advanced wet process mixes incorporating fine CRM (AdvWet1 and AdvWet2), and one engineered CRM mix produced through the dry process (ECRM). Construction activities were closely monitored, and plant-produced mixes were sampled and subjected to a comprehensive laboratory evaluation including IDEAL Cracking Tolerance (IDEAL-CT), moisture damage resistance, stiffness characterization, rutting resistance, and four-point

bending (4PB) fatigue testing. The laboratory testing results were subsequently incorporated into mechanistic-empirical analyses, life cycle cost analyses (LCCA), and life cycle environmental assessments (LCA).

The research demonstrated that RHMA-D mix design can be successfully accomplished by starting with an existing dense-graded HMA design and adapting it using balanced mix design (BMD) principles. The results indicate that RTR can be incorporated into dense-graded HMA using several different technologies while maintaining acceptable volumetric properties and constructability. The findings also demonstrate that the optimum RHMA-D design depends on the intended pavement application. Mixes with relatively high stiffness are better suited for intermediate-layer applications, whereas mixes with lower stiffness and higher cracking resistance are more appropriate for surface layers.

The initial agency cost of the RHMA-D mixes used in the Levee Road pilot project was only slightly higher than that of the Control HMA, with estimated premiums ranging from approximately $2 to $13 per ton of asphalt mix. Despite these modest increases in initial cost, the improved fatigue-cracking performance of the RHMA-D mixes resulted in substantial life cycle cost savings and reductions in global warming potential (GWP). For the surface-layer case study, life cycle agency cost reductions ranged from approximately 40% to 70% over a 20-year analysis period. For the intermediate-layer case study, life cycle agency cost reductions ranged from approximately 15% to 40% over a 40-year analysis period. Corresponding reductions in life cycle GWP were of similar magnitude.

The RHMA-D alternatives evaluated in this research achieved life cycle benefits comparable to those traditionally associated with RHMA-G, while maintaining lower initial costs and avoiding many of the production and construction challenges associated with conventional asphalt rubber technologies. Among the alternatives evaluated for intermediate-layer applications, the AdvWet1 mix provided particularly favorable results, achieving substantial life cycle cost and environmental benefits while requiring only a minimal increase in initial cost.

Based on the findings of this research, the following recommendations are made:

- Continue monitoring the Levee Road pilot project to evaluate long-term field performance, with particular attention to reflective cracking associated with the cement-stabilized base.
- Implement a second pilot project in which RHMA-D is used as an intermediate layer rather than as a surface layer to validate the mechanistic-empirical predictions presented in this report.
- Continue refining RHMA-D mix design procedures within a balanced mix design (BMD) framework to optimize performance for specific pavement applications.
- Investigate the combined use of recycled tire rubber (RTR) and elastomeric polymer modifiers, such as styrene-butadiene-styrene (SBS), particularly for terminal blend (TB) binder technologies, to further improve cracking resistance and reduce temperature susceptibility.

Overall, the results of this research demonstrate that RHMA-D is a practical and promising technology for increasing the use of RTR in California pavements. The RHMA-D mixes evaluated in this study were successfully produced and constructed, exhibited improved cracking performance relative to conventional dense-graded HMA, and demonstrated the potential for substantial reductions in life cycle costs and environmental impacts. These findings support continued implementation and evaluation of RHMA-D as part of California's broader efforts to improve pavement sustainability and increase beneficial use of recycled tire rubber.

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LIST OF ABBREVIATIONS

4PB	Four-point bending
AADTT	Annual average daily truck traffic
AC	Asphalt concrete
AdvWet	Advanced wet
AMPT	Asphalt Mixture Performance Tester
ARNMA	Asphalt, rubber, and non-mineral admixtures
BMD	Balanced mix design
CRM	Crumb rubber modifier
ECRM	Engineered crumb rubber modifier
ESALs	Equivalent single axle loads
FDR-C	Full-depth recycling with cement
GWP	Global warming potential
HMA	Hot mix asphalt
HWT	Hamburg Wheel-Tracking
IDEAL-CT	IDEAL Cracking Tolerance
JMF	Job mix formula
LCA	Life cycle assessment
LCCA	Life cycle cost analysis
LCI	Life cycle inventory
MiST	Moisture-induced Stress Tester
MTOA	Mid-term oven aging
NMA	Non-mineral admixtures
NPV	Net present value
OPC	Ordinary portland cement
Pb	Binder content
PCI	Pavement condition index
PG	Performance grade
PGH	Performance grade high temperature

PGI	Performance grade intermediate temperature
PGL	Performance grade low temperature
PLC	Portland-limestone cement
PMS	Pavement management system
PTE	Passenger tire equivalent
QC/QA	Quality control and quality assurance
RAP	Reclaimed asphalt pavement
RHMA-D	Rubberized hot mix asphalt–dense-graded
RHMA-G	Rubberized hot mix asphalt–gap-graded
RHMA-O	Rubberized hot mix asphalt–open-graded
RLT	Repeated load testing
RTR	Recycled tire rubber
SBS	Styrene-butadiene-styrene
SSD	Saturated surface-dry
TB	Terminal blend
TI	Traffic index
TMM	Total mass of the mix
TRACI	Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts
UAV	Unmanned aerial vehicle
Va	Air-voids in asphalt
VMA	Voids in the mineral aggregate
Wf	Fracture energy
WIM	Weigh-in-motion
Wε	Deformation energy

LIST OF TEST METHODS AND SPECIFICATIONS

AASHTO M 320-23	Standard Specification for Performance-Graded Asphalt Binder
AASHTO R 30-02 (2019)	Standard Practice for Mixture Conditioning of Hot Mix Asphalt (HMA)
AASHTO T 283-22	Standard Method of Test for Resistance of Compacted Asphalt Mixtures to Moisture-Induced Damage
AASHTO T 308-24	Standard Method of Test for Determining the Asphalt Binder Content of Asphalt Mixtures by the Ignition Method
AASHTO T 324-23	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 C150-24	Standard Specification for Portland Cement
ASTM C595-25	Standard Specification for Blended Hydraulic Cements
ASTM D6433-24	Standard Practice for Roads and Parking Lots Pavement Condition Index Surveys
ASTM D7870-20	Standard Practice for Mobile Infrared Inspection of Asphalt Pavements
ASTM D8159-19	Standard Guide for Characterizing Asphalt Pavement Condition Using Portable Seismic Property Analyzers
ASTM D8225-19	Standard Guide for Establishing an Asphalt Pavement Crack Rating System
ASTM D8237-21	Standard Guide for Establishing an Asphalt Pavement Distress Survey Data and Analysis System
California Test 320-2025	Provisional Method of Test for Laboratory Conditioning of Dense-Graded Asphalt Mixtures

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

Recycled tire rubber (RTR) is used by the California Department of Transportation (Caltrans) in two asphalt mix types: rubberized hot mix asphalt–gap-graded (RHMA-G) and rubberized hot mix asphalt–open-graded (RHMA-O). Both are used solely as surface layers. RTR is also used by California cities and counties, mainly in gap-graded asphalt rubber mixtures similar to Caltrans RHMA-G and, occasionally, in dense-graded hot mix asphalt (HMA) through a binder production process known as terminal blend (TB), described below.

In both RHMA-G and RHMA-O, the RTR is incorporated as ground tire rubber also known as "crumb rubber modifier" (CRM), shown in Figure 1.1. Following Caltrans Standard Specifications (Section 39), the CRM has a maximum particle size of 0.09 in. (2.4 mm; passing #8 sieve), and it includes particles from that size down to approximately 0.01 in. (0.25 mm). The CRM is blended with plain binder and extender oil—a petroleum-derived aromatic hydrocarbon—and kept in an interaction tank at a temperature of 375-425°F (190-220°C) for a minimum of 45 minutes. The resulting blend, known as asphalt rubber binder, is then mixed with heated aggregates in an asphalt mixing plant to produce RHMA-G or RHMA-O. Caltrans Standard Specifications require 18% to 22% CRM in the asphalt rubber binder.



Figure 1.1: Crumb rubber modifier.

RHMA-G is Caltrans' preferred surface mix for projects below 3,000 ft. elevation for several reasons. First, its high resistance to reflective cracking makes it an excellent choice for asphalt overlays on cracked pavements and for surface layers in general. Extensive research—including many UCPRC studies *(1-2)*—has consistently shown that RHMA-G performs well against top-down cracking, bottom-up fatigue cracking, reflective cracking, age-related block cracking, and low-temperature cracking, which are the main challenges for asphalt overlays. The second reason is that RHMA-G incorporates RTR. California law requires Caltrans to use CRM in asphalt mixes, as stated in 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 2022, 35.8% of the asphalt mix tonnage placed by Caltrans contained CRM, mainly placed as RHMA-G, which diverted around 2.6 million waste passenger tire equivalents (PTE[1]) from landfills *(3)*. The same year, the California Department of Resources Recycling and Recovery (CalRecycle) reported that around 49,000 tons of crumb rubber—i.e., 4.9 million PTE—were used for all asphalt paving projects in California *(4)*. However, RHMA-G presents the following challenges to its more widespread use:

(1) Relatively high cost: In 2022, Caltrans reported that asphalt mixes containing crumb rubber—primarily RHMA-G—cost about $17 per ton more than conventional dense-graded HMA with plain binder *(3)*. This difference represents roughly a 17.5% increase compared to conventional HMA. Local agencies often report even higher cost premiums, sometimes 40% or more. A recent survey of 30 California local agencies found that 77% of them consider cost a significant barrier to adopting rubberized mixes *(5)*.

(2) Production and compaction challenges: Producing RHMA-G requires significantly higher temperatures than conventional dense-graded HMA with plain binder. While conventional HMA is typically mixed at 300–330°F (150–165°C), with the asphalt binder heated to a similar temperature range, RHMA-G is mixed at around 340°F (170°C) and requires heating the asphalt rubber binder to 375–425°F (190–220°C). These higher temperatures demand more energy to heat both the binder and the aggregates and lead to increased emissions, including more smoke and stronger odors. Compacting RHMA-G is also challenging due to its shorter compaction temperature window (compared to conventional HMA), its gap gradation, and the rebound effect caused by the CRM particles.

(3) Relatively low stiffness: The stiffness of RHMA-G is, on average, around 40% lower than that of conventional dense-graded HMA with plain binder. The relatively low stiffness of the RHMA-G is related to its gap gradation and the relatively high binder content, at least 7.5% by total mass of the mix (TMM), compared to conventional dense-graded HMA. While this lower stiffness helps reduce reflective and age-related block cracking when used as a surface layer, it limits RHMA-G's suitability for intermediate and bottom layers of the asphalt pavement structure. Optimal pavement design generally calls for relatively stiff mixes, such as conventional HMA, in the layers below the surface to minimize overall pavement deformation under traffic loads *(6)*.

The production and compaction challenges of RHMA-G are largely due to the relatively large CRM particles used in the asphalt rubber binder. As explained above, the CRM particles can be up to about 0.09 in. (2.4 mm) in size. The higher production temperatures, the requirement for extender oil use and a minimum 45-minute interaction time, the shorter compaction window, and the rebound effect could all benefit from using smaller CRM particles. Additionally, the relatively low stiffness of RHMA-G is partly a result of its gap-graded structure (Figure 1.2), which is necessary to create voids in the aggregate skeleton to accommodate the large CRM particles. However, advances in CRM grinding

[1] PTE means passenger tire equivalent, defined by CalRecycle (14 CCR § 17225.770) as 20 pounds of rubber.

technologies over the past two decades have made it now feasible to produce CRM with smaller particle sizes, opening the possibility to re-engineer how CRM is incorporated into the mix.

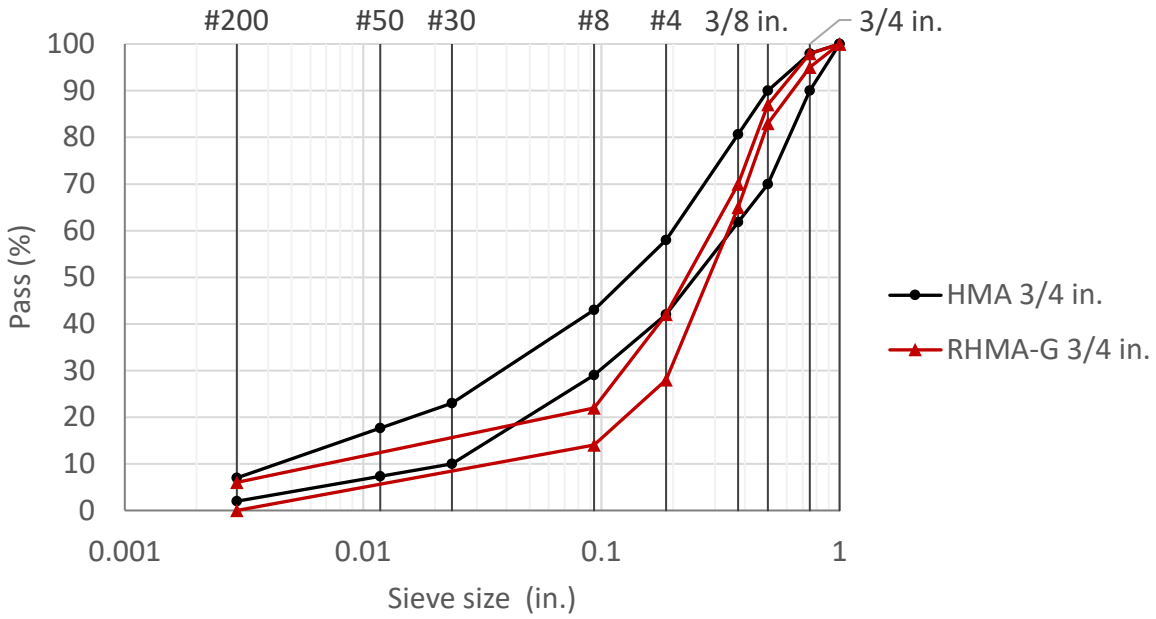


Figure 1.2: Gradation limits of RHMA-G versus HMA (Caltrans Standard Specifications, 3/4 in. max. aggregate size).

In California, relatively small CRM particles—maximum size 0.016 in. (0.4 mm; passing #40 sieve)—have been used to efficiently produce asphalt rubber binder. Thanks to the small particle size, the binder can be produced at typical HMA mixing temperatures, without extender oil and without the need for interaction time. This new technology is known as the "advanced wet process."

In addition to advancements in CRM grinding technologies, a new family of CRM-derived products—known as engineered CRM (ECRM)—has emerged in recent years (Figure 1.3). ECRM consists of CRM particles that have been pre-treated with asphalt binder or other oils in an industrial facility. The process typically involves blending the CRM particles with oil or binder at standard mix production temperatures—around 300-330°F (150-165°C)—and maintaining agitation for a short period of time. The mixture is then cooled to ambient temperature and coated with powder to prevent the treated particles from clumping together. The ECRM can be incorporated into the mix using what is known as the "dry process." In this method, ECRM is handled in the same way as reclaimed asphalt pavement (RAP).



Figure 1.3: Engineered CRM: RARx by Neotech Asphalt (left) and SmartMIX by Liberty Tire Recycling (right).

The use of RTR in terminal blend (TB) binder has also gained popularity during the last several decades. The TB asphalt binder is produced by treating the CRM with asphalt binder at very high temperatures, on the order of 600°F (315°C), in specialized industrial facilities with inert atmosphere systems (such as nitrogen blanketing) or other controls to prevent oxidation and maintain safe operating conditions at these extreme temperatures. The elevated temperature breaks the sulfur bonds of vulcanization in the tire rubber, reducing the rubber into micrometer-sized particles that can be uniformly dispersed in the asphalt binder. The resulting product is a TB concentrate with rubber content that typically varies from 10 to 40%, depending on the production technology, and visually resembles asphalt binder (Figure 1.4). The concentrate is blended with asphalt binder and possibly other polymers or binder additives (rejuvenators or anti-stripping agents) in an industrial facility, typically the binder terminals, to produce the rubber-modified asphalt binder frequently referred to as "terminal blend asphalt binder." This enables the manufacture of the final binder to a target performance grade (PG) without additional handling at the asphalt plant.



Figure 1.4: Terminal blend concentrate: TRMAC by Wright Asphalt Products Co. (left), and SigmaBond by US Polyco (right).

Advancements in technologies for producing RTR-derived products for asphalt mixes raise important questions about how these innovations can be applied to improve RHMA-G and RHMA-O in terms of cost, constructability, and performance, and how they might be used to incorporate the benefits of RTR into dense-graded HMA in different applications in the pavement structure. This report focuses on the latter.

1.2 Problem Statements

RTR has been successfully used to produce gap-graded and open-graded mixes that offer clear performance advantages over conventional dense-graded HMA with plain binder. However, Caltrans dense-graded HMA contains no RTR, and there are currently no validated guidelines for incorporating RTR into dense-graded HMA.

The fabrication of many RTR-derived products—ground tire rubber (i.e., CRM) being one of the few exceptions—is proprietary, and the production processes are often not well known. Although suppliers typically provide recommendations for using their products, the claimed benefits generally lack independent validation.

The interaction between rubber particles and asphalt binder at high temperatures can lead to differences in properties between laboratory- and plant-produced mixes, which need to be evaluated. Further, experience has shown that adding RTR particles to dense-graded HMA can lead to constructability issues if not properly implemented.

Caltrans, like many state transportation departments and other highway agencies in the United States, is adopting the asphalt balanced mix design (BMD) specification framework. Under the BMD

approach, asphalt mixes must meet performance-related criteria rather than relying solely on volumetric properties. In this context, the potential benefits of adding RTR must be evaluated. Based on RHMA-G experience, RTR enhances cracking resistance while maintaining rutting resistance. However, research is needed to quantify the effects on dense-graded HMA.

Adding RTR to dense-graded HMA may increase initial production and construction costs, which could be offset by improved performance. Life cycle cost analysis (LCCA) and environmental life cycle assessment (LCA) are needed to quantify the potential long-term economic and environmental benefits of using RTR.

As noted previously, approximately 4.9 million PTE per year are diverted from landfills and recycled into paving applications in California. However, this accounts for only a small portion of the roughly 60 million PTE waste tires generated in the state annually, of which about 50% are still being disposed of in landfills *(4)*. Notably, adding 10% RTR by total binder weight to dense-graded HMA used below surface layers could increase Caltrans' overall RTR usage substantially and address the challenges that some local governments face with RHMA-G.

1.3 Goal and Questions to Answer

The goal of this research study is to determine the feasibility of incorporating RTR into dense-graded HMA and to evaluate its constructability through a field pilot. The resulting mix is referred to as rubberized hot mix asphalt—dense-graded (RHMA-D). The study was designed to address the following questions:

(1) What is the appropriate approach for conducting RHMA-D mix designs?

(2) Do the fabrication and placement of RHMA-D mixes present any major challenges?

(3) Are there significant differences between plant-produced and laboratory-produced RHMA-D?

(4) What are the performance-related properties of the RHMA-D compared to conventional dense-graded HMA with plain binder?

(5) What are the life cycle cost and environmental impacts of RHMA-D use compared to conventional dense-graded HMA with plain binder?

1.4 Research Approach

The experimental data for this study were collected from a pilot implementation of RHMA-D mixes during the rehabilitation of Levee Road on the University of California, Davis (UCD) campus, constructed in May–June 2025. One of the two lanes was paved with a conventional dense-graded HMA with plain binder, which is the control mix for this study and is referred to as "Control HMA." The second lane was paved with five RHMA-D alternatives. The Levee Road pilot is described in Chapter 2.

The five RHMA-D alternatives were selected based on several principles. First, include at least one product from each of the three main technology groups identified during the initial research phase: terminal blend (TB), CRM added via the advanced wet process, and engineered CRM added via the dry process. Second, subject all selected products to preliminary laboratory testing to minimize potential

compactability issues during construction. Third, require a minimum production of 200 tons per RHMA-D mix to maintain steady plant operation, which required test sections of at least 0.25 miles in length and limited the number of RHMA-D mixes to five. The five mixes used in the Levee Road pilot are referred to in this report as follows:

(1) TB1 RHMA-D: produced using a terminal blend asphalt binder. The terminal blend binder TB1 contained no polymers other than RTR.

(2) TB2 RHMA-D: produced using a terminal blend asphalt binder different from TB1. The terminal blend binder TB2 contained no polymers other than RTR.

(3) AdvWet1 RHMA-D: produced using CRM (passing #40 sieve) added via the advanced wet process.

(4) AdvWet2 RHMA-D: produced using CRM (passing #40 sieve) added via the advanced wet process. The difference between AdvWet1 and AdvWet2 is the binder content, which is higher in AdvWet2 than in AdvWet1.

(5) ECRM RHMA-D: produced using an ECRM added via the dry process.

The research included the following steps:

(1) Develop the design of the RHMA-D mixes (Chapter 3). The design of the Control HMA was adapted to introduce the RTR. A BMD approach was followed in all cases, although the specific method varied depending on the technology. This step addressed the first research question: *What is the appropriate approach for conducting RHMA-D mix designs?*

(2) Build the Levee Road pilot project (Chapter 4). The first segment of the pilot was paved on May 1-2, 2025, and the second segment on June 13, 2025. The underlying pavement included a cemented recycled layer that had shrinkage cracks. The construction was closely monitored, and all mixes were sampled at the plant. Mix temperatures were continuously tracked during paving. Additionally, the construction crew was interviewed to gather insights on the workability and compactability of the mixes, and compaction was evaluated through coring. This step addressed the second research question: *Do the fabrication and placement of RHMA-D mixes present any major challenges?*

(3) Evaluate Control HMA and RHMA-D mixes in the laboratory (Chapter 5). The Control HMA and the five RHMA-D mixes, all of them sampled at the plant during the construction, were tested in the laboratory following a comprehensive set of performance-related tests. The tests included stiffness, age-related and fatigue-cracking resistance, rutting resistance, and moisture damage susceptibility. Some of the tests had also been conducted on the laboratory-produced mixes prior to the construction, which served to address the third research question: *Are there significant differences between plant-produced and laboratory-produced RHMA-D?* The comparison of the laboratory testing results obtained for each of the five plant-produced RHMA-D mixes versus the plant-produced Control HMA served to

address the fourth research question: *What are the performance-related properties of the RHMA-D compared to conventional dense-graded HMA with plain binder?*

(4) Evaluate the life cycle benefits or disbenefits of using RHMA-D compared with the Control HMA (Chapter 6). The potential benefits and disbenefits of RHMA-D are driven by potentially improved performance and the resulting reduction in future maintenance and rehabilitation needs. Reduced maintenance needs, such as seal coats and thin overlays, would be primarily associated with improved resistance to age-related block cracking[2], whereas reduced rehabilitation needs would be primarily driven by improved resistance to fatigue-related cracking under heavy traffic[3]. For clarity, these two types of benefits are evaluated independently:

   (a) The improvement in age-related cracking resistance is evaluated based on how the addition of RTR changes mix stiffness at intermediate temperatures, and how these changes are expected to affect the time until age-related cracking appears. Because an age-related mechanistic cracking model has not yet been developed for use in Caltrans pavement design, the analysis of age-related cracking is only intended to provide preliminary first-order results.

   (b) The potential improvement in fatigue-related cracking resistance is evaluated using *CalME*[4] *(7)* to predict fatigue cracking, and then using the predicted cracking to determine the rehabilitation schedule. The benefits or disbenefits are quantified through life cycle cost and environmental assessments. The analysis estimates the cost and global warming potential (GWP) associated with rehabilitating a pavement section each time it reaches a critical level of cracking over a defined period, referred to as the analysis period. This approach assumes an unrestricted-funding scenario. Although such a scenario is unrealistic, the results are expected to provide an order-of-magnitude estimate of the potential long-term savings associated with the use of RHMA-D compared with standard HMA. Two asphalt pavement rehabilitation case studies were formulated, each assuming the Control HMA was used in either the surface or intermediate layer below the surface. The same case studies were modeled with *CalME* using the different RHMA-D mixes. LCCA and LCA were performed using *RealCost*

[2] Age-related block cracking originates at the pavement surface as a result of asphalt binder aging combined with thermal stresses caused by expansion and contraction of the asphalt mix under temperature day/night and seasonal fluctuations. The cracking initiates as transverse cracking followed by longitudinal cracking, which then forms block cracking.

[3] Fatigue cracking results from repeated heavy truck and bus loading, which induces stresses in the asphalt mix that eventually lead to material fatigue damage and then crack initiation. It may initiate at the bottom of the asphalt layers as they bend downward under traffic loading, but it can also develop because of stress concentrations around cracks in the existing pavement. The latter mechanism leads to reflective cracking, which is typically the most critical form of cracking in overlays on older asphalt pavements.

[4] *CalME* is Caltrans' mechanistic-empirical design software for asphalt pavements.

California[5] *(8)* and *eLCAP*[6] *(9)*, respectively, over a 20- or 40-year analysis period (20 years for evaluating the use as a surface layer and 40 years for evaluating the use as an intermediate layer).

The potential improvement in age-related cracking resistance (RHMA-D versus the Control HMA), together with the improvement in fatigue-related cracking resistance, the latter quantified through LCCA and LCA, addressed the fifth research question: *What are the life cycle cost and environmental impacts of RHMA-D use compared to conventional dense-graded HMA with plain binder?*

1.5 Scope of the Research

The RHMA-D mixes were used as the surface layer in the Levee Road pilot. However, this research also considers their use in layers below the surface, referred to as the "intermediate layer." Consequently, the case studies presented in Chapter 6 include both possible applications of RHMA-D: as surface and intermediate layers within the asphalt pavement structure.

Not included in this study is the longer-term monitoring of the Levee Road sections for reflective and age-related cracking and rutting performance. That monitoring will be included in a subsequent project.

1.6 RHMA-D Mixes, RTR Products, RTR Addition Technologies, and ARNMA Concept

1.6.1 RHMA-D Mixes

As noted previously, RHMA-D stands for rubberized hot mix asphalt—dense-graded. RHMA-D is a dense-graded asphalt mix similar to conventional HMA (such as Caltrans Type A HMA), but it incorporates RTR. Both RHMA-D and HMA have a continuous aggregate gradation close to the maximum density line and comparable total asphalt binder contents. From a fabrication standpoint, the primary difference between RHMA-D and HMA is the inclusion of RTR. This definition of RHMA-D does not assume any specific RTR content.

1.6.2 RTR Products

The RTR product is the actual material that contains the RTR, the most common of which in California is the CRM (Figure 1.1). CRM consists solely of rubber extracted from waste tires and does not include any other ingredients. The two other main categories of RTR-derived products are the terminal blend (TB) asphalt binder and the engineered CRM (ECRM).

As explained above, TB asphalt binder is a type of polymer-modified asphalt binder in which the polymer is the RTR (Figure 1.4). Typically, TB asphalt binder is supplied, handled, and used for mix

[5] *RealCost* California is Caltrans' software for performing life-cycle cost analysis for transportation infrastructure projects.

[6] *eLCAP* stands for Environmental Life-Cycle Assessment for Pavements, and it is Caltrans' software for calculating the environmental impacts of pavements throughout their entire life cycle.

fabrication like any other polymer-modified asphalt binder. However, it has also been supplied in a pelletized form, which requires different supply, handling, and mix fabrication approaches.

Terminal blend binders typically include elastomeric polymers such as styrene-butadiene-styrene (SBS). The combination of RTR and SBS is expected to reduce temperature susceptibility and improve the cracking resistance of the mix. Mixes produced with RTR-SBS modified binders are therefore recommended for rehabilitation of cracked pavements and for surface layers on heavily trafficked roadways. However, the objective of this research was to isolate and evaluate the effect of RTR itself; therefore, the TB binders were used without any additional polymers.

As also explained above, the ECRM consists of CRM particles that have been pre-treated with asphalt binder or other oils in an industrial facility (Figure 1.3). The product typically includes, in addition to RTR, asphalt binder or other oils used in the fabrication process and the powder—such as limestone ($CaCO_3$) or quicklime (CaO)—used to prevent the treated particles from clumping together. The product is typically supplied in supersacks, the same as standard CRM.

1.6.3 RTR Addition Technologies

Regardless of the RTR product, it must be incorporated into the mix during fabrication. There are two main approaches for this: the wet process and the dry process, each of which has several variants.

In the wet process, the RTR product is blended with the virgin asphalt binder before being mixed with the aggregates at the plant mixing unit. Two main variants of the wet process have been widely used so far, referred to as "high viscosity" and "no agitation" in Caltrans Asphalt Rubber Usage Guide *(10)*:

- Wet process-high viscosity: This is the technology used to produce RHMA-G and RHMA-O in California. In this process, CRM is blended with plain asphalt binder and extender oil and kept in an interaction tank at 375-425°F (190-220°C) for a minimum of 45 minutes. The resulting asphalt rubber binder is then mixed with heated aggregates to produce the rubberized mix. Due to the relatively large CRM particle size (passing #8) and high CRM content (18-22%), the asphalt rubber binder has a high viscosity—1,500 to 4,000 centipoises at 375°F (190°C)—and requires continuous agitation to maintain uniform dispersion of the CRM particles. The agitation requires special augers or paddles in the interaction tank. This technology was not evaluated in the Levee Road pilot project.
- Wet process-no agitation (terminal blend): This is the technology used with TB asphalt binder supplied in liquid form (not pelletized). As explained above, the TB asphalt binder is typically supplied, handled, and used like any other polymer-modified asphalt binder. Since the RTR is broken into micrometer-sized particles, it remains dispersed through normal circulation within the binder storage tank, without the need for special augers or paddles—hence the "no agitation" designation. This technology was employed with the TB1 and TB2 RHMA-D mixes in the Levee Road pilot project.

A new variant of the wet process takes advantage of the small CRM particles made possible by advances in CRM grinding technologies over the past two decades. This variant, known as the advanced wet process, is described below:

- Advanced wet process: In this technology, relatively small CRM particles—maximum size 0.016 in. (0.4 mm; passing #40 sieve)—are blended with plain asphalt binder at typical HMA mixing temperatures. The small particle size allows the asphalt rubber binder to be produced without extender oil and without any interaction time. To date, the blending has been carried out in the blending unit and interaction tank normally used for the wet process-high viscosity. However, it is believed that the technology could also be implemented using much simpler blending units, such as inline mixers, enabling its use in asphalt plants that are not equipped with an interaction tank. This technology was employed with the two AdvWet RHMA-D mixes in the Levee Road pilot project.

The dry process is another main technology for incorporating the RTR product during mix fabrication. This process is described below:

- Dry process: In this technology, the RTR product is handled like RAP. In a drum mixing plant, the RTR is added through the RAP feeder collar. In a batch mixing plant, the RTR can be added together with the RAP or directly into the plant's mixing unit. This method has been used historically to incorporate CRM into the mix in other states, referred to as the "dry process," and is the standard approach for adding ECRM. It can also be used with TB asphalt binder when supplied in pelletized form. The technology can be implemented in any asphalt plant equipped with a RAP feeder. However, it can be challenging if a drum mixing plant, the most common type in California, has only one RAP feeder and the mix contains RAP; in such cases, the use of a secondary feeder is recommended. Alternatively, the RTR product can be pre-blended with the RAP and then fed as a single blend during mix fabrication using the plant's sole RAP feeder—an approach followed with the ECRM RHMA-D mix in the Levee Road pilot project.

1.6.4 ARNMA Concept

ARNMA stands for "asphalt, rubber, and non-mineral admixtures." The term refers collectively to all rubberized asphalt components that bind the aggregate in any mix containing RTR, as listed below:

- Asphalt binder in the RAP
- Virgin asphalt binder
- RTR, regardless of its condition
- Non-mineral admixtures

In the RHMA-G and RHMA-O mixes, the extender oil—typically added at a rate of 2% by mass of the virgin asphalt binder—is regarded as a non-mineral admixture. In RHMA-D, the non-mineral admixtures may include recycling agents—typically used with high RAP contents—warm-mix

additives, oils (including asphalt binder) used in the production of engineered CRM, and potentially other additives. The non-mineral admixtures do not include the rock dust, slag dust, hydrated lime, or hydraulic cement, collectively referred to as "supplemental fine aggregate" in Caltrans specifications. The powder used in the fabrication of the engineered CRM, which prevents the treated CRM particles from clumping together, is not regarded as a non-mineral admixture either.

The rubber content by total mass of ARNMA is 18–22% in the RHMA-G and RHMA-O mixes used by Caltrans and other specifications in California. While RHMA-D does not require any specific amount of RTR, contents around 10–20% by total mass of ARNMA have been successfully used in the Levee Road pilot project. The meaning of rubber content by total mass of ARNMA is clarified in Equation 1.1.

$$\frac{\text{Mass of RTR}}{\text{Mass of RAP asphalt binder+Mass of virgin asphalt binder+Mass of RTR+Mass of non mineral admixtures}} \quad \textbf{(1.1)}$$

The binder content of a mix is denoted as P_b and is usually calculated as a percentage of the total mass of the mix (TMM). In this study, a new term, $P_{b;\,ARNMA}$, is introduced to represent all rubberized asphalt components that bind the aggregate in mixes containing RTR binder. The meaning of $P_{b;\,ARNMA}$ is clarified in Equation 1.2.

$$P_{b;\,ARNMA} = \frac{\text{Mass of RAP asphalt binder+Mass of virgin asphalt binder+Mass of RTR+Mass of non mineral admixtures}}{\text{Mass of mix}} \quad \textbf{(1.2)}$$

2 THE LEVEE ROAD PILOT PROJECT

2.1 The Project

The Levee Road pilot project consists of a 1.7-mile pavement rehabilitation/reconstruction segment at the University of California, Davis campus (Figure 2.1). Although the project extends along Hopkins Road, Levee Road, Brooks Road, and Garrod Drive, all of which are campus roadways, it is referred to in this report simply as the Levee Road project for convenience. The first section of the project, 1.2 miles along Hopkins, Levee, and Brooks Roads, was rehabilitated with an asphalt overlay of 2.4 in. (61 mm). The second section, 0.5 miles along Garrod Drive, was reconstructed using full-depth recycling with cement (FDR-C) of the existing badly cracked asphalt pavement, and the same asphalt overlay thickness (Figure 2.2). The westbound direction of the Levee Road project was surfaced with the Control HMA (made with plain binder) and the eastbound direction with five different RHMA-D mixes: two with TB binders, two with CRM added through the advanced wet process, and one with ECRM added through the dry process. The five RHMA-D mixes are referred to as TB1, TB2, AdvWet1, AdvWet2, and ECRM, respectively, in this report (Figure 2.1).

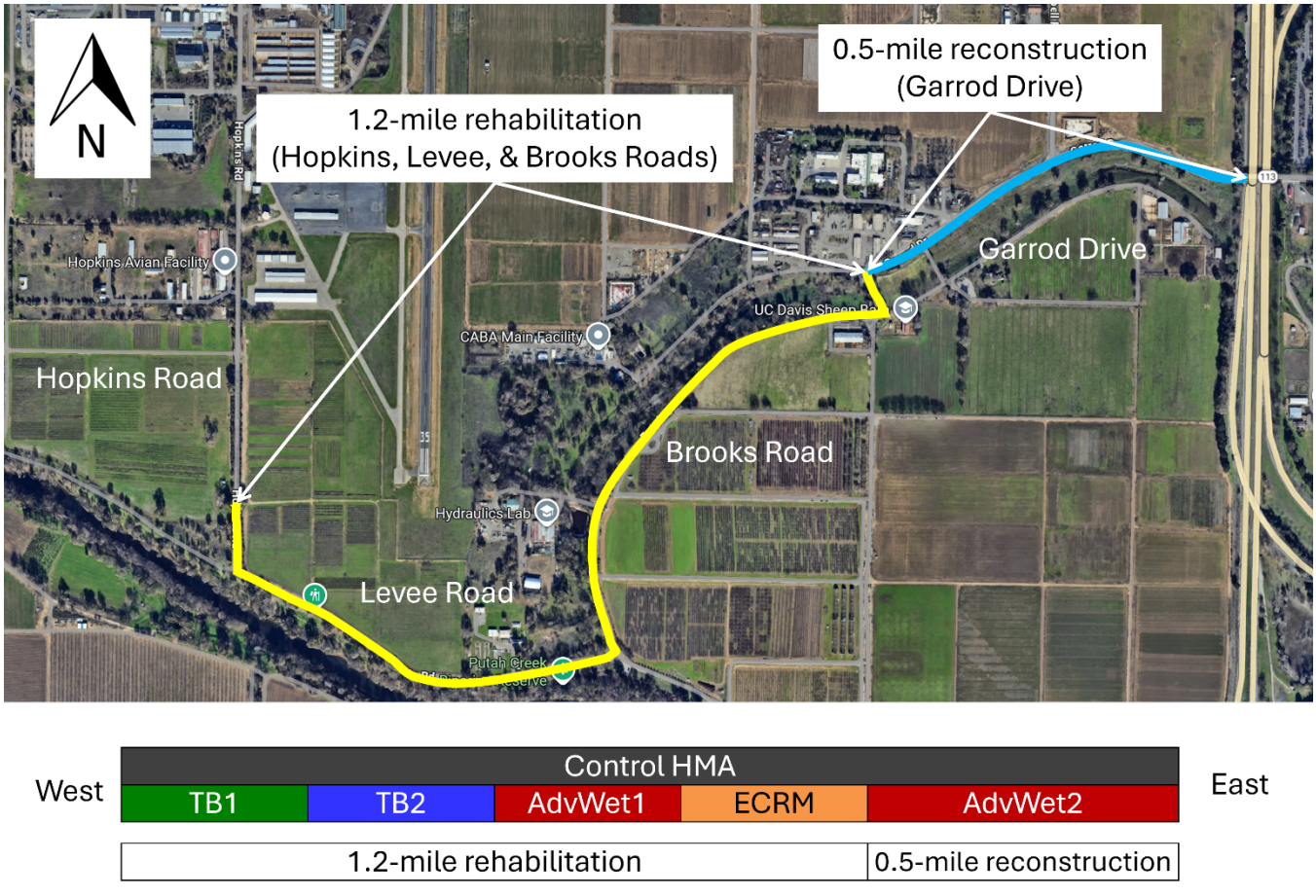


Figure 2.1: Levee Road pilot layout.

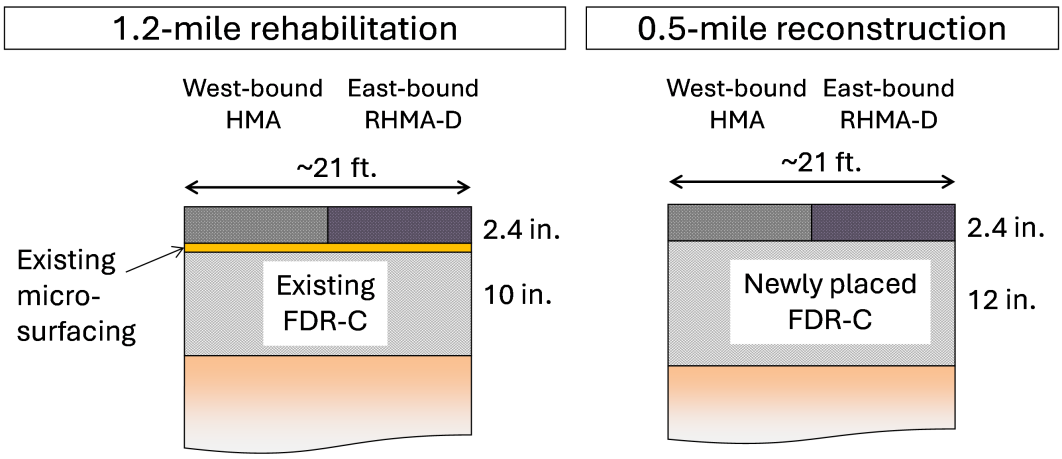


Figure 2.2: Levee Road pilot sections.

The existing section at Hopkins/Levee/Brooks Roads (1.2-mile rehabilitation) included an FDR-C base and a microsurfacing built for a research project about FDR-C microcracking techniques in 2016 *(11)*. The microsurfacing had exceeded its design life and was in poor condition, primarily due to shrinkage cracking in the FDR-C base that had reflected through the microsurfacing. The microsurfacing also had extensive wear (Figure 2.3 through Figure 2.5). UCD Facilities Maintenance had placed cold mix skin patches at numerous locations along the road to slow the progression of potholing and maintain a serviceable riding surface. Because the FDR-C base remained in relatively stable structural condition other than the shrinkage cracking, the UCPRC recommended placing an asphalt overlay to stop further raveling, prevent continued moisture intrusion and carbonation damage, and restore the functional condition of the roadway. The potential for reflective cracking made this project an appropriate candidate for evaluating the cracking resistance of the RHMA-D mixes.



Notes: Edge raveling, loss of the microsurfacing wearing course, and carbonation of the exposed FDR-C base prior to pothole repair.

Figure 2.3: Levee Road, looking east (before rehabilitation).



Notes: Microsurfacing lost in several areas, exposing the FDR-C base in areas not previously repaired by pothole patching.

Figure 2.4: Close-up of potholing and severe surface raveling on Levee Road (before rehabilitation).



Notes: FDR-C shrinkage cracks reflecting through the microsurfacing, recently repaired with cold mix.

Figure 2.5: Brooks Road, looking west (before rehabilitation).

To assess potential future reflective cracking in the rehabilitated section, one area was mapped for cracking for each of the four RHMA-D mixes in Hopkins/Levee/Brooks Roads (Table 2.1). The mapped area encompasses the two lanes, one paved with the Control HMA and the other paved with an RHMA-D mix, and it is around 50 ft. (15 m) long. The crack mapping methodology was as follows:

- Each mapping area was geolocated for future identification and locating purposes.
- Cracks that were visible on the surface were marked with spray paint.
- Aerial photos were taken of the cracking using an unmanned aerial vehicle (UAV) at a fixed spacing of 16 ft. with a 3.2 ft. × 3.2 ft. grid for scaling.

Table 2.1: Crack Mapping Sections

Section	RHMA-D Mix
A	TB1
B	TB2
C	AdvWet1
D	ECRM

A portion of each of the four mapped areas is shown in Figure 2.6 through Figure 2.9.



Figure 2.6: Section A (TB1): surface condition before rehabilitation.

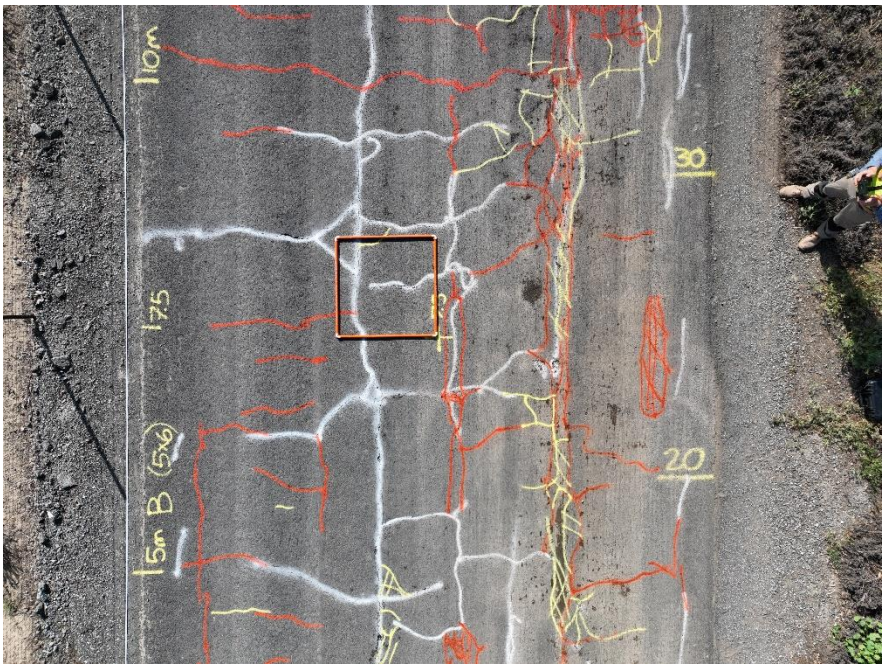


Figure 2.7: Section B (TB2): surface condition before rehabilitation.

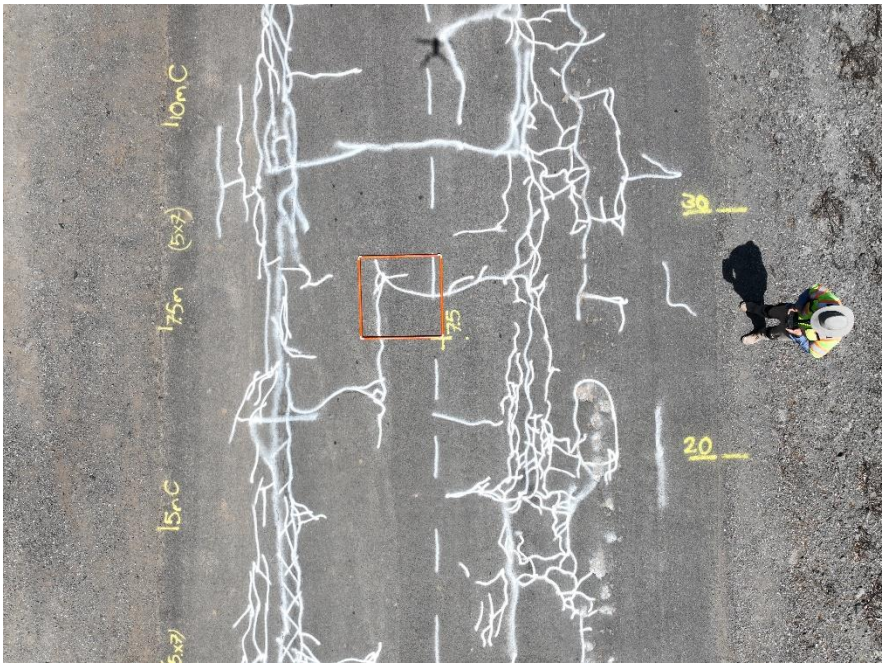


Figure 2.8: Section C (AdvWet1): surface condition before rehabilitation.



Figure 2.9: Section D (ECRM): surface condition before rehabilitation.

The existing pavement on Garrod Drive exhibited extensive block cracking, surface raveling, and structural distress throughout (Figure 2.10 and Figure 2.11). The severity of the deterioration indicated that the existing pavement structure had failed and that the road was not a good candidate for mill-and-fill or a conventional asphalt overlay. The UCPRC recommended the reconstruction using FDR-C.



Notes: Extensive block cracking, longitudinal cracking, and outside wheelpath rutting and potholing.

Figure 2.10: Garrod Drive, looking west (before reconstruction).



Notes: Block cracking throughout the pavement surface and outside wheelpath rutting, indicating inadequacy of the existing base and aged condition of the surface asphalt layer.

Figure 2.11: Garrod Drive, looking east (before reconstruction).

The reconstruction of Garrod Drive included 12 in. (305 mm) of in-place recycling of the existing pavement—which consisted of roughly 2–3.5 in. (50–90 mm) of asphalt and the underlying aggregate base. The recycled material was stabilized with either portland-limestone cement (ASTM C595-25 Type IL) or ordinary portland cement (ASTM C150-24 Type II/V) added at 3% by dry weight of the RAP and aggregate blend.

Table 2.2 summarizes the test sections in the Levee Road pilot project.

Table 2.2: Summary of Levee Road Pilot Test Sections

Routes	Direction	Surface Mix	Length (mi.)	Treatment Type
Hopkins/Levee/ Brooks	Westbound	Control HMA	1.2	Overlay
Hopkins/Levee/ Brooks	Eastbound	TB1, TB2, AdvWet1, ECRM	1.2	Overlay
Garrod Drive	Westbound	Control HMA	0.5	FDR-C and Overlay
Garrod Drive	Eastbound	AdvWet2	0.5	FDR-C and Overlay

The first segment of the pilot (Hopkins/Levee/Brooks Roads) was paved on May 1–2, 2025, and the second segment (Garrod Drive) was paved on June 13, 2025. Construction was closely monitored, and all mixes were sampled at the plant for comprehensive laboratory evaluation. Details of the construction are presented in Chapter 4.

2.2 Climate and Traffic

The city of Davis, California, is in Yolo County, in the Inland Valley climate region *(12)*. This region has a Mediterranean climate, with hot, dry summers and relatively mild, wet winters. The city's average annual mean temperature is 62°F (17°C), with mean monthly values that range from 45°F (7°C) in January to 74°F (23°C) in July. The average high temperature in July is about 93°F (34°C) and the average low temperature in January is about 39°F (4°C), with the hot July weather resulting in aging of the asphalt surfaces and the cold January weather resulting in thermal contraction that will create tensile stresses that will drive age-related cracking. Davis's average annual mean rainfall is 19 in. (483 mm), and its wet season generally runs from November through March while its driest period generally lasts from June to September.

The project has very few trucks and low volumes of automobile traffic. Most cracking in the asphalt overlay is expected to be reflective, originating from the older FDR-C base on Hopkins/Levee/Brooks Roads and the new FDR-C base on Garrod Drive, as well as additional age-related cracking. Incorporating RTR into the control HMA is expected to enhance resistance to both types of cracking.

3 DEVELOPMENT OF RHMA-D MIX DESIGNS

The control mix on the Levee Road pilot project, referred to as Control HMA, is a dense-graded HMA with plain binder. The mix has a 3/4 in. (19 mm) nominal maximum aggregate size, contains 25% RAP by aggregate replacement, and has a binder content of 4.7% by total mass of the mix (TMM). The virgin binder is graded PG 58-22. The mix meets Caltrans Standard Specifications Section 39 HMA Type A requirements and has been previously used by the producer for paving projects for Caltrans and other clients.

The RAP content of the Control HMA, 25%, is relatively high for a surface mix, but it was chosen as a means to lower the cost and environmental impact of the mix. The virgin binder grade, PG 58-22 (AASHTO M 320-23), follows Caltrans requirements: the climate zone calls for PG 64-16, but Caltrans specifications mandate a 6°C "step-down" in binder grade for RAP contents between 15% and 25% (by aggregate replacement). Therefore, although the climate zone requires PG 64-16, the use of 25% RAP necessitates using a PG 58-22 virgin binder.

The mixing and compaction temperatures of the Control HMA are 325°F (163°C) and 277°F (136°C), respectively.

The Control HMA was designed by Teichert Materials at its Perkins plant in the Sacramento area. The plant sources aggregate from an alluvial deposit. No anti-stripping agent or treatment is required, and the mix does not include a recycling agent or warm-mix additive.

The gradation of the Control HMA is presented in Figure 3.1, while two key volumetric properties—air-voids in asphalt (Va) and voids in the mineral aggregate (VMA)—as functions of binder content (Pb) are shown in Figure 3.2. The Va and VMA values correspond to 85 gyrations, the Caltrans-specified Ndesign, and were determined by the UCPRC using a laboratory-produced mix. The data in Figure 3.2 (left) confirm the selected total binder content of 4.7%, while the data in Figure 3.2 (right) indicate a relatively low VMA, slightly below the minimum required by Caltrans specifications for laboratory-produced HMA.

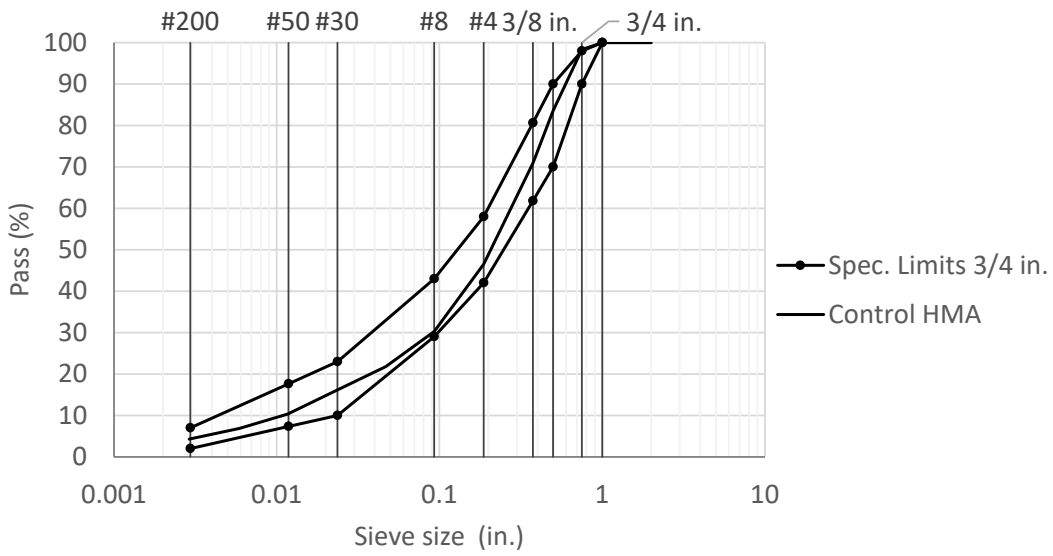


Figure 3.1: Control HMA gradation.

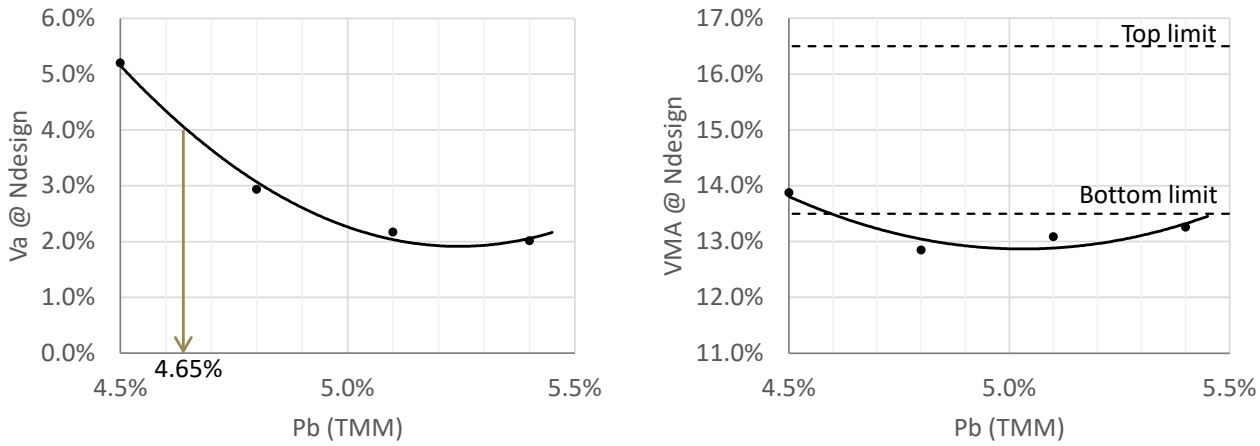


Figure 3.2: Control HMA volumetrics: Va (left) and VMA (right).

The Control HMA design was adapted to incorporate each RTR product and develop RHMA-D mixes intended for use as surface layers. Accordingly, the primary objective of the RHMA-D design was to maximize cracking resistance while still meeting rutting resistance requirements. This objective would be different if the RHMA-D design was optimized for use as an intermediate layer. In an intermediate layer there is less risk of rutting, and stiffer mixes will reduce bending stresses that contribute to fatigue cracking.

3.1 Design of the TB RHMA-D Mixes

Two RHMA-D mixes with terminal blend (TB) asphalt binder—referred to as TB1 and TB2—were used in the Levee Road pilot project. The terminal blend binder contained 14.5% rubber in mix TB1 and 30.0% in mix TB2 by mass of binder. In both cases, the manufacturer formulated the binder to meet the required PG 58-22 grade. The binder PG was verified at the UCPRC laboratory before construction,

and the results are summarized in Table 3.1, where PGH, PGI, and PGL denote the high, intermediate, and low performance grades, respectively.

Table 3.1: Performance Grade of the Terminal Blend Asphalt Binders

Binder	PGH (°F) [°C]	PGI (°F) [°C]	PGL (°F) [°C]
PG 58-22 requirements	≥ 136 (58)	≤ 72 (22)	≤ −8 (−22)
Control mix virgin binder (PG 58-22)	146 (63.3)	67 (19.3)	−17 (−27.4)
TB1 terminal blend virgin binder	150 (65.4)	71 (21.9)	−12 (−24.6)
TB2 terminal blend virgin binder	140 (59.9)	68 (19.8)	−20 (−28.7)

Figure 3.3 shows the PG of the binders minus the PG 58-22 requirements (Table 3.1 data). In the figure, positive values of PGH and negative values of PGI and PGL indicate compliance with the PG 58-22 specification. Although both TB binders meet PG 58-22 requirements, their PG grades do not differ considerably from that of the control mix's virgin binder.

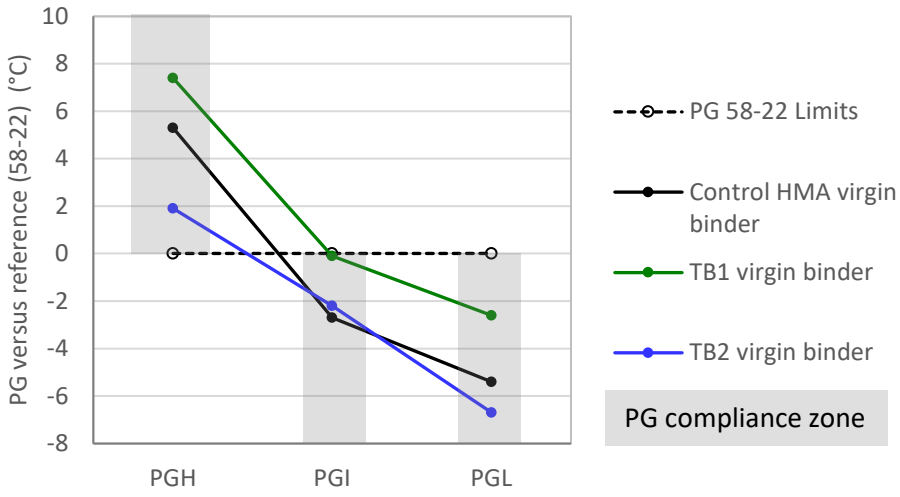


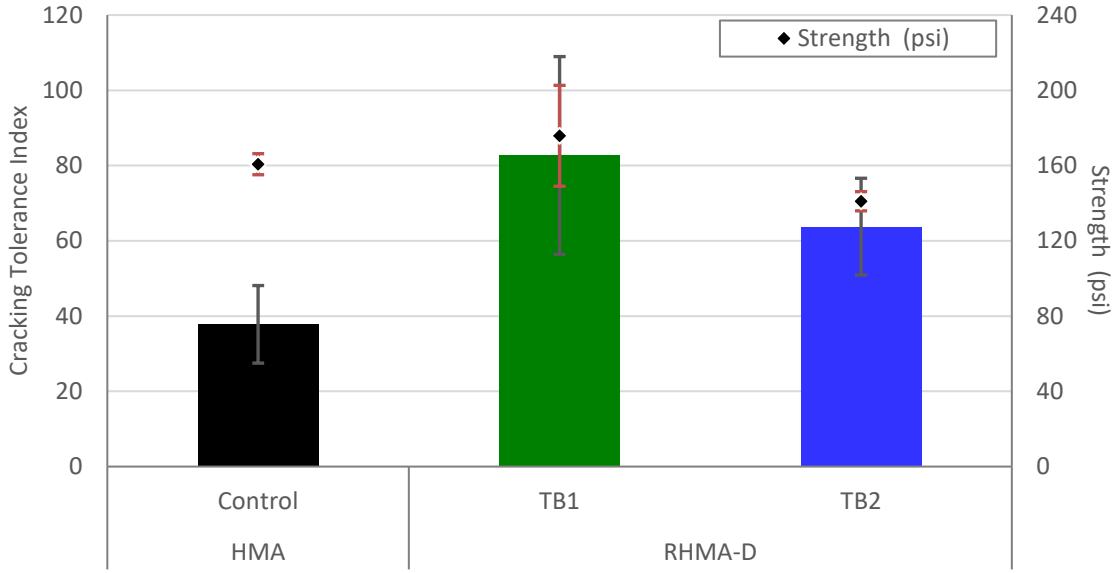
Figure 3.3: Performance grade of the terminal blend asphalt binders.

The two RHMA-D mixes with TB binder were designed using a BMD approach, increasing the binder content to improve cracking resistance while still meeting Caltrans' rutting resistance requirement based on the Hamburg Wheel-Tracking (HWT) test. The upper limit for the total binder content was set at 5.2% by total mass of the mix (TMM), which was expected to yield about 2% air-voids at 85 gyrations. Although the rutting performance would be evaluated in the laboratory before construction, the confidence in the test's ability to predict field rutting was not sufficient to justify using a higher binder content without additional adjustments to the mix design. Economic considerations also supported this limit, as TB binders are generally more expensive than plain binders, and the goal was to keep the initial cost of the RHMA-D mixes close to that of the Control HMA.

The aggregate gradation of the two RHMA-D mixes was the same as in the Control HMA, including the 25% RAP aggregate replacement.

The mixes' cracking resistance was assessed using the IDEAL Cracking Tolerance (IDEAL-CT) test in accordance with ASTM D8225-19. Rutting performance was evaluated with the HWT test following AASHTO T 324-23 at the Caltrans-specified temperature of 122°F (50°C). All mixes were produced in the laboratory and subjected to short-term oven aging for 4 hours at 275°F (135°C), following the former AASHTO R 30-02 (2019) standard. The two RHMA-D mixes, TB1 and TB2, were mixed and compacted at the same temperatures as the Control HMA. Results from the IDEAL-CT and HWT tests are summarized in Figure 3.4 and Figure 3.5, respectively.

As shown in Figure 3.4, the combination of TB and increased binder content substantially improved the Cracking Tolerance Index (CT_{Index}) and likely the resistance of the mix to cracking. The IDEAL-CT strength values were similar for the three mixes, indicating similar stiffnesses at the test temperature of 76°F (25°C). Although the rutting performance of the two RHMA-D mixes was slightly lower than that of the Control HMA, the rut measured in the HWT test remained well below the Caltrans threshold of 0.5 in. at 15,000 wheel passes, as illustrated in Figure 3.5. Consequently, the two RHMA-D mix designs were adopted for the pilot project construction.



Note: Error bars indicate ±1 standard deviation.

Figure 3.4: IDEAL-CT testing results of the lab mixes with terminal blend asphalt binders.

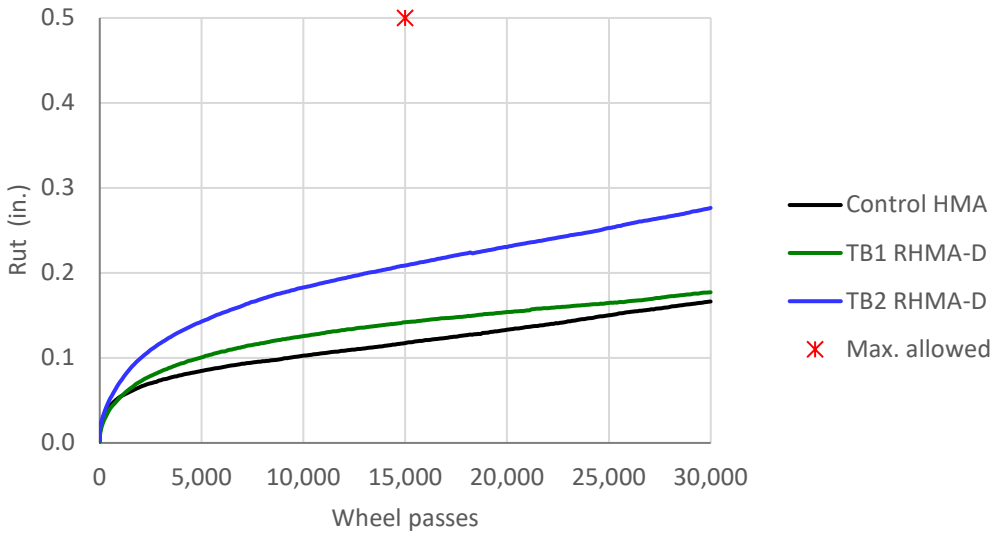


Figure 3.5: Hamburg Wheel-Tracking test results of the lab mixes with terminal blend asphalt binders.

3.2 Design of the AdvWet RHMA-D Mix

Two of the Levee Road pilot RHMA-D mixes—referred to as AdvWet1 and AdvWet2—were fabricated using the advanced wet technology and CRM particles passing the #40 sieve (<0.016 in. [0.4 mm]). The original plan called for only one AdvWet mix, designed for use as a surface layer. However, during plant production for the rehabilitation portion of the pilot project on Hopkins/Levee/Brooks Roads (Figure 2.1), the target binder content was mistakenly set substantially lower than intended. The resulting mix, referred to as AdvWet1, was therefore relatively dry and better suited for use as an intermediate layer rather than as a surface mix. The AdvWet mix produced for the reconstruction portion of the pilot project on Garrod Drive (Figure 2.1) was manufactured with the correct asphalt binder content and is identified in this report as AdvWet2.

The mix design presented below focuses on the AdvWet mix intended for use as a surface layer and corresponds to the RHMA-D identified as AdvWet2 in the remaining chapters of this report.

The mix design followed a BMD approach, increasing the binder content to improve cracking resistance while still meeting Caltrans' rutting resistance requirement based on the HWT test. The aggregate gradation was slightly adjusted from that of the Control HMA to create additional space for binder and CRM particles while still meeting Caltrans specification limits for HMA Type A with a 3/4-in. maximum aggregate size and maintaining the 25% RAP aggregate replacement. Because the Control HMA gradation was already near the specification boundaries, only minor changes were required (Figure 3.6).

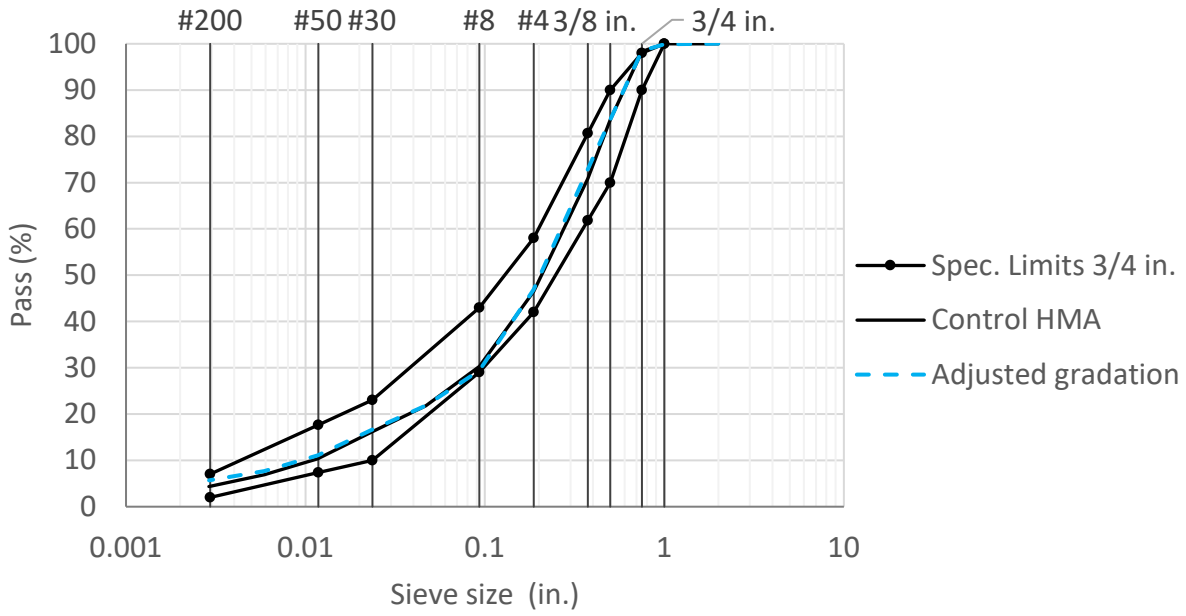


Figure 3.6: Modified gradation for the AdvWet mix.

As described above, the mix design followed a BMD approach to determine the binder content. In this case, however, two variables were involved: the content of asphalt binder and the content of rubber, added as CRM. To simplify the process, the asphalt rubber binder was produced at a fixed CRM content of 11.8% by mass of binder, i.e., the asphalt rubber binder contained 11.8% CRM and 88.2% virgin binder. Three binder contents were evaluated: 5.80%, 6.25%, and 6.65% by TMM, where these values represent the total amount of asphalt binder plus rubber. The breakdown of these amounts is provided in Table 3.2, including the contribution of the RAP binder to the total binder. The adjective "trial" is added to each of the three AdvWet mixes since they were evaluated to select one for the pilot project construction.

Table 3.2: Breakdown of AdvWet RHMA-D Binder Content (Percent Total Mass of Mix)

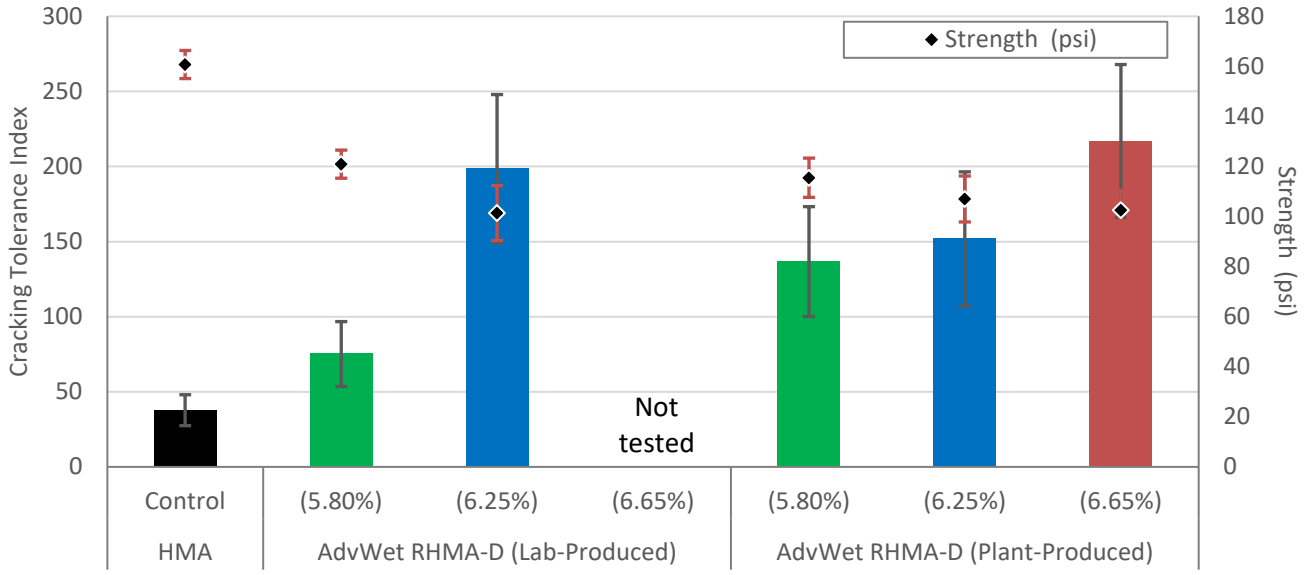
Binder Component	Trial RHMA-D		
	AdvWet (5.80)	AdvWet (6.25)	AdvWet (6.65)
RAP binder	1.17	1.16	1.16
Virgin binder (PG 58-22)	4.08	4.49	4.84
CRM (passing #40 sieve)	0.55	0.60	0.65
Total	5.80	6.25	6.65

The three AdvWet trial mixes were fabricated both in the laboratory and at the Teichert asphalt plant that would produce the mixes for the pilot project. The mixing temperature matched that of the Control HMA. The plant-produced mixes were sampled in metal buckets at the plant and transported to the UCPRC laboratory. The mixes (laboratory- and plant-produced) were then tested for cracking

resistance using the IDEAL-CT test and for rutting resistance using the HWT test at the Caltrans-specified temperature of 122°F (50°C).

The laboratory-produced mixes were subjected to short-term oven aging for four hours at 275°F (135°C), following the former AASHTO R 30-02 (2019) standard, before test specimen fabrication. The plant-produced mixes followed the reheating procedure described in California Test 320-2025: the buckets were heated to extract the material, which was then reheated in an oven for two hours at the compaction temperature to allow specimen preparation in the gyratory compactor. The compaction temperature for both laboratory- and plant-produced mixes was the same as that used for the Control HMA.

Results from the IDEAL-CT and HWT tests are summarized in Figure 3.7 and Figure 3.8, respectively. Based on these results, a binder plus rubber content of 6.25% was selected for the pilot project construction. The lowest binder plus rubber content—5.80%—was rejected due to concerns that it might not provide a significant improvement in cracking resistance (see the CT_{Index} of the laboratory-produced mix in Figure 3.7). The strength values were similar for the plant-produced mixes but decreased with increased binder content for the laboratory-produced mixes, indicating reduced stiffness. The highest binder plus rubber content—6.65%—was rejected due to concerns with the rutting resistance. As shown in Figure 3.8, the plant-produced mix at the highest binder plus rubber content exhibits a stripping inflection point at approximately 20,000 wheel passes.



Note: Error bars indicate ±1 standard deviation.

Figure 3.7: IDEAL-CT testing results of the AdvWet RHMA-D for laboratory- and plant-produced mixes.

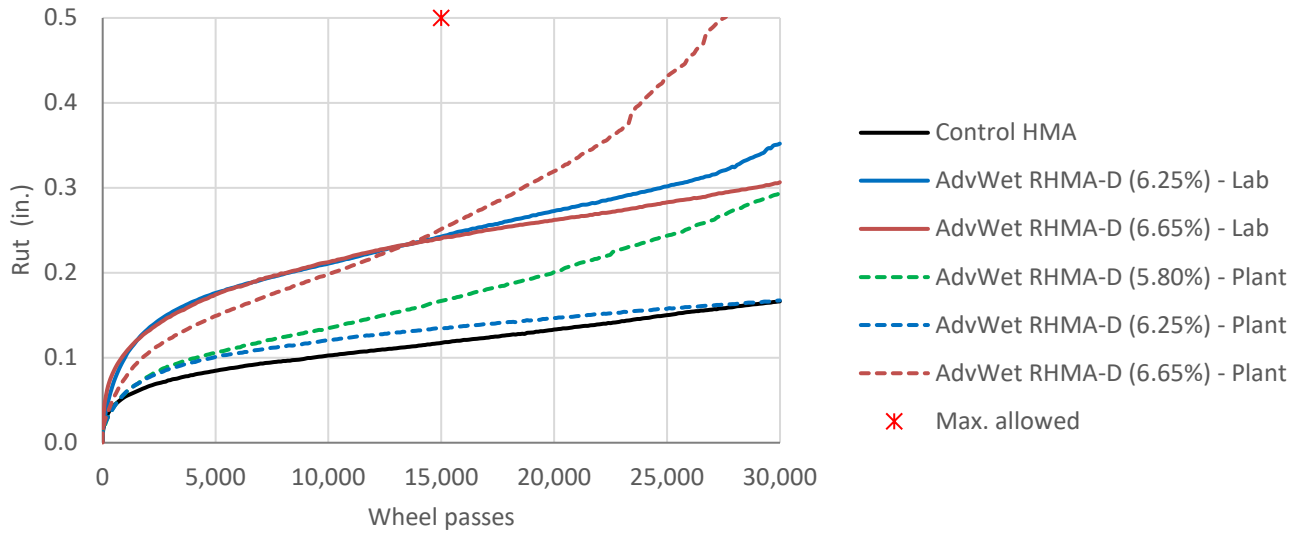


Figure 3.8: Hamburg Wheel-Tracking test results of the AdvWet RHMA-D for laboratory- and plant-produced mixes.

The moisture susceptibility of the laboratory-produced mix was evaluated by determining the retained strength after wet conditioning. Strength was measured using the IDEAL-CT test, while wet conditioning was performed with the Moisture-Induced Stress Tester (MiST) following ASTM D7870-20. During MiST conditioning, the asphalt specimens were submerged in water inside a pressure chamber, which was immediately heated to 140°F (60°C), and subjected to 3,500 water pressure cycles. Each cycle consists of a one-second pressure pulse at 40 psi (280 kPa). The MiST simulates pore pressures induced in a wet pavement by moving traffic and has been shown to produce damage comparable to that of AASHTO T283 conditioning *(13)*. The retained strength (wet divided by dry strength) of the AdvWet RHMA-D at the selected binder plus rubber content of 6.25% was 93%, indicating very good performance (very low moisture susceptibility).

3.3 Design of the ECRM RHMA-D Mix

One of the Levee Road pilot RHMA-D mixes—referred to as ECRM RHMA-D—was produced using the dry process with an engineered CRM. Since the maximum particle size of the CRM used to produce the engineered CRM, passing #30 sieve, was similar to that of the CRM used in the AdvWet mix, passing #40 sieve, the same mix design was adopted for both RHMA-D mixes. Consequently, the main features of the ECRM RHMA-D design are as follows:

- The same aggregate gradation as the AdvWet RHMA-D, shown as the adjusted gradation in Figure 3.6. As noted previously, the adjusted gradation includes 25% RAP content by aggregate replacement, as in the Control HMA.
- The same mixing and compaction temperatures as the Control HMA, 325°F (163°C) and 277°F (136°C), respectively.
- A total asphalt plus rubber content of 6.25% TMM, with 0.6% TMM corresponding to rubber. The binder component breakdown, including virgin asphalt, RAP asphalt, and rubber

components, is provided in Table 3.3. The ECRM used in the pilot project consists of 60% RTR, 20% asphalt binder, and 20% coating powder made of limestone (calcium carbonate) and slaked lime (calcium hydroxide).

Table 3.3: Breakdown of Engineered Crumb Rubber Modifier Binder and Rubber Content

Binder Component	Content (% TMM)
RAP binder	1.16
Virgin binder (PG 58-22)	4.29
CRM (passing #30 sieve)	0.60
Asphalt used in ECRM fabrication	0.20
Total	6.25

3.4 ARNMA Breakdown of the RHMA-D Mix

As explained in 1.6.4, ARNMA stands for "asphalt, rubber, and non-mineral admixtures" and refers collectively to all components that bind the aggregate in any mix containing RTR:

- Asphalt binder in the RAP (the RAP has a binder content of 4.72%, TMM)
- Virgin asphalt binder
- RTR, regardless of its condition
- Non-mineral admixtures (NMA)

The ARNMA breakdown of the five RHMA-D mixes used in the Levee Road pilot project is summarized in Table 3.4 and illustrated in Figure 3.9. For reference to current Caltrans practice, the ARNMA composition of a typical RHMA-G is also included in both the table and figure.

Table 3.4: Breakdown of Asphalt Rubber and Non-Mineral Admixtures in the Levee Road RHMA-D Mixes

Binder Component	Content (% TMM)						
	HMA Control	RHMA-D					Typical RHMA-G
		TB1	TB2	AdvWet1	AdvWet2	ECRM	
Asphalt binder in RAP	1.18	1.17	1.17	1.17	1.16	1.16	—
Virgin asphalt binder[a]	3.52	3.44	2.82	3.55	4.49	4.29	6.00
RTR	—	0.59	1.21	0.48	0.60	0.60	1.35
NMA	—	—	—	—	—	0.20	0.15
Total	4.70	5.20	5.20	5.20	6.25	6.25	7.50
RTR/Total	0	11.3	23.3	9.2	9.6	9.6	18.0

[a] The virgin asphalt binder in the Control HMA and in the AdvWet1, AdvWet2, and ECRM RHMA-D mixes is the PG 58-22 binder supplied for the pilot project construction. However, the virgin asphalt binders in the TB1 and TB2 RHMA-D mixes are those used by the supplier to produce each of the two TB binders.

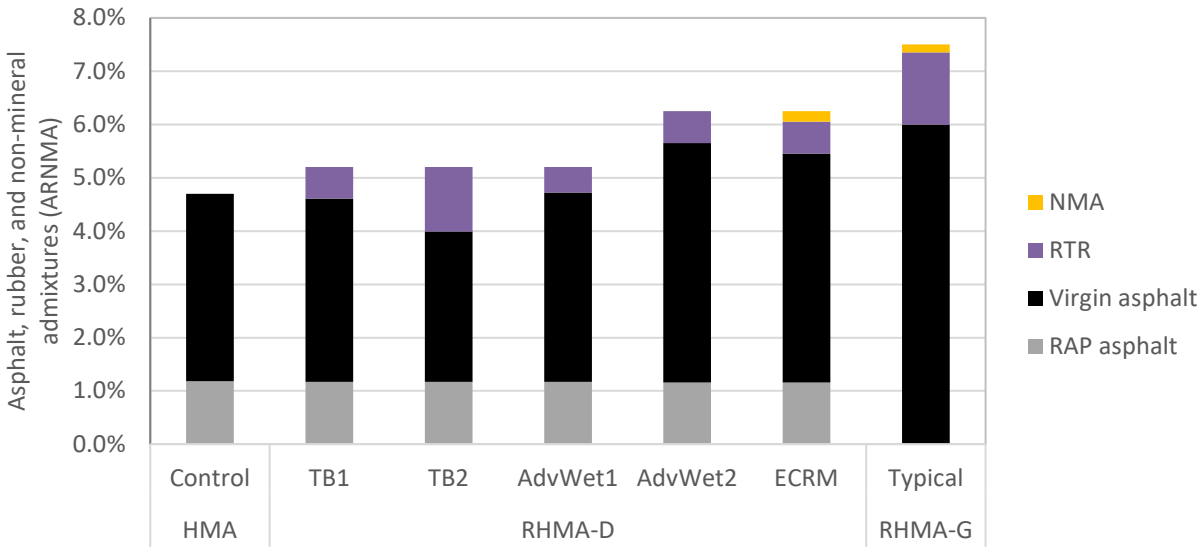


Figure 3.9: ARNMA breakdown of the Levee Road RHMA-D mixes.

It should be noted that the ARNMA components shown in Figure 3.9 do not necessarily exist as physically separate components. In the TB binders, the RTR and virgin asphalt are intimately blended during the TB binder manufacturing process, and the same is true for these two components in the ECRM. The oil used in producing the ECRM is included as a non-mineral admixture in Figure 3.9, as is the extender oil used in the fabrication of RHMA-G.

4 LEVEE ROAD PILOT CONSTRUCTION

The Levee Road pilot was completed in two phases. In the first phase, the 1.2-mile rehabilitation was constructed, consisting of placement of a tack coat and the asphalt overlay on May 1–2, 2025. In the second phase, the 0.5-mile reconstruction was carried out. The existing pavement was pulverized on June 9, 2025, the FDR-C base was built between June 10 and 11, 2025, and the asphalt overlay was placed two days later, on June 13. The westbound direction of the Levee Road pilot was surfaced with the Control HMA and the eastbound direction with the five RHMA-D mixes, as shown in Figure 2.1. Each of the five mixes was sampled at the asphalt plant twice per paving day, as shown in Table 4.1.

Table 4.1: Sampling Lots for the Levee Road Mixes

Mix	1.2-mile Rehabilitation (Hopkins/Levee/Brooks Roads)		0.5-mile Reconstruction (Garrod Drive)			
	Lot 1	Lot 2	Lot 1	Lot 2	Lot 3	Lot 4
Control HMA	May 1	May 1	—	—	June 13	June 13
TB1	May 2	May 2	—	—	—	—
TB2	May 2	May 2	—	—	—	—
AdvWet1	May 2	May 2	—	—	—	—
AdvWet2	—	—	June 13	June 13	—	—
ECRM	May 1	May 1	—	—	—	—

The construction of the Levee Road pilot is described below, beginning with the FDR-C base construction (Section 4.1), followed by the RTR addition approaches used at the asphalt plant (Section 4.2), the asphalt paving operations (Section 4.3), and the quality control and quality assurance (QC/QA) testing results for the asphalt mixes (Section 4.4).

4.1 Construction of the FDR-C Base

The 0.5-mile section along Garrod Drive was reconstructed using full-depth recycling with cement (FDR-C) base. The FDR-C base construction included pulverization of approximately 10 in. (254 mm) of the existing pavement—consisting of a thin asphalt layer and the underlying aggregate base—followed by FDR-C to a depth of 12 in. (305 mm). The Garrod Drive reconstruction also provided an opportunity for comparing the use of portland-limestone cement (PLC) and ordinary portland cement (OPC) in FDR-C.

In FDR-C construction, up to 100% of the existing pavement materials—asphalt, aggregate base, and subgrade—are pulverized, blended with cement, and recompacted in place. On the Garrod Drive project, the recycled material was used to re-establish the road crown for positive drainage and to construct shoulder backing, so that the full volume of pulverized material was retained on site.

The FDR-C base on Garrod Drive was constructed over three days (June 9–11, 2025) by a multi-contractor team. Pulverization, recycling, and initial compaction were performed by Pavement Recycling Systems, grading and final compaction by Teichert Construction, and QC testing by Pavement Engineering Inc. Fog sealing was performed by Pacific Northwest Oil at the end of each shift to maintain surface moisture and prevent premature drying of the FDR-C material.

On June 9, the existing pavement was pulverized to a depth of approximately 10 in. (254 mm) using a Wirtgen W 210i cold milling machine (Figure 4.1(a)). Following pulverization, the material was graded to the design profile using a Cat 14M motor grader (Figure 4.1(b)) and compacted using a CS11 roller compactor (Figure 4.1(c)) to prepare the subgrade surface for FDR-C treatment. A Cat 613C scraper was used for earthwork and material redistribution as needed. The prepared surface was graded and compacted in preparation for FDR-C treatment the following day (Figure 4.1(d)).



(a)



(b)



(c)



(d)

Figure 4.1: (a) Wirtgen W 210i pulverizing existing pavement, (b) Cat 14M motor grader establishing design profile, (c) Cat CS11 GC roller compacting pulverized material at Garrod Drive/Campbell Road, and (d) overview of prepared surface with water trucks and equipment.

On June 10, FDR-C treatment began on approximately 0.2 miles of Garrod Drive using portland-limestone cement (PLC; ASTM C595-25 Type IL), sourced from National Cement in Lebec, California. The PLC was applied at 3% by dry weight of the RAP and aggregate blend using a dry bulk tandem axle cement spreader truck, loaded on site by pneumatic bulk cement transport trucks. The cement-treated material was recycled to the full 12 in. (305 mm) design depth using a Wirtgen WR 250i recycler connected to a 4,000-gallon water truck (Figure 4.2(a) and Figure 4.2(b)) for moisture addition during mixing. A second 4,000-gallon water truck was used to maintain surface moisture of the FDR-C material throughout the shift. Following mixing, the FDR-C material was initially compacted using a 31-ton Rex 3-70A padfoot compactor (Figure 4.2(c)), followed by a Cat 14M motor grader to re-establish grade, and a Cat 613C scraper and JD 210 skip loader used for material handling. Final compaction was achieved using a Cat CS11 GC 12.5-ton smooth-drum roller (Figure 4.2(d)). Pacific Northwest Oil applied a fog seal at the end of each shift.



(a) (b)

(c) (d)

Figure 4.2: (a) Cement spread and mixing train during FDR-C operations, (b) Wirtgen WR 250i recycler connected to water truck, (c) Rex 3-70A padfoot compactor on FDR-C material, and (d) Cat CS11 GC smooth-drum roller; shoulder backing visible at left.

Production on June 10 was limited to approximately 0.2 miles due to construction delays associated with the PLC supply logistics. National Cement in Lebec supplied the PLC and is located approximately 330 miles from the construction site. The long-haul distance introduced scheduling complexity that limited the volume of PLC that could be delivered and placed within the first day's production window.

On June 11, the remaining Garrod Drive project area was treated. A short segment (approximately 0.05 miles) was treated with PLC to complete the PLC study section, and the remaining segment, approximately 0.25 miles, was treated with OPC (ASTM C150 Type II/V), sourced from a terminal in Stockton, California. Both the PLC and OPC sections were constructed at the same cement application rate of 3% by dry weight. A fog seal was applied by Pacific Northwest Oil at the end of the shift, shown in Figure 4.3(a) and Figure 4.3(b).

A microcracking study had been planned for the Garrod Drive FDR-C base to evaluate the effectiveness of early-age microcracking in reducing shrinkage crack severity. However, coordination challenges between the mixing and compaction operations resulted in the compaction window exceeding the two-hour limit specified in Caltrans Section 30 for hydraulic cement-treated materials. The extended exposure led to carbonation of the upper lift, preventing the prime coat from bonding to a cohesive FDR-C surface and precluding effective microcracking. QC testing on the FDR-C base was performed by Pavement Engineering Inc. The testing results are documented in a separate UCPRC report on the FDR-C construction. The asphalt overlay on Garrod Drive was placed approximately two days after FDR-C completion, on June 13, 2025.



(a) (b)

Figure 4.3: (a) Completed FDR-C base on Garrod Drive looking east; fog-sealing application, and (b) completed FDR-C base on Garrod Drive looking east; fog-sealed surface prior to RHMA-D overlay placement.

4.2 RTR Addition Approaches

All asphalt mixes for the Levee Road pilot project were produced at the Teichert Materials asphalt plant located at the Perkins facility in the Sacramento area (Figure 4.4). The plant is a Gencor counterflow continuous drum plant equipped with seven aggregate cold-feed bins, a rotary dryer/drum mixer, one recycled cold-feed bin, and two 300-ton mix storage silos. The plant also includes two 80-ton asphalt binder storage tanks and a rubber blending plant—a two-hopper, stationary, Caltrans-certified system used for blending asphalt rubber binder for RHMA-G production. The rubber blending plant is equipped with three 30-ton storage tanks fitted with pugmills at the bottom for agitation. The existing plant infrastructure accommodated the different RTR addition technologies required for the five RHMA-D mixes. The rubber blending plant was dedicated exclusively to the Levee Road project during paving operations, and the plant lines were flushed prior to the project start.



Note: Rotary dryer/drum mixer, baghouse, aggregate conveyors, and storage silos.

Figure 4.4: Teichert Materials Perkins asphalt plant (Gencor counterflow continuous drum plant).

The plant sources aggregate from an alluvial deposit in the nearby region. The mix designs for all Levee Road mixes include 25% RAP by aggregate replacement. The RTR addition approach varied by mix type. The sections below describe the plant setup, material handling, and production procedures used for each of the three RTR technologies: terminal blend, advanced wet process, and dry process with engineered CRM.

4.2.1 Terminal Blend Binders (TB1 and TB2 RHMA-D)

Two RHMA-D mixes with terminal blend (TB) asphalt binder—referred to as TB1 and TB2—were used in the Levee Road pilot project. Both TB binders were supplied as finished liquid asphalt binders formulated to meet the required PG 58-22 grade. Neither TB binder contains polymers other than recycled tire rubber (RTR).

The TB1 binder (TRMAC) was manufactured by Wright Asphalt Products Co. at their facility in Arizona (Figure 4.5) as a concentrate, diluted to 14.5% rubber content, and transported by tanker truck to the Teichert Materials Perkins plant in Sacramento. The TB2 binder (SigmaBond) was manufactured by US Polyco at their manufacturing facility in Texas as a concentrate, transported by rail to the company's Pacific Northwest Oil terminal in Stockton, California, where it was diluted to the specified rubber content of 30.0%. The finished TB2 binder was then transported by tanker truck to the same Teichert Materials plant.



Note: Facility where the TRMAC terminal blend concentrate is produced under controlled conditions.

Figure 4.5: Wright Asphalt Products Co. manufacturing facility in Arizona.

At the Teichert Perkins plant, the two TB binders were stored separately in dedicated compartments within the rubber interaction tank. Prior to receiving the TB binders, each compartment was drained and flushed; approximately 2 tons of residual PG 64-16 binder was left in each compartment to protect the heating coils. Despite the long-haul distance from Texas, the TB2 binder maintained adequate temperature during transport and was delivered without incident.

Because the rubber in both TB binders had been fully processed into micrometer-sized particles during manufacturing at the suppliers' industrial facilities, the RTR particles remained homogeneously dispersed through normal circulation within the storage vessels. No special agitation equipment, extender oil, or interaction time was required at the plant. No differences in viscosity, pumping, or metering behavior were observed between the two TB binders; both were handled operationally like plain binders and could be pumped from the tank compartments to the drum plant mixing unit through the same piping and metering system used for conventional asphalt binder.

The production sequence for the TB1 and TB2 RHMA-D mixes followed the same procedure as the Control HMA. The TB binder was injected into the drum mixer at the design binder content of 5.20% ($P_{b;\,ARNMA}$, TMM). The mixing temperature was identical to that of the Control HMA temperature. No modifications to the plant's standard operating procedures were required for the TB mixes.

To manage the transition between the TB1 and TB2 binders on the paving day, it was assumed that a transition period would occur as residual binder in the lines was displaced by the incoming binder. Loose mix samples were not collected until at least 50 tons of mix had been produced after each binder changeover. Special coordination between the UCPRC project team and each rubber supplier was essential to the project's success; several pre-construction meetings were held both in person and online to prepare the production sequence.

4.2.2 Advanced Wet Process (AdvWet1 and AdvWet2 RHMA-D)

The AdvWet RHMA-D mix was produced using CRM passing the #40 sieve (<0.016 in. [0.4 mm]), supplied by Crumb Rubber Manufacturers. The CRM was delivered to the Teichert Perkins plant in supersacks (Figure 4.6).



Figure 4.6: CRM supersacks staged at the Teichert Perkins plant for the AdvWet RHMA-D production.

The advanced wet blending was carried out using the Teichert Perkins plant's two-hopper, one-feed tank, stationary, Caltrans-certified asphalt rubber blending system. This is the same equipment normally used for producing conventional asphalt rubber binder for RHMA-G (Figure 4.7). However, only one hopper was used and no extender oil was necessary, as the blending involved a single CRM product rather than the two separate rubber products and extender oil typically required for RHMA-G.



Note: Supersacks being hoisted by telehandler for discharge into the rubber blending system hopper, with additional supersacks staged on the ground.

Figure 4.7: CRM supersacks.

The CRM was introduced into the rubber blending system through a hopper-based metering system that controlled the batching process (Figure 4.8). A declumping system integrated into the rubber hoppers broke up any CRM clumps before the material exited the hopper, ensuring a consistent feed.



Note: Blending plant hoppers, screw feeders, insulated piping, and shear blending system at the Teichert Perkins plant, used for blending the CRM #40 with virgin asphalt binder in the advanced wet process.

Figure 4.8: Rubber blending system.

The PG 58-22 plain binder and the CRM were blended in the shear mixing tank at a rate corresponding to 11.8% CRM by mass of the total rubberized binder (virgin binder + CRM). The blending was performed at approximately 350°F (177°C) binder production temperature, consistent with the binder storage temperatures used for producing the Control HMA. The blended binder was then sent to one of three 30-ton reaction compartments in the interaction tank for additional mixing before being pumped to the drum plant.

Because no minimum interaction time is required for the advanced wet process, the contact time between CRM and binder varied from the minimum batch time of approximately 15 minutes to several hours depending on the production sequence and tank inventory. By comparison, conventional RHMA-G production requires a minimum 45-minute interaction period.

Once blended, the rubberized binder was pumped from the reaction tank to the drum plant mixing unit for combination with the heated aggregates (including 25% RAP). A sample of the rubberized binder is shown in Figure 4.9.



Note: The binder has a more smooth, homogeneous appearance with smaller CRM particles, in contrast to conventional asphalt rubber binder with larger CRM particles.

Figure 4.9: Sample of the AdvWet rubberized binder (11.8% CRM #40, PG 58-22 base binder).

The viscosity of the CRM-modified binder ranged from approximately 900 to 1,500 centipoises, substantially lower than the 2,500–4,000 centipoise range typical of conventional asphalt rubber binder produced with PG 64-16, extender oil, and standard CRM blends per Caltrans Section 39 requirements. The reduced viscosity is attributed to the use of finer CRM #40 particles (versus standard CRM passing the #8 sieve), the use of a softer PG 58-22 base binder, and a lower rubber

concentration. The lower viscosity facilitated pumping and metering and resulted in no issues with aggregate coating or plant production.

An initial operational challenge was encountered during setup: the plant control software required bypassing the two-hopper metering sequence that is a Caltrans requirement for conventional RHMA-G binder production (which requires two separate rubber products). Once this software configuration was resolved, no further challenges were reported.

The existing rubber blending system was used for the advanced wet process without any hardware modifications. The elimination of extender oil, the shorter blending cycle, and the absence of a minimum interaction time simplify the production process relative to conventional asphalt rubber binder.

It is believed that the advanced wet process could also be implemented using simpler blending equipment, such as inline mixers, for asphalt plants that are not equipped with interaction storage tanks. The relatively low viscosity of the CRM-modified binder and the absence of a required interaction time suggest that an inline mixing system could achieve adequate blending, provided it generates sufficient shear to disperse the fine CRM particles. This would increase the number of asphalt plants capable of producing RHMA-D using the advanced wet technology, as most plants do not have dedicated rubber blending equipment.

4.2.3 Dry Process with Engineered CRM (ECRM RHMA-D)

The ECRM RHMA-D mix was produced using RARx, an engineered CRM manufactured by Neotech Asphalt. The RARx consists of CRM particles that have been pre-treated with asphalt binder and coated with limestone and slaked lime powder to prevent clumping. The mass composition of the RARx used in the Levee Road pilot is 60% CRM, 20% asphalt binder, and 20% limestone and slaked lime powder. The ECRM was delivered to the plant in supersacks and staged near the RAP feeder.

The ECRM was incorporated into the mix using the dry process, in which the product is handled like RAP—added through the drum plant RAP collar. Because the plant's mix design includes 25% RAP and the ECRM is added through the same feeder system, the ECRM was pre-blended with the RAP by a front-end-loader bucket with weighing capabilities, prior to introduction into the drying and mixing drum. The ECRM was blended at a rate of 80 lb. per ton of RAP (Figure 4.10 and Figure 4.11). Uniformity was ensured by carefully turning the product several times near a saturated surface-dry (SSD) moisture condition to minimize dust creation. The ECRM flowed well from the supersacks and had no visible clumping. The pre-blended RAP/ECRM material was fed into the drum mixer through the plant's RAP feeder at a combined rate calibrated to deliver the design proportions of RAP aggregate and ECRM. The virgin PG 58-22 asphalt binder was injected separately at the design virgin binder content of 4.29% (TMM). The mixing temperature was 325°F (163°C), identical to the Control HMA.



Figure 4.10: Stockpile of front loader-blended 3/8 in. RAP and ECRM.



Figure 4.11: Detail of stockpile of front loader-blended 3/8 in. RAP and ECRM.

The dry process approach indicates that ECRM can be incorporated into dense-graded HMA using standard plant equipment available at any facility with a RAP feeder, without requiring an interaction tank or modifications to the binder handling system.

4.2.4 Summary

Table 4.2 summarizes the key features of the three RTR addition technologies as implemented at the Teichert Perkins plant for the Levee Road pilot project.

Table 4.2: Summary of Recycled Tire Rubber Addition Approaches at the Teichert Perkins Plant

Description	Terminal Blend (TB1 & TB2)	Advanced Wet (AdvWet1 & AdvWet2)	Engineered CRM Dry (ECRM)
RTR product and concentration	TB binder containing 14.5% (TB1) or 30% (TB2) RTR by mass of virgin binder	Asphalt rubber binder containing 11.8% CRM	Engineered CRM added at a rate of 80 lb./ton of RAP
RTR product and supplier	TB1: TRMAC by Wright Asphalt Products Co. TB2: SigmaBond by US Polyco	CRM passing #40, by Crumb Rubber Manufacturers	RARx by Neotech Asphalt
Rubber modification mechanism	Thermochemical breakdown of vulcanized rubber (devulcanization and, depending on supplier process, partial depolymerization) at elevated temperature under controlled atmospheric conditions. Rubber is reprocessed into the binder matrix at the supplier's facility.	Fine CRM particles dispersed in hot binder by high-shear mixing. Rubber particles remain discrete.	Fine CRM particles pre-treated with asphalt binder and coated with limestone and slaked lime powder at the supplier's facility. Rubber particles remain discrete.
Addition point	Binder storage tank (pre-blended at supplier facility)	Rubber blending plant shear mixer	Front-end loader stockpile blended with RAP
Interaction time	Not required (interaction completed during binder manufacture at supplier facility)	Not required (~15 min. to several hours)	Not applicable (dry process); loose mix held at least 30 min. in storage silo to allow rubber–binder interaction
Extender oil	None	None	None
Binder viscosity	Same as plain binder	900–1,500 cP at 350°F (177°C)	N/A (dry process)
Mixing temperature	325°F (163°C) (same as Control HMA)	325°F (163°C) (same as Control HMA)	325°F (163°C) (same as Control HMA)
Compaction temperature	277°F (136°C) (same as Control HMA)	277°F (136°C) (same as Control HMA)	277°F (136°C) (same as Control HMA)
Plant modifications – short term	None (tank compartments drained and flushed prior to delivery)	Software configuration to rubber plant system	None
Plant modifications – long term	Additional binder storage tanks	None	Additional recycle cold-feed hoppers or equivalent

4.3 Asphalt Paving

4.3.1 Paving Schedule and Sequence

Asphalt paving was conducted on three days: May 1 and 2, 2025, for the 1.2-mile rehabilitation section (Hopkins/Levee/Brooks Roads), and June 13, 2025, for the 0.5-mile reconstruction section (Garrod Drive). The overlay thickness was 2.4 in. (61 mm) for all sections.

On May 1, the westbound lane was paved with the Control HMA, followed by the ECRM RHMA-D on the eastbound lane. On May 2, the eastbound lane was paved with the TB1, TB2, and AdvWet1 RHMA-D in sequence, with transitions between mixes managed by the 50-ton buffer protocol described in Section 4.2.1. On June 13, the westbound lane of Garrod Drive was surfaced with the Control HMA and the eastbound lane with the AdvWet2 RHMA-D. Table 4.3 summarizes the weather conditions on each paving day.

Table 4.3: Weather Conditions During Asphalt Paving

Date	Activity	Daily Temperature Range (°F) [°C]	Wind Direction, Speed (mph)	General Condition
May 1, 2025	Paving (Control & ECRM)	53–86 (12–30)	S, 5–10	Sunny
May 2, 2025	Paving (TB1, TB2, & AdvWet1)	55–78 (13–26)	SW, 5–12	Sunny
June 13, 2025	Paving (Control & AdvWet2)	53–84 (12–29)	SW, 5–10	Sunny

4.3.2 Control HMA Paving at Rehabilitation Section

On May 1, the Control HMA asphalt overlay was paved on the 1.2-mile rehabilitation section. Prior to the overlay placement, a tack coat of SS-1H emulsion was applied on the existing microsurfacing (Figure 4.12(a)).

The asphalt overlay paving was performed by Teichert Construction using a Cat AP1055 paver. The asphalt mix was transported from the Teichert Perkins plant to the Levee Road project site in bottom-dump haul trucks and placed in a windrow ahead of the paver (Figure 4.12(b)). A BOMAG pickup machine was used to pick up the windrow and transfer the mix into the paver hopper (Figure 4.12(c)). Breakdown and intermediate compaction were performed using two Cat CB10 vibratory smooth-drum rollers (Figure 4.12(d)), followed by a Cat CB2.5 finish roller.



(a)



(b)



(c)



(d)

Figure 4.12: (a) Tack coat application, (b) bottom-dump haul trucks queued behind the paving train; fresh Control HMA mat at right, (c) Cat AP1055 paver with BOMAG pickup machine placing Control HMA on the westbound lane, and (d) Cat CB10 smooth-drum roller compacting the Control HMA overlay.

4.3.3 RHMA-D Paving at Rehabilitation Section

On May 1 and 2, four RHMA-D mixes were placed on the eastbound lane of the 1.2-mile rehabilitation section. The ECRM RHMA-D was placed on May 1. On May 2, the TB1 RHMA-D was placed first, followed by the TB2 RHMA-D, and then the AdvWet1 RHMA-D. The paving equipment was the same as used for the Control HMA (Figure 4.12(a)–(c)).

A field core extracted during RHMA-D paving is shown in Figure 4.13(d), illustrating the 2.4 in. (61 mm) overlay. The alluvial aggregate and RAP particles are visible in the cross section.



(a)



(b)



(c)



(d)

Figure 4.13: (a) Bottom-dump truck discharging RHMA-D mix into windrow ahead of paver, (b) shoulder machine placing aggregate shoulder material adjacent to the completed overlay, (c) project team and paving crew at the completion of RHMA-D paving, and (d) field core showing RHMA-D overlay cross section.

4.3.4 Mix Temperatures During Paving

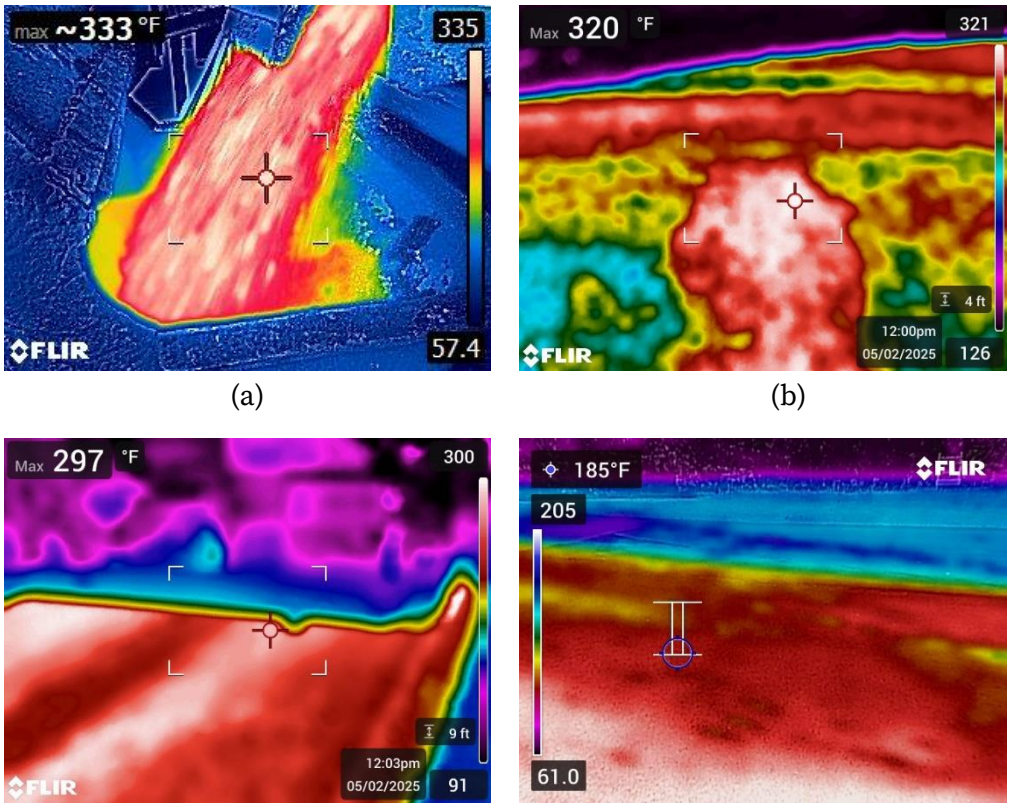
Mix temperatures were monitored continuously during paving. Three thermal cameras were used for QA monitoring, in addition to routine equipment used by the plant, paving, and QC operators. Temperatures were recorded at three key points: at the discharge from the plant drum unit, at the windrow ahead of the paver, and behind the paver screed/roller compaction.

Temperatures measured during construction were approximately 325°F (163°C) at the discharge of the mixing unit, 300–315°F (149–157°C) at the windrow, and 260–290°F (127–143°C) behind the paver, as summarized in Table 4.4. These values are consistent with conventional dense-graded HMA. No notable temperature differences were observed between the Control HMA and the five RHMA-D mixes.

Table 4.4: Mix Temperatures

Date	Mix	Discharge (°F) [°C]	Windrow (°F) [°C]	Behind the Paver (°F) [°C]	Final Compaction (°F) [°C]
May 1, 2025	Control HMA	320–340 [160–171]	295–315 [146–157]	275–280 [135–138]	150–190 [66–88]
	ECRM	320–360 [160–182]	310–330 [154–166]	275–295 [135–146]	200–220 [93–104]
May 2, 2025	TB1	330–350 [166–177]	300–315 [149–157]	270–290 [132–143]	150–170 [66–77]
	TB2	330–350 [166–177]	305–320 [152–160]	275–295 [135–146]	180–200 [82–93]
	AdvWet1	330–350 [166–177]	305–320 [152–160]	270–300 [132–149]	185–220 [85–104]
June 13, 2025	Control HMA	320–340 [160–171]	295–325 [146–163]	270–300 [132–149]	150–190 [66–88]
	AdvWet2	325–345 [163–174]	290–325 [143–163]	275–305 [135–152]	150–190 [66–88]

Examples of the thermal images during paving are shown in Figure 4.14(a) through Figure 4.14(d).



(a) (b)

(c) (d)

Figure 4.14: (a) Asphalt plant discharge temperature profile, (b) windrow temperature profile, (c) behind the paver temperature profile (AdvWet1), and (d) final compaction (AdvWet1).

4.3.5 Compaction and Workability Observations

Roller compaction procedures for the RHMA-D mixes were similar to those used for the Control HMA. The only challenge was encountered with the compaction of the AdvWet1 mix, which required 50% to 75% more breakdown and finish compaction passes than the other RHMA-D mixes because of the low asphalt binder content.

Paver and roller operators reported favorable impressions of all RHMA-D mixtures. Comments from the crew included: “Much easier to work with than RHMA-G,” “Same or easier to compact than HMA,” “Far less smoke and smell than RHMA-G,” and “Working with conventional RHMA-G typically leaves a rubber taste in the mouth and a strong odor on skin and clothing, whereas the RHMA-D mixes produced none of these effects or very slight ones.” These observations are consistent with the lower mixing and compaction temperatures of the RHMA-D mixes relative to RHMA-G (around 70°F [39°C] lower) and the absence of extender oil. The appearance of the RHMA-D mixes after paving is shown in Figure 4.15(a) to Figure 4.15(d).



(a) (b)

(c) (d)

Figure 4.15: (a) Eastbound RHMA-D lane (left) on Levee Road looking west (TB1), (b) eastbound RHMA-D lane (left) on Levee Road looking west (TB2), (c) eastbound RHMA-D lane (right) on Brooks Road looking east (AdvWet1), and (d) eastbound RHMA-D lane (right) on Brooks Road (ECRM).

4.3.6 Control HMA and AdvWet2 Paving at the Reconstruction Section

The 0.5-mile reconstruction section on Garrod Drive was paved on June 13, 2025. The westbound lane was surfaced with the Control HMA and the eastbound lane with the AdvWet2 RHMA-D mix.

The decision to place an additional AdvWet RHMA-D section on Garrod Drive was made after the 1.2-mile rehabilitation paving was completed and the QC/QA results became available and confirmed that the binder content had been mistakenly set to 5.20% instead of the intended 6.25% ($P_{b;\,ARNMA}$, TMM). The resulting mix—AdvWet1—was therefore relatively dry and better suited for use as an intermediate layer rather than as a surface mix. The AdvWet mix produced for the reconstruction portion of the pilot project (Garrod Drive) was manufactured with the correct asphalt binder content of 6.25% ($P_{b;\,ARNMA}$, TMM) and is identified in this report as AdvWet2. The appearance of the AdvWet2 RHMA-D after paving is shown in Figure 4.16(a) through Figure 4.16(d).



(a) (b)

(c) (d)

Figure 4.16: (a) Garrod Drive approach looking west from the bridge (AdvWet2), (b) completed overlay with paving equipment in the distance (AdvWet2), (c) completed surface at dusk, looking east (AdvWet2), and (d) completed surface at dusk, looking east (AdvWet2).

4.3.7 Binder Content Discrepancy Between AdvWet1 and AdvWet2

During plant production for the 1.2-mile rehabilitation on May 2, 2025, the target binder content for the AdvWet RHMA-D mix was mistakenly left set to the TB2 5.20% instead of the intended 6.25% ($P_{b;\,ARNMA}$, TMM), resulting in a total ARNMA content approximately 1.0% lower than the design value. The error occurred during the mix transition from TB2 to AdvWet production. The QA manager identified the discrepancy during a daily debrief with the plant operator and immediately reported the issue to the UCPRC project team.

Errors of this type are an inherent risk in non-standard research mix trials, where multiple mix designs are produced in rapid succession and the production team is operating outside routine procedures. The UCPRC and Teichert teams addressed the situation constructively: Teichert offered to produce an additional 0.5 miles of AdvWet RHMA-D at the correct binder content on the Garrod Drive reconstruction section.

The lower ARNMA content of AdvWet1 had measurable effects on the mix properties: higher Va at Ndesign, lower field density (though still above the Caltrans 91% minimum), lower CT_{Index} with higher strength in the IDEAL-CT test, and reduced rutting in the HWT test—consistent with a stiffer, lower-binder-content mix. Throughout this report, the AdvWet RHMA-D produced at 5.20% $P_{b;\,ARNMA}$ is identified as AdvWet1, while AdvWet RHMA-D produced at 6.25% $P_{b;\,ARNMA}$ is identified as AdvWet2.

Although unintended, the production of the AdvWet1 mix proved beneficial to the research program. As discussed in Chapter 6, the stiffer, leaner AdvWet1 mix is suited for intermediate-layer applications. The AdvWet2 RHMA-D, with its higher binder content and lower stiffness, is better suited for surface-layer applications where cracking resistance is the primary concern.

4.4 Asphalt Paving QC/QA

4.4.1 Asphalt Mixes

The binder content of the mixtures was determined using the ignition oven method in accordance with AASHTO T 308-24. Correction factors for the Control HMA and the two RHMA-D mixes with terminal blend binders (TB1 and TB2) were established by comparing the ignition oven results with those obtained from automated binder extraction performed in accordance with ASTM D8159-19. The correction factors for the RHMA-D mixes containing CRM particles (AdvWet and ECRM) were established by comparing the ignition oven results with the known binder content of mixes prepared in the laboratory. The correction factors of the mixes are listed in Table 4.5.

The raw results of the ignition oven tests were adjusted by subtracting the values reported in Table 4.5 to estimate the $P_{b;\,ARNMA}$ of each mix and lot. $P_{b;\,ARNMA}$ includes the asphalt binder, the rubber, and the non-mineral admixtures (NMA) in the ECRM (see Section 1.6.4 for a detailed explanation of $P_{b;\,ARNMA}$). The corrected $P_{b;\,ARNMA}$ of the different mixes and lots are shown in Figure 4.17, together with the acceptance interval (design value -0.3% to +0.5%). As explained above, the design binder content of the Control HMA was 4.70% TMM while the design $P_{b;\,ARNMA}$ was 5.20% for the TB1, TB2, and AdvWet1 mixes and 6.25% for the AdvWet2 and ECRM mixes.

Table 4.5: Binder Content Correction Factors for Ignition Oven Results (Percent Total Mass of Mix)

HMA Control	RHMA-D				
	TB1	TB2	AdvWet1	AdvWet2	ECRM
0.60	0.80	0.80	0.55	0.55	0.55

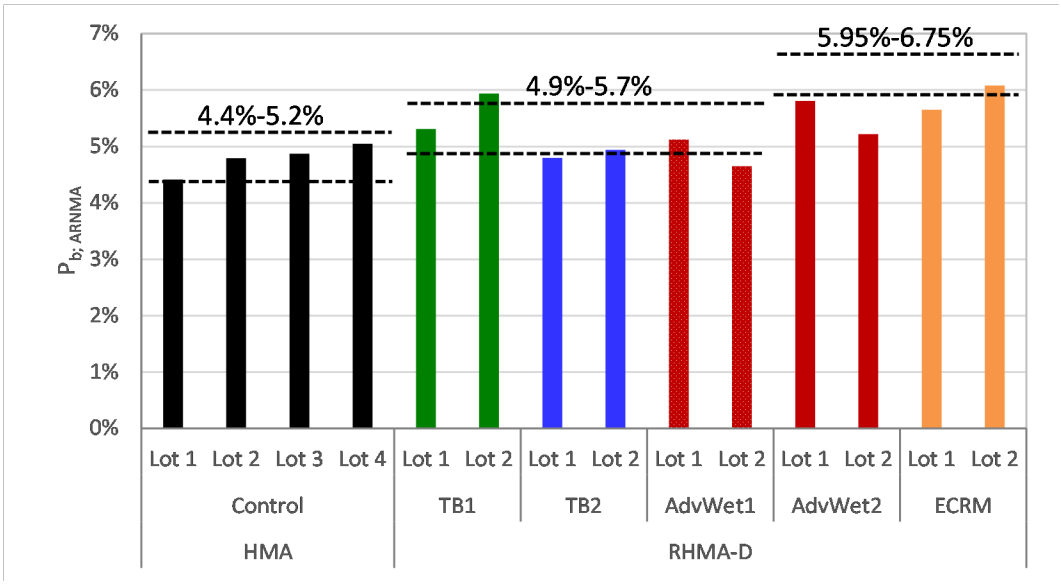


Figure 4.17: ARNMA content of the Levee Road mixes (total mass of the mix).

Except for the TB1, the ARNMA content of the RHMA-D mixes was somewhat low, at or below the lower bound of the acceptance interval.

Figure 4.18 shows the air-void content (Va) of the mixes at 85 gyrations (Ndesign). Except for the AdvWet1, the Va of the RHMA-D mixes was lower than the Va of the Control HMA.

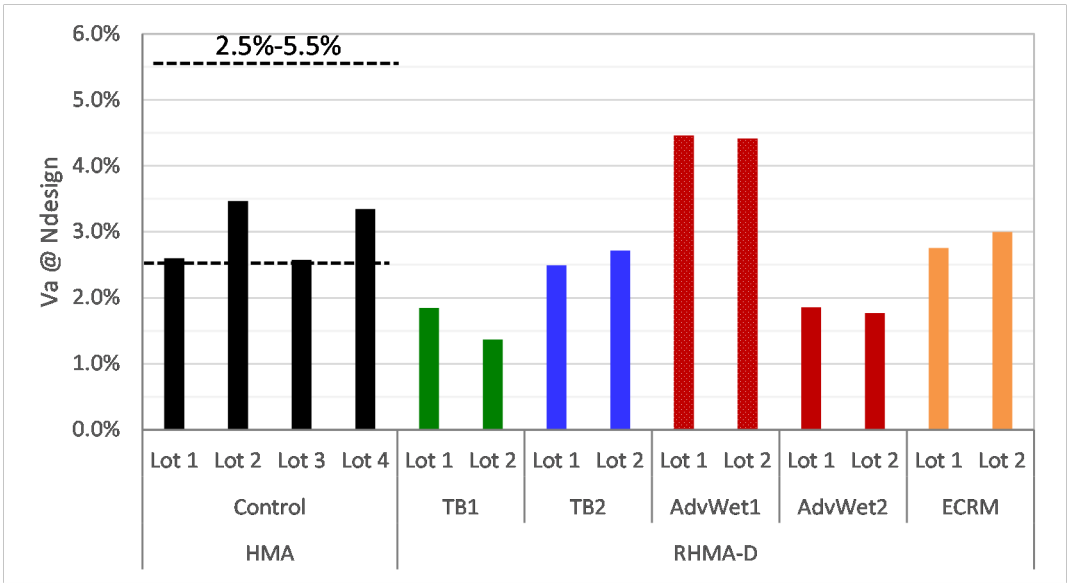


Figure 4.18: Air-voids in asphalt at Ndesign of the Levee Road mixes.

Although the ARNMA content was somewhat below the acceptance limits, the in-place densities of all cores exceeded the minimum requirement of 91% (9% Va) specified in the Caltrans Standard Specifications (Figure 4.19). In addition, except for AdvWet1 with the low binder content, the Va of the RHMA-D mixes was lower than that of the Control HMA, indicating good compactability for the RHMA-D mixes.

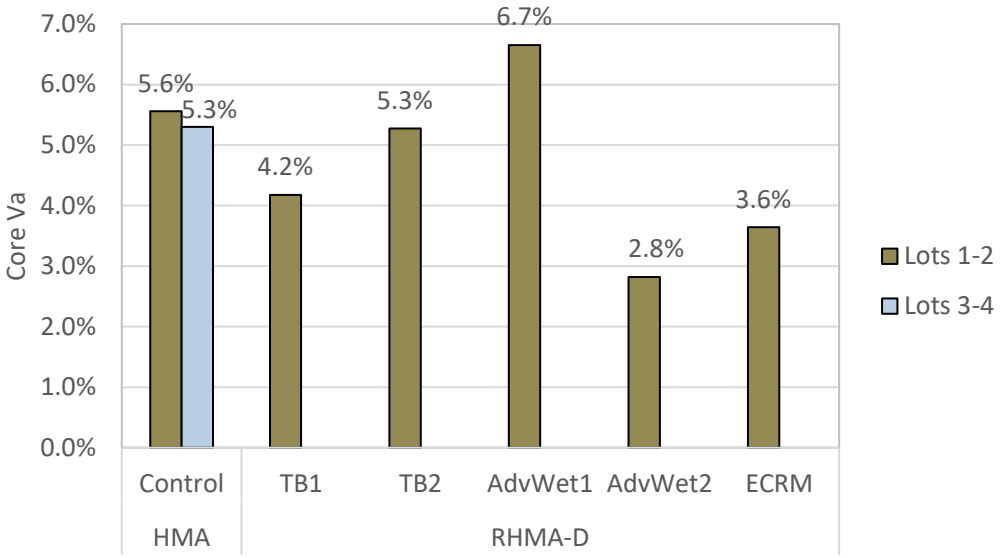


Figure 4.19: Field air-voids in asphalt of the Levee Road mixes.

The aggregate gradations of the mixes, determined by sieving the ignition oven residue, were overall within the acceptance limits, as shown in Figure 4.20.

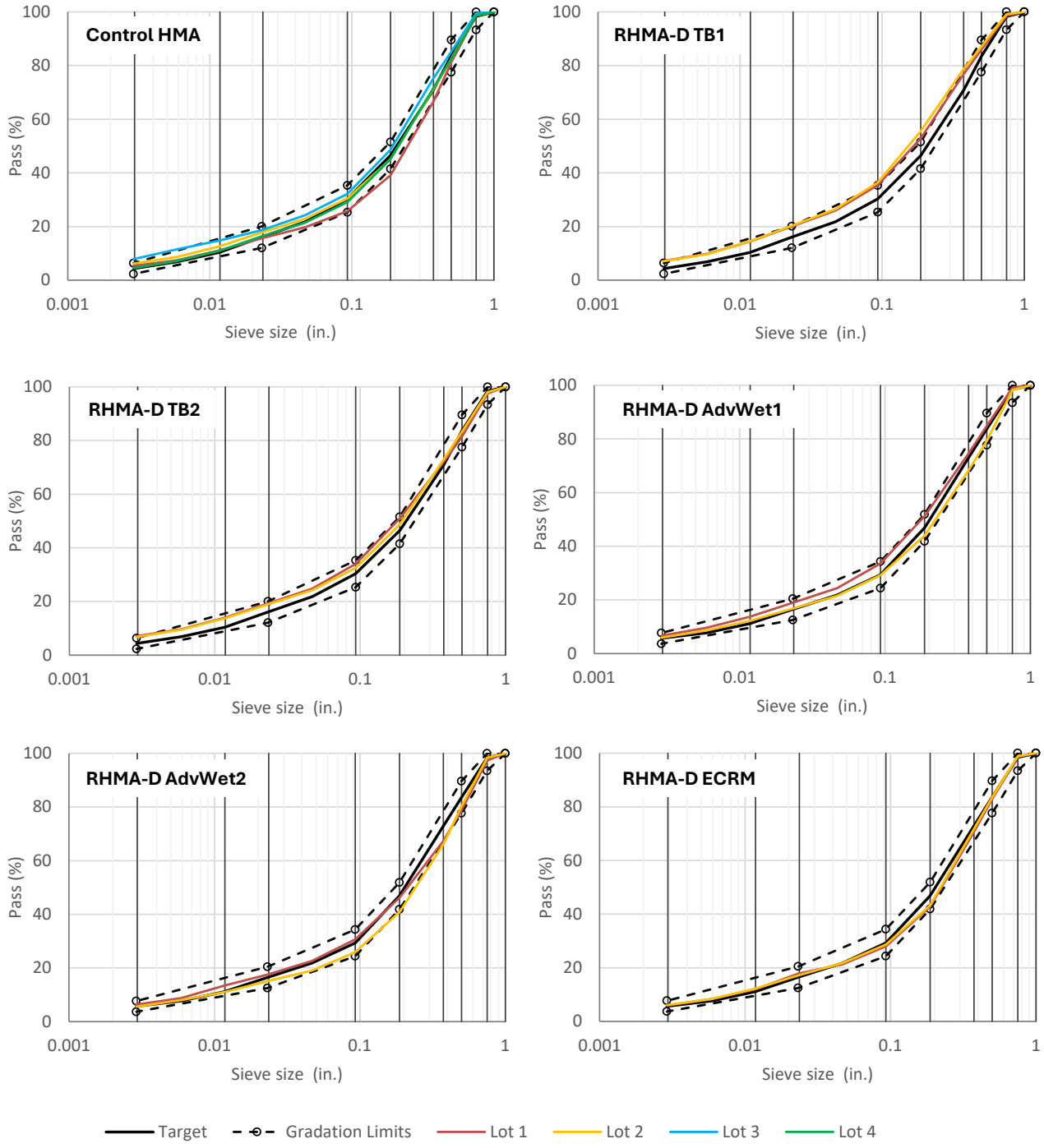


Figure 4.20: Aggregate gradation of the Levee Road mixes from plant-produced samples.

Each sampled lot was evaluated for cracking resistance using the IDEAL-CT test and for rutting resistance using the HWT test. The results are presented in Figure 4.21 and Figure 4.22. The results of the IDEAL-CT and the HWT tests fell within the ranges expected based on testing of the mixtures produced in the laboratory prior to construction of the pilot project. The IDEAL-CT strength values were consistent between lots. The AdvWet1 produced in the laboratory was not evaluated.

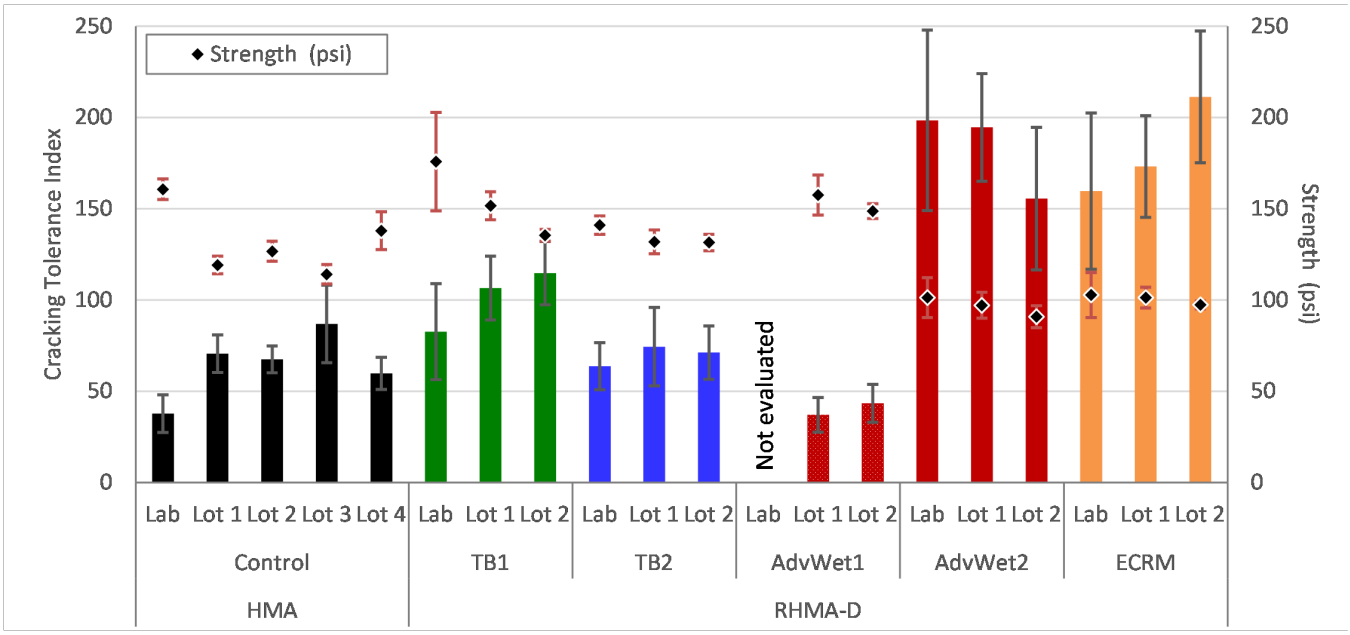
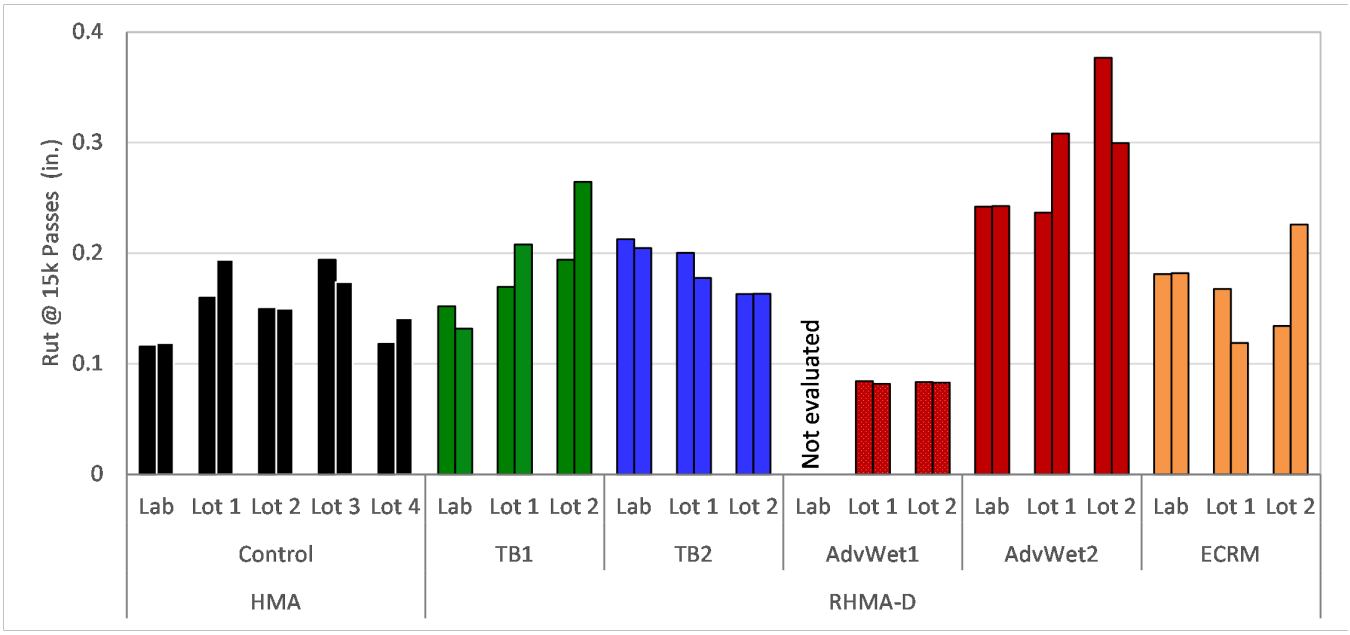


Figure 4.21: IDEAL-CT testing results of the Levee Road mixes.



Note: The two values shown for each lot correspond to the left and right wheels of the HWT test.

Figure 4.22: Hamburg Wheel-Tracking test results of the Levee Road mixes at 122°F (50°C).

4.4.2 Asphalt Binders

The virgin binders of the Control HMA and the RHMA-D mixes were tested for performance grade (PG) according to AASHTO M 320-23. The virgin binders of the different mixes are listed below:

- Control HMA: Its virgin binder is a plain binder graded as PG 58-22.
- RHMA-D mixes TB1 and TB2: The virgin binders are terminal blend binders with 14.5% (TB1) and 30.0% (TB2) recycled tire rubber (RTR), respectively. In both cases, the manufacturer formulated the binder to meet the required PG 58-22 grade.
- RHMA-D mixes AdvWet1 and AdvWet2: The virgin binder is a blend of the Control HMA virgin binder (PG 58-22) and passing #40 mesh CRM (<0.016 in. [0.4 mm]). The proportions of the virgin binder are 88.2% asphalt and 11.8% CRM by mass. No extender oil was used.
- RHMA-D mix ECRM: The virgin binder is the same as the Control HMA virgin binder (PG 58-22). The RTR is added through the dry process.

The PG testing was conducted twice. The first testing was conducted by UCPRC on the supplied virgin binder during the laboratory mix design phase, prior to the pilot construction. The second testing was performed by ABT Group Inc. on binders sampled during the pilot project construction. The results are presented in Table 4.6. The only discrepancy between the UCPRC and ABT Group Inc. results was observed for the TB2 binder. Further testing by UCPRC confirmed that this discrepancy was due to actual differences between the binder used in the mix design and the one used during the pilot project construction, with the former being softer than the latter.

Table 4.6: Performance Grade of the Virgin Asphalt Binders

Binder	Source	Laboratory	PGH (°F) [°C]	PGI (°F) [°C]	PGL (°F) [°C]
PG 58-22 requirements	—	—	≥ 136 (58)	≤ 72 (22)	≤ −8 (−22)
Control HMA virgin binder (PG 58-22)	Virgin binder, mix design phase	UCPRC	146 (63.3)	67 (19.3)	−17 (−27.4)
	Virgin binder, sampled during construction	ABT Group Inc.	142 (61.0)	65 (18.6)	−13 (−24.8)
TB1 virgin binder (14.5% RTR)	Virgin binder, mix design phase	UCPRC	150 (65.4)	71 (21.9)	−12 (−24.6)
	Virgin binder, sampled during construction	ABT Group Inc.	149 (64.8)	70 (21.0)	−13 (−25.2)
TB2 virgin binder (30.0% RTR)	Virgin binder, mix design phase	UCPRC	140 (59.9)	68 (19.8)	−20 (−28.7)
	Virgin binder, sampled during construction	ABT Group Inc.	151 (65.9)	72 (22.1)	−10 (−23.4)
AdvWet virgin binder (11.8% RTR)	Virgin binder, blended in the laboratory, mix design phase	UCPRC	169 (76.1)	52 (11.0)	−22 (−30.0)
	Virgin binder, blended in the plant, sampled during construction	ABT Group Inc.	164 (73.3)	60 (15.6)	−18 (−28.0)

Figure 4.23 shows the PG of the binders relative to the PG 58-22 requirements. In the figure, positive values of PGH and negative values of PGI and PGL indicate compliance with the PG 58-22. Although both TB binders meet PG 58-22 requirements, their PG grades do not differ considerably from that of the control mix's virgin binder. In contrast, the PG of the rubberized binder used with the two AdvWet RHMA-D mixes far exceeds the PG 58-22 requirements, particularly at high and intermediate temperatures.

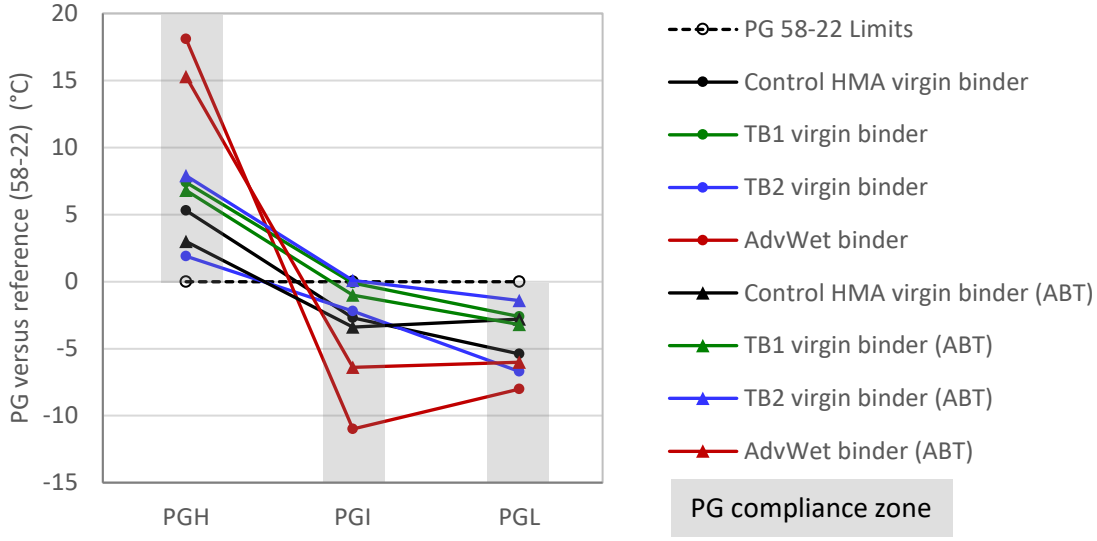


Figure 4.23: Performance grade of the virgin asphalt binders.

5 MECHANICAL PROPERTIES EVALUATION OF THE CONTROL AND RHMA-D MIXES

This chapter details the results of the mechanical testing of the mixes sampled during the construction. The mixes were sampled in metal buckets at the plant and brought to the UCPRC laboratories in Davis and Berkeley for specimen production and testing.

5.1 Specimen Production

Specimen production followed one of two procedures in accordance with California Test 320-2025:

- Reheating: This procedure is intended to reproduce the mix as collected from the plant, without introducing any intentional aging. The process consists of the following steps:
  (1) Heat the mix in the buckets, with the lid loosely fitted, for 4 hours at 275°F (135°C).
  (2) Recombine the mix from three to four buckets using a splitter and place it in metal pans with the required amount of material based on the specimen type.
  (3) Heat the metal pans in the oven for 2 hours at the compaction temperature, stirring the mix after 1 hour.
  (4) Proceed to compaction.
- Mid-term oven aging (MTOA): This procedure is intended to reproduce the aging expected to occur in California at 0.5 in. (12.5 mm) depth after about 5–10 years in service. The process follows the same steps as the reheating, with the addition of an intermediate aging step between Steps 2 and 3, consisting of 20 hours at 212°F (100°C).

Unless otherwise indicated, the test results presented in this chapter correspond to specimens prepared following the reheating procedure.

5.2 IDEAL-CT Cracking Tolerance Testing

The IDEAL-CT test results for the Control HMA and the five RHMA-D mixes are presented in Figure 5.1 (load-displacement curves) and Figure 5.2 (CT_{Index} and tensile strength). For each mix, the results correspond to the average of all sampled lots (Table 4.1).

As shown in Figure 5.1, all RHMA-D mixes except for AdvWet1 exhibit an improved deformation capacity compared to the Control HMA, as indicated by the rightward shift of the load-displacement curves relative to the Control HMA. This improvement is particularly evident for the TB1, AdvWet2, and ECRM RHMA-D mixes. Consequently, the CT_{Index} of these three RHMA-D mixes is substantially higher than that of the Control HMA (Figure 5.2). As expected, the reduced binder content of the AdvWet1 mix compared to AdvWet2 resulted in higher strength and lower CT_{Index}.

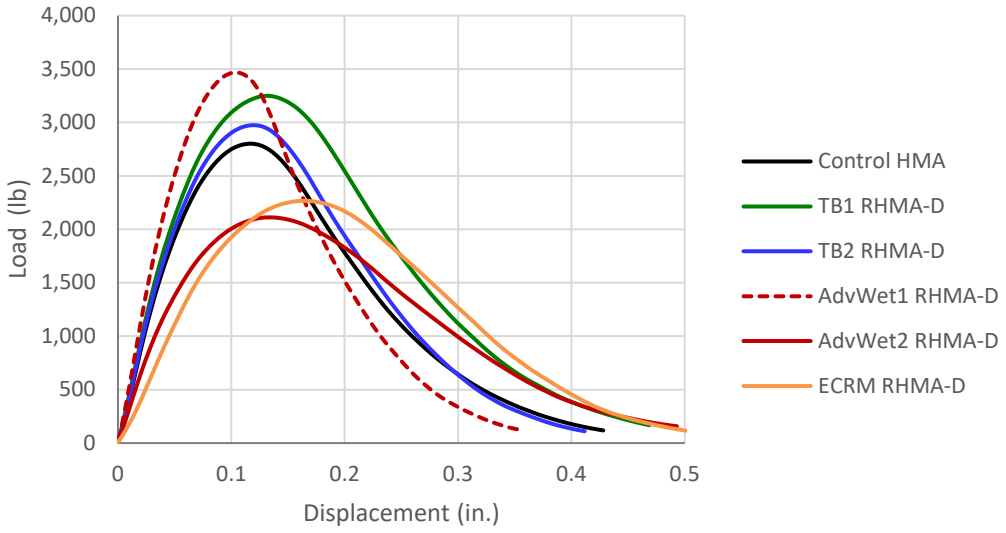


Figure 5.1: IDEAL-CT testing results of the Levee Road mixes: load versus displacement.

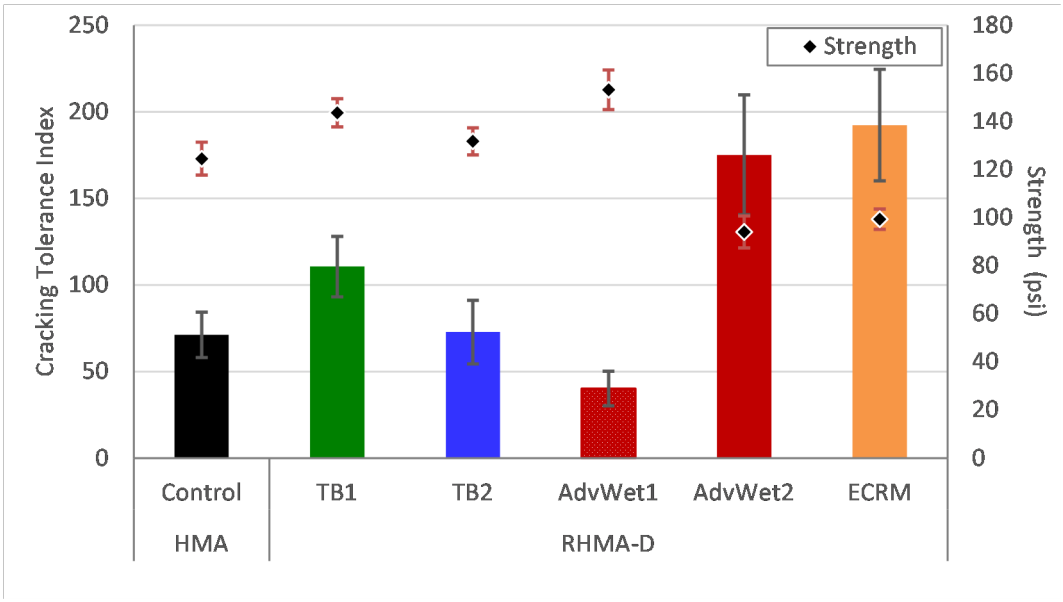


Figure 5.2: IDEAL-CT testing results of the Levee Road mixes: CT_{Index} versus strength.

The effects of the mix design adjustments, including the addition of RTR, are illustrated in Figure 5.3 within the CT_{Index}–Strength space. In this representation, the constant fracture energy (Wf) line defines the expected variation of CT_{Index} as the strength changes while the fracture energy remains constant (Equation 5.1). Movement along the constant Wf line therefore reflects mix softening or hardening without a change in fracture energy. For example, the AdvWet2 RHMA-D mix exhibits lower strength and higher CT_{Index} than the Control HMA while maintaining roughly the same fracture energy. All RHMA-D mixes plot at or above the constant Wf line, indicating enhanced mechanical performance relative to the Control HMA. However, while the AdvWet2 and ECRM RHMA-D mixes are located to the left of the Control HMA (lower strength), the TB1, TB2, and AdvWet1 RHMA-D mixes plot to the right (higher strength), suggesting a more optimized design for intermediate-layer applications.

$$CT_{Index} = CT_0 \, (S_0/Strength)^3 \quad \textbf{(5.1)}$$

Where:

CT_0 = CT_{Index} of the Control HMA

S_0 = Strength of the Control HMA

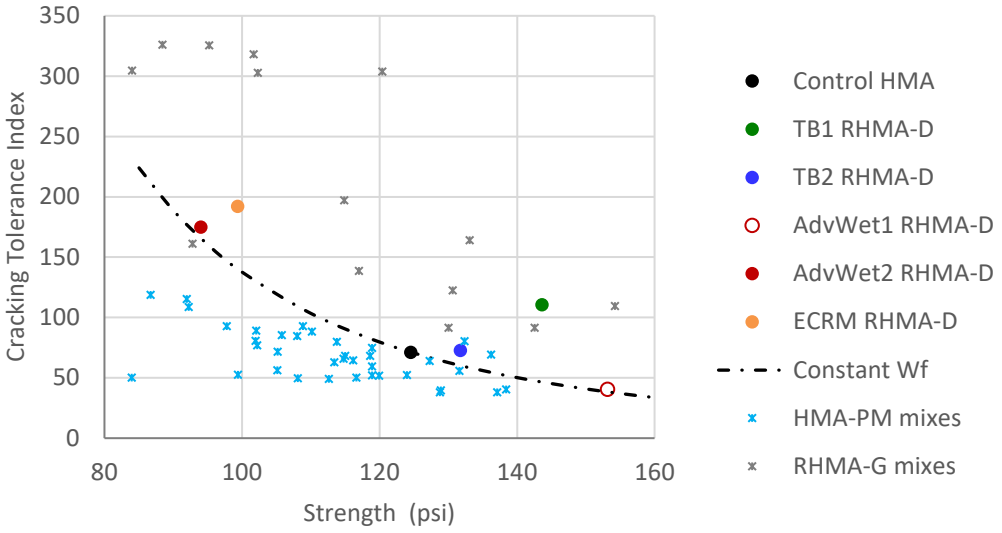


Figure 5.3: IDEAL-CT testing results of the Levee Road mixes: CT_{Index} versus strength space.

5.3 Aging Susceptibility Testing

One lot per mix was used to evaluate the aging susceptibility[7]. The aging conditioning consisted of maintaining the loose mix in an oven at 212°F (100°C) for 20 hours, following the Caltrans MTOA procedure described in California Test 320-2025. The aged mix was tested using the IDEAL-CT, and the results were compared with those of the reheated mix that was not subjected to any intentional aging. The comparison is presented in Figure 5.4 and Figure 5.5 for the CT_{Index} and in Figure 5.6 for the strength. Figure 5.5 and Figure 5.6 also present the same comparison for a collection of asphalt concrete (AC) mixes tested by the UCPRC in recent years. For this collection of mixes, the MTOA resulted, on average, in a 38% reduction in CT_{Index} and a 22 psi (150 kPa) increase in strength; this effect did not seem to depend on the mix type, binder PG, or binder source *(14)*. Based on the results presented in Figure 5.5 and Figure 5.6, the impact of the MTOA on the RHMA-D mixes did not differ from its impact on other AC mixes.

[7] Control HMA (Lot 4), TB1 RHMA-D (Lot 1), TB2 RHMA-D (Lot 1), AdvWet1 RHMA-D (Lot 1), AdvWet2 RHMA-D (Lot 2), and ECRM RHMA-D (Lot 1).

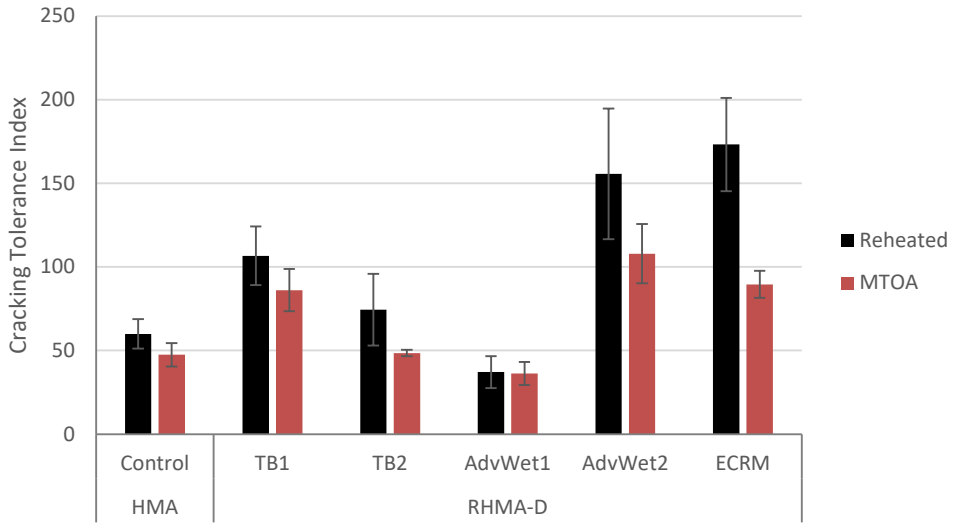


Figure 5.4: IDEAL-CT testing results of the Levee Road mixes: reheated and MTOA CT_{Index}.

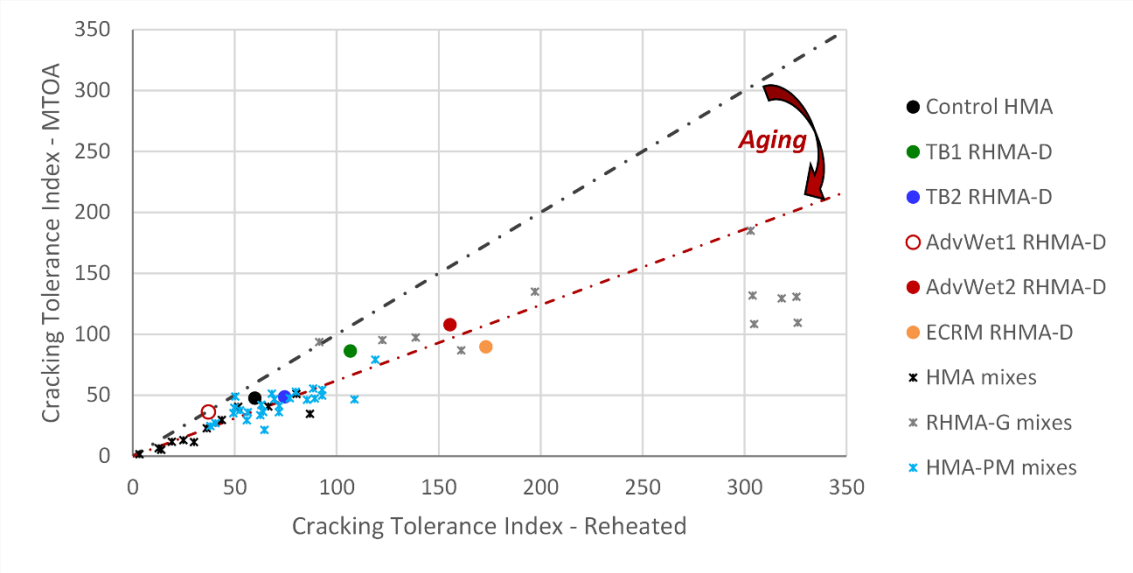


Figure 5.5: Comparison of reheated and MTOA CT_{Index} for the Levee Road mixes.

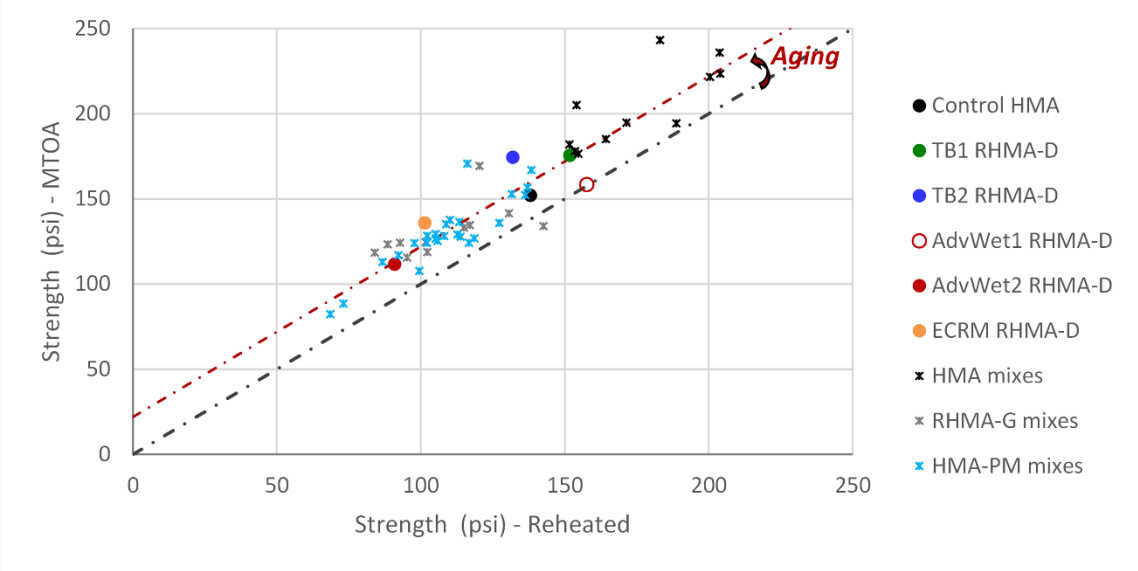


Figure 5.6: Reheated versus MTOA strength for the Levee Road mixes.

5.4 Moisture Damage Resistance Testing

The moisture damage resistance was also evaluated for one lot per mix[8]. The moisture conditioning was conducted with the Moisture-Induced Stress Tester (MiST) device (Figure 5.7), following ASTM D7870-20. In the MiST conditioning, the asphalt specimen is submerged in water inside a pressure chamber, which is immediately set to high temperature—140°F (60°C) in this research—and then the specimen inside the chamber is subjected to 3,500 water pressure cycles. Each cycle consists of a 1-second-long pressure pulse of 40 psi (280 kPa). The MiST is intended to simulate the pore pressure induced in a wet pavement by the passing/moving traffic loading and has been shown to produce damage comparable to that of AASHTO T 283 conditioning *(13)*.

[8] Control HMA (Lot 4), TB1 RHMA-D (Lot 1), TB2 RHMA-D (Lot 1), AdvWet1 RHMA-D (Lot 1), AdvWet2 RHMA-D (Lot 2), and ECRM RHMA-D (Lot 1).



Figure 5.7: MiST device: specimens added to the chamber (left), chamber filled with water (center), and ongoing test (right).

The moisture damage resistance was evaluated using specimens prepared following the reheating and the MTOA procedures. The evaluation consisted of comparing the strength after MiST conditioning with the strength of dry specimens. The results for all mixes are presented in Figure 5.8. The ratio between the strength of the MiST-conditioned and dry specimens, referred to as the *retained strength after MiST*, is presented in Table 5.1. In all cases, the retained strength is at least 75%, indicating high resistance to moisture damage. The AdvWet2 and ECRM RHMA-D mixes improved the ratio relative to the Control HMA under the two aging conditions (reheated and MTOA).

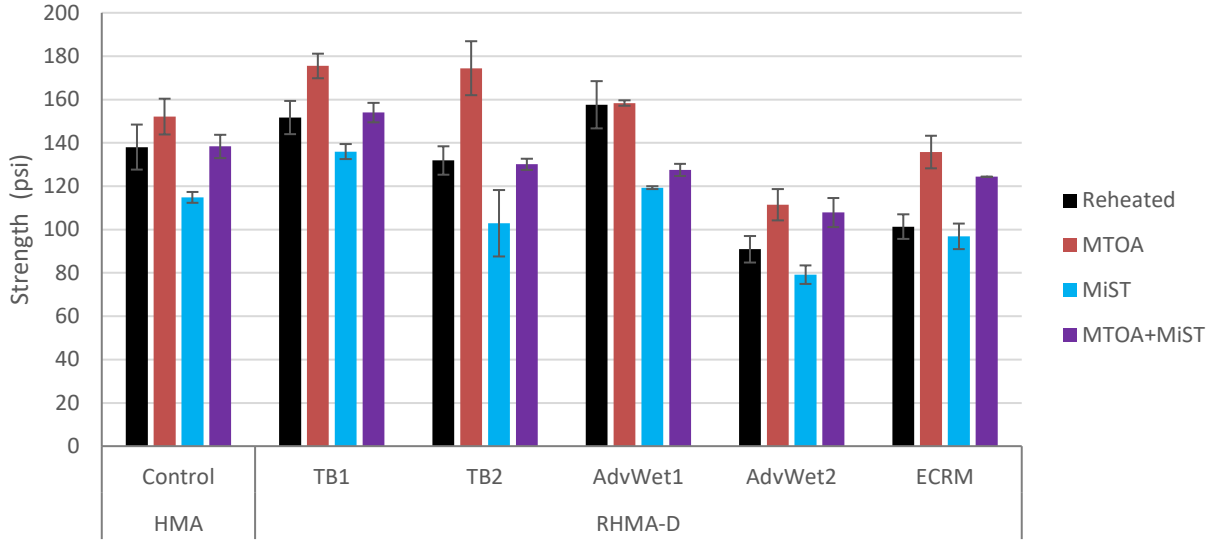


Figure 5.8: IDEAL-CT testing results comparing strength under reheated, MTOA, MiST, and MTOA+MiST conditions for the Levee Road mixes.

Table 5.1: Retained Strength After MiST

Condition	HMA Control (%)	RHMA-D				
		TB1 (%)	TB2 (%)	AdvWet1 (%)	AdvWet2 (%)	ECRM (%)
Reheated	83.2	89.6	78.0	75.7	87.1	95.5
MTOA	91.0	87.7	74.6	80.5	96.7	91.6

5.5 Stiffness Testing

Two lots of the Control HMA and one lot of each of the RHMA-D mixes[9] were tested for flexural stiffness using the four-point bending (4PB) device, in accordance with ASTM D8237-21, and for axial stiffness using the Asphalt Mixture Performance Tester (AMPT), following AASHTO T 378-22.

Testing was conducted over a range of loading frequencies (0.01–15 Hz for the 4PB and 0.1–25 Hz for the AMPT) and temperatures (50–86°F [10–30°C] for the 4PB and 39–129°F [4–54°C] for the AMPT). The dynamic modulus data were fitted using a sigmoidal master curve based on the time-temperature superposition principle. The master curves for the different mixes are presented in Figure 5.9 (4PB) and Figure 5.12 (AMPT). The normalized dynamic modulus, referenced to the Control HMA, is shown in Figure 5.10 (4PB) and Figure 5.13 (AMPT). Finally, the relationship between dynamic modulus and phase angle (Black space) is presented in Figure 5.11 (4PB) and Figure 5.14 (AMPT).

Two main differences exist between stiffness measured in 4PB and AMPT. The 4PB test measures flexural stiffness, which is representative of the stiffness of the mixture in the horizontal direction, i.e., perpendicular to the compaction direction. In contrast, the AMPT measures the axial stiffness of the specimen, which corresponds to the compaction direction. In other words, the 4PB measures stiffness perpendicular to the compaction direction (horizontal), while the AMPT measures stiffness in the compaction direction (vertical). The second main difference is that the 4PB test is conducted under tension–compression, whereas the AMPT test is conducted under compression only. As a result, the aggregate skeleton of the mixture plays a more significant role in the AMPT response than in the 4PB response. Based on Figure 5.9 (4PB) and Figure 5.12 (AMPT) data, the ratio of axial to flexural stiffness of the Control HMA is around 2. In contrast, this ratio is significantly lower—ranging from 1.2 to 1.5—for the RHMA-D mixes, likely due to their higher binder content, which reduces the relative contribution of the aggregate skeleton.

The effects of the mix design adjustments, including the addition of RTR, vary from one RHMA-D mix to another. For mixes with discrete CRM particles (AdvWet1, AdvWet2, and ECRM), the stiffness at low reduced frequency (high temperature) increases while the stiffness at intermediate and high reduced frequency (intermediate and low temperature) either changes little (based on 4PB, Figure 5.10) or decreases (AMPT, Figure 5.13). This effect is highly desirable for a surface mix: increased stiffness at high temperatures helps reduce rutting, whereas reduced stiffness at intermediate and low

[9] Control HMA (Lots 1 & 4), TB1 RHMA-D (Lot 1), TB2 RHMA-D (Lot 1), AdvWet1 RHMA-D (Lot 1), AdvWet2 RHMA-D (Lot 2), and ECRM RHMA-D (Lot 1).

temperatures helps mitigate fatigue, block, and thermal cracking. For the mixes with TB asphalt binder, the stiffness increase at low reduced frequencies (high temperatures) is not that evident. Further, at intermediate and high reduced frequencies, the stiffness either remains unchanged (AMPT, Figure 5.13) or increases (based on 4PB, Figure 5.10). This increase may have a negative impact on fatigue and age-related cracking when the mix is used as a surface layer.

Based on the plot of phase angle versus stiffness in the Black space (Figure 5.11 and Figure 5.14), the mixes with discrete CRM particles (AdvWet and ECRM) have lower phase angle than the Control HMA for the same stiffness, particularly at high temperature. The lower phase angle indicates higher elasticity, which is likely due to the CRM mechanical properties.

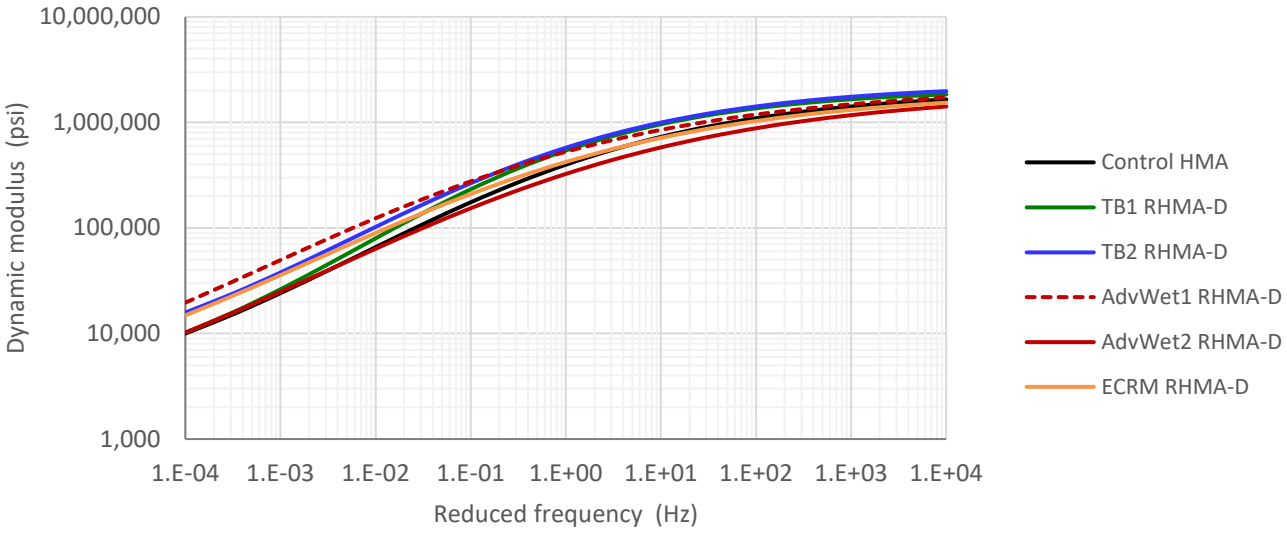


Figure 5.9: 4PB stiffness testing results of the Levee Road mixes: dynamic modulus.

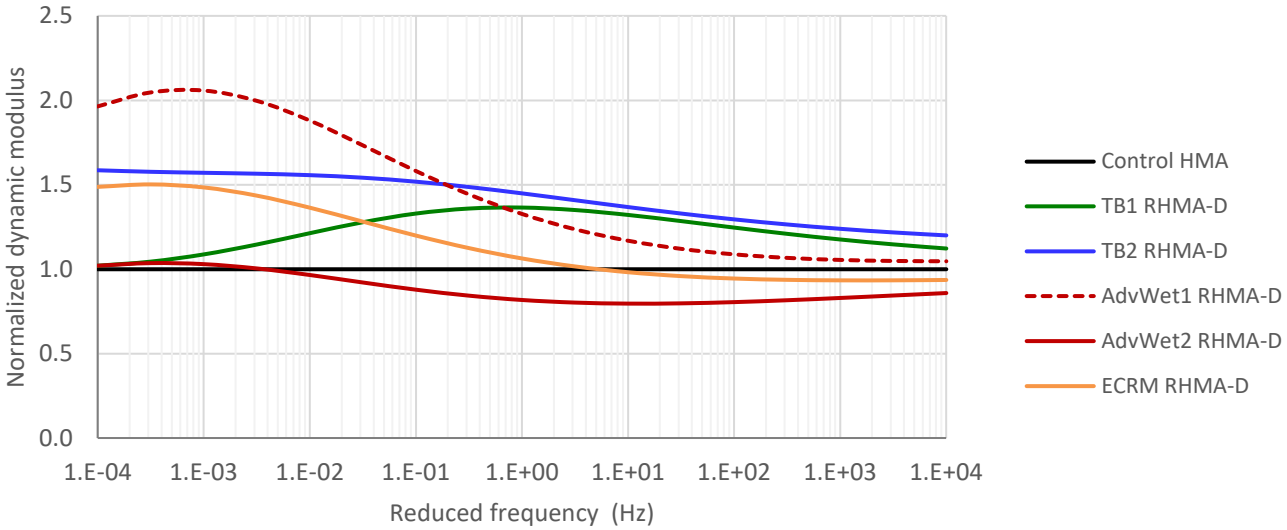


Figure 5.10: 4PB stiffness testing results of the Levee Road mixes: normalized dynamic modulus.

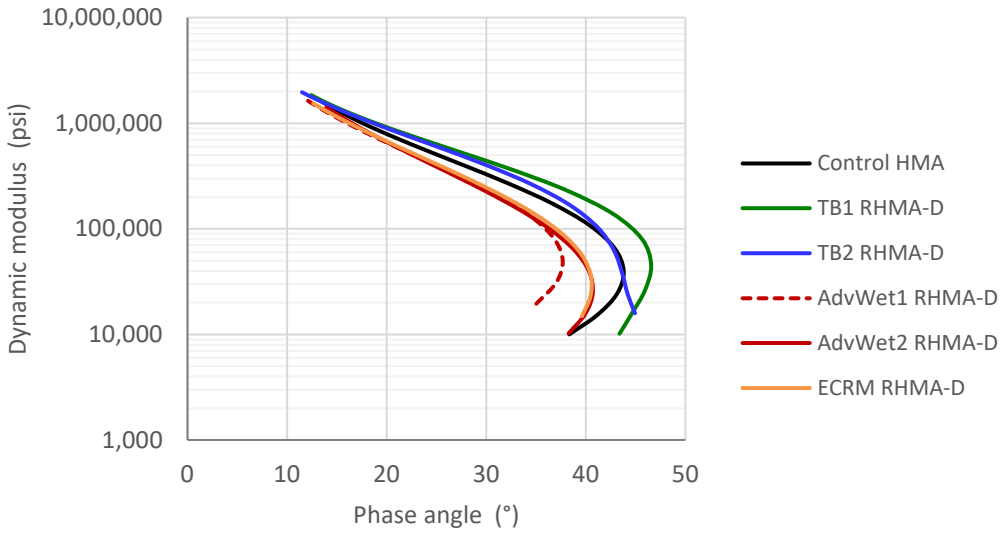


Figure 5.11: 4PB stiffness testing results of the Levee Road mixes: Black space.

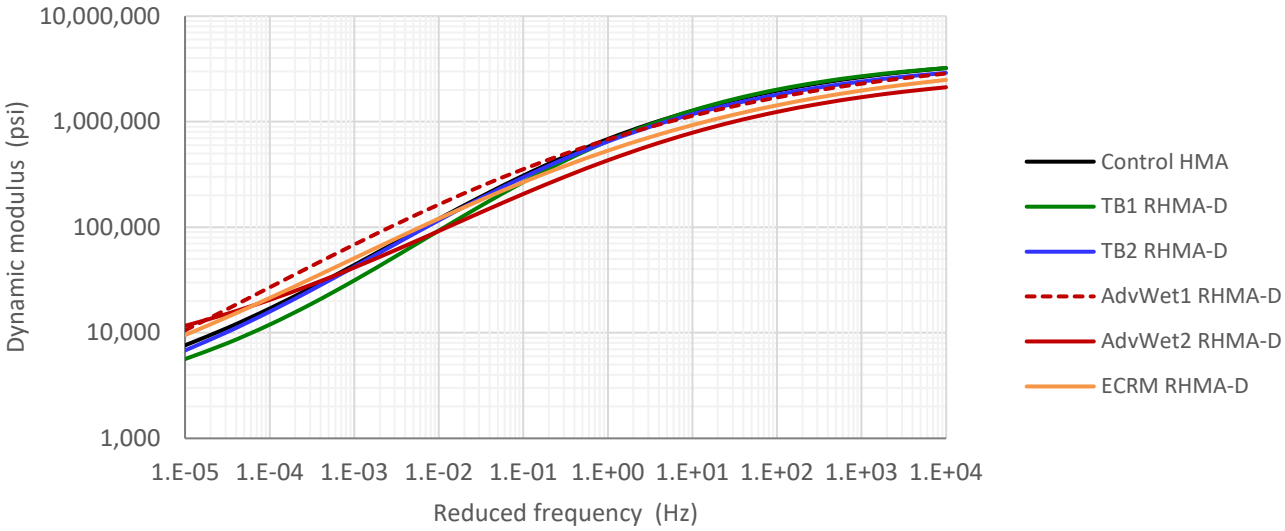


Figure 5.12: AMPT stiffness testing results of the Levee Road mixes: dynamic modulus.

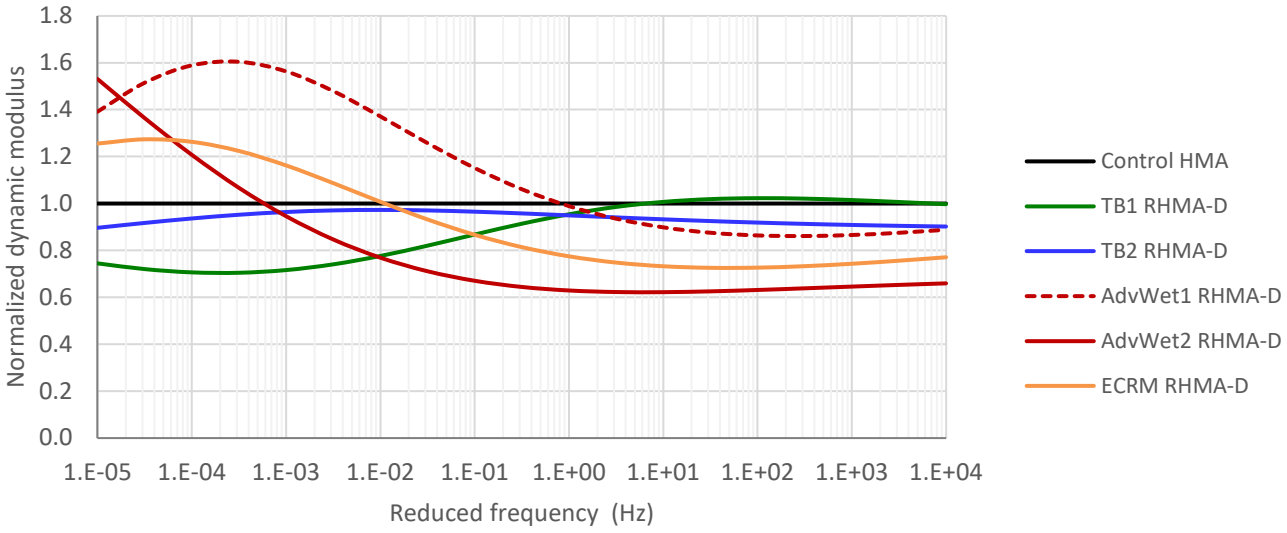


Figure 5.13: AMPT stiffness testing results of the Levee Road mixes: normalized dynamic modulus.

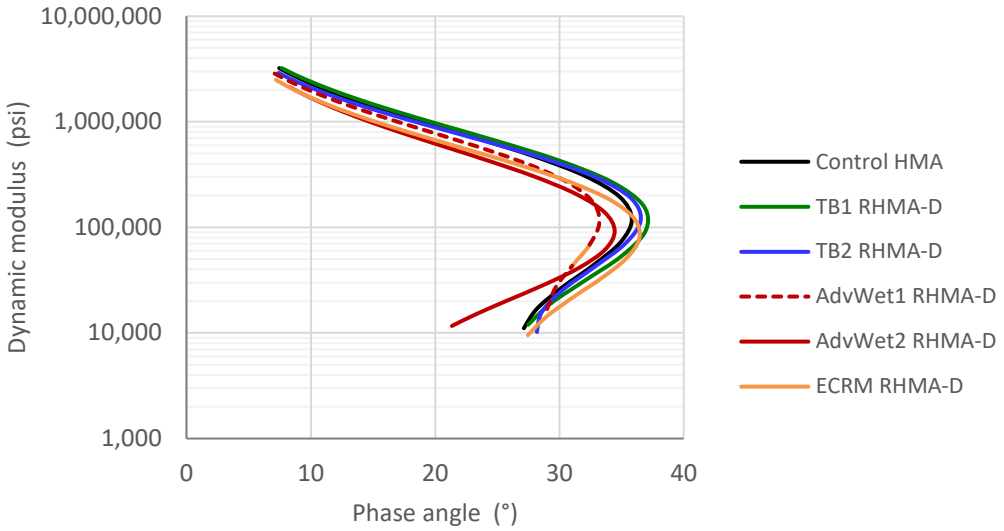


Figure 5.14: AMPT stiffness testing results of the Levee Road mixes: Black Space.

5.6 Rutting Resistance Testing

The rutting resistance of the Control HMA and the RHMA-D mixes was evaluated with the HWT test following AASHTO T 324-23 at the Caltrans-specified temperature of 122°F (50°C) and with the AMPT repeated load testing (RLT) following AASHTO T 378-22, also conducted at 122°F (50°C) under confined conditions (5 psi [35 kPa] confinement).

The HWT test results presented below (Figure 5.15 and Figure 5.16) correspond to the average of all sampled lots (Table 4.1). The AMPT RLT results presented below (Figure 5.17) correspond to two lots of the Control HMA and one lot of each of the RHMA-D mixes[10].

As shown in Figure 5.15, all mixes pass the HWT requirement in Caltrans Standard Specifications (rut depth less than 0.5 in. at 15,000 passes). Overall, all RHMA-D mixes exhibited rutting performance comparable to that of the Control HMA, except for the AdvWet RHMA-D mixes. The AdvWet2 mix showed slightly poorer performance compared to the Control HMA. In contrast, the AdvWet1, because of the reduced binder content, considerably improved the rutting performance of the Control HMA. Similar conclusions were drawn from the AMPT RLT results shown in Figure 5.17.

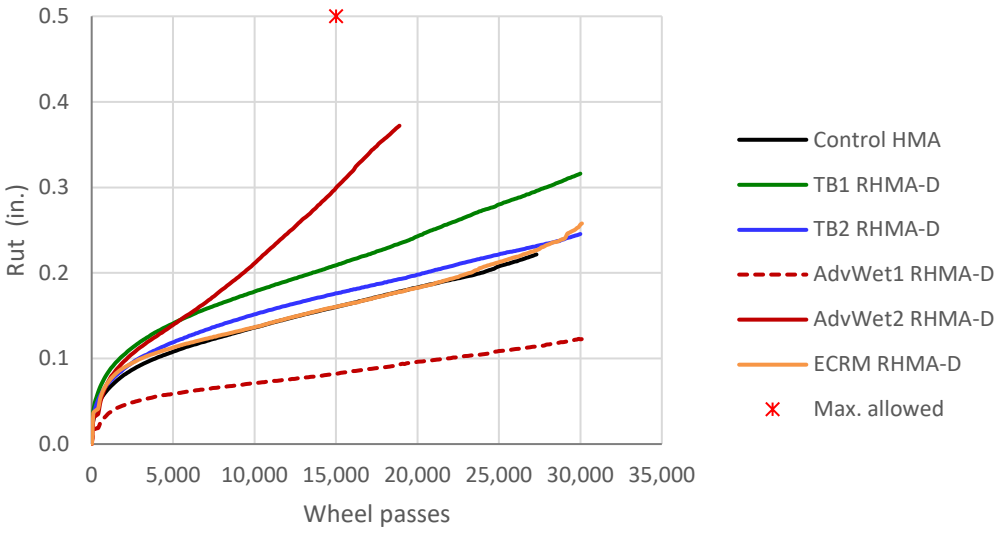


Figure 5.15: Hamburg Wheel-Tracking test results of the Levee Road mixes (122°F [50°C]): rut versus wheel passes.

[10] Control HMA (Lots 1 & 4), TB1 RHMA-D (Lot 1), TB2 RHMA-D (Lot 1), AdvWet1 RHMA-D (Lot 1), AdvWet2 RHMA-D (Lot 2), and ECRM RHMA-D (Lot 1).

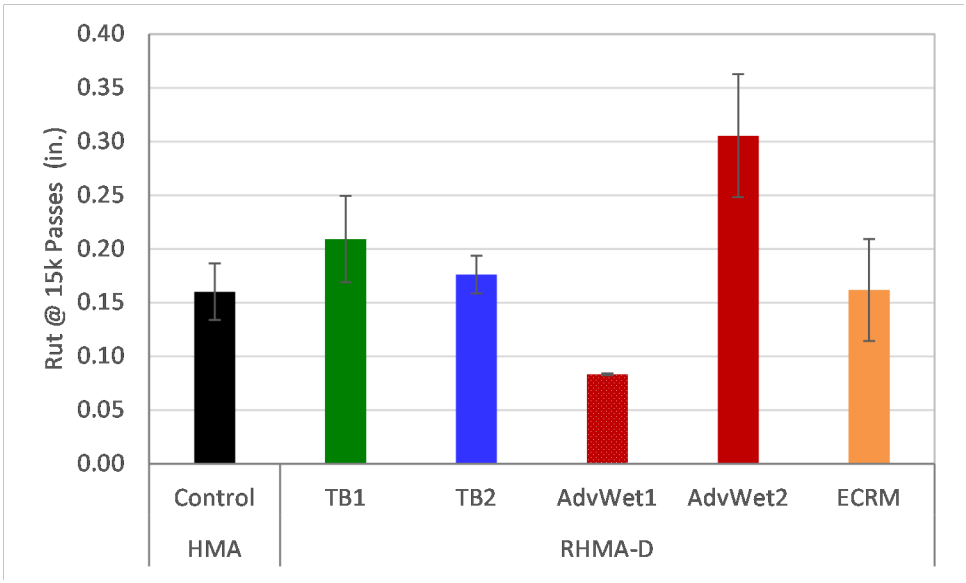


Figure 5.16: Hamburg Wheel-Tracking test results of the Levee Road mixes (122°F [50°C]): rut at 15,000 wheel passes.

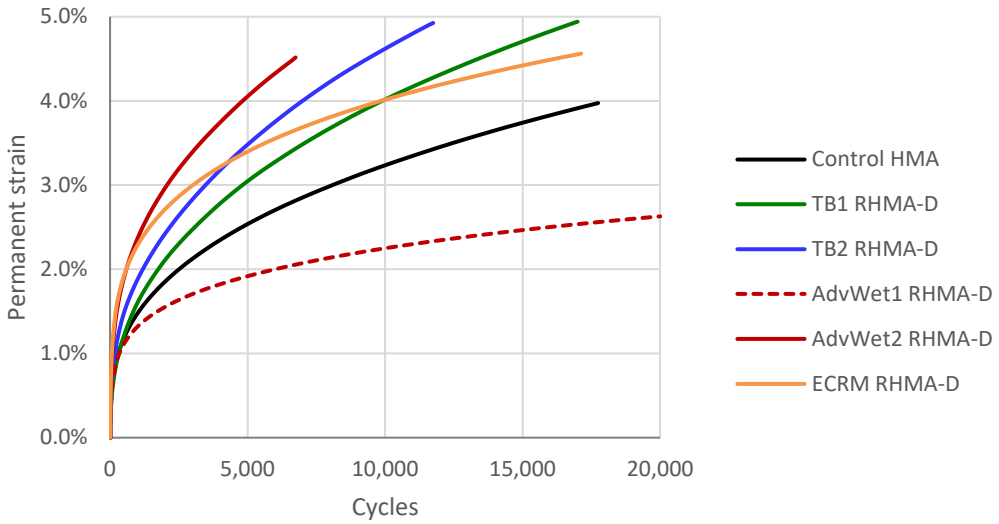


Figure 5.17: AMPT RLT results of the Levee Road mixes (confined; 122°F [50°C]).

5.7 4PB Fatigue Resistance Testing

The fatigue resistance of the Control HMA and the RHMA-D mixes was evaluated using the 4PB test in accordance with ASTM D8237-21, at a temperature of 68°F (20°C) and a loading frequency of 10 Hz. The testing was conducted on two lots of the Control HMA and one lot of each RHMA-D mix[11].

As shown in Figure 5.18, the effect of the mix design adjustments, including the addition of RTR, varies from one RHMA-D mix to another. For mixes with discrete CRM particles (AdvWet2 and ECRM), the fatigue life increases substantially compared with the Control HMA. At a strain level of 300 με, which is at the upper range of strains developed under traffic loading in the field, the fatigue lives of these two mixes are approximately 2.7 times (AdvWet2) and 4.6 times (ECRM) that of the Control HMA. As expected, the reduced binder content of the AdvWet1 (5.20% $P_{b;\,ARNMA}$, TMM) mix resulted in a considerable reduction of the fatigue life compared to the AdvWet2 mix produced with the intended binder content of 6.25% ($P_{b;\,ARNMA}$, TMM).

The two mixes with TB asphalt binder (TB1 and TB2) do not considerably improve the fatigue life compared with the Control HMA. This outcome is partly due to the relatively high stiffness of these mixes. As shown in Figure 5.10, the flexural stiffness of the RHMA-D mixes TB1 and TB2 is approximately 30–40% higher than that of the Control HMA at a reduced frequency of 10 Hz, which corresponds to the temperature and loading frequency used in the 4PB fatigue test.

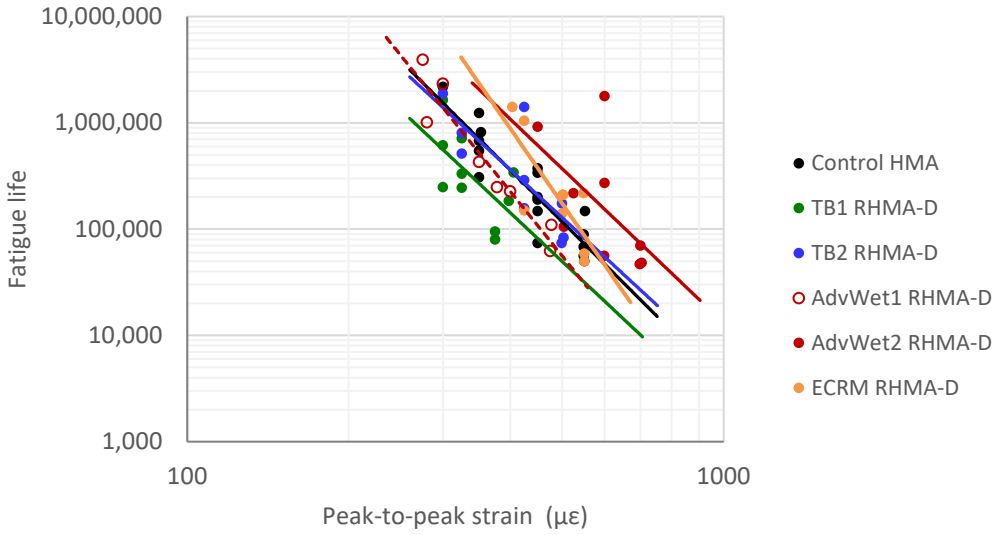


Figure 5.18: 4PB fatigue testing results of the Levee Road mixes: Wöhler curves.

The effects of the mix design adjustments, including the addition of RTR, are illustrated in Figure 5.19 within the Fatigue Life–Stiffness space. In this representation, the strain that results in 1 million (10^6) repetitions to failure, denoted as ε_6, is plotted versus the flexural stiffness of the mix, denoted as E*. The constant deformation energy (Wε) line defines the expected variation of ε_6 as the stiffness changes

[11] Control HMA (Lots 1 & 4), TB1 RHMA-D (Lot 1), TB2 RHMA-D (Lot 1), AdvWet1 RHMA-D (Lot 1), AdvWet2 RHMA-D (Lot 2), and ECRM RHMA-D (Lot 1).

while the deformation energy remains constant (Equation 5.2). Movement along the constant Wε line therefore reflects mix softening or stiffening without a change in the capacity to sustain deformation energy. All RHMA-D mixes plot at or above the constant Wε line, indicating enhanced fatigue performance relative to the Control HMA. However, the TB1, TB2, and AdvWet1 RHMA-D mixes are located to the right of the Control HMA (higher stiffness), suggesting a less optimized design for thin surface-layer applications compared to the AdvWet2 and ECRM RHMA-D mixes, although the greater stiffness would be expected to reduce bending in the asphalt and therefore reduce fatigue damage when used as an intermediate layer. Data in Figure 5.19 also indicate that the capacity of the AdvWet2 and ECRM RHMA-D mixes to resist imposed deformation (ε_6) is at the lower end of the range observed for RHMA-G and HMA mixes with polymer-modified binders.

$$\varepsilon_6 = \varepsilon_{6;0} \, (E^*_0/E^*)^{0.5} \qquad \textbf{(5.2)}$$

where $\varepsilon_{6;0}$ and E^*_0 are ε_6 and E* of the Control HMA, respectively.

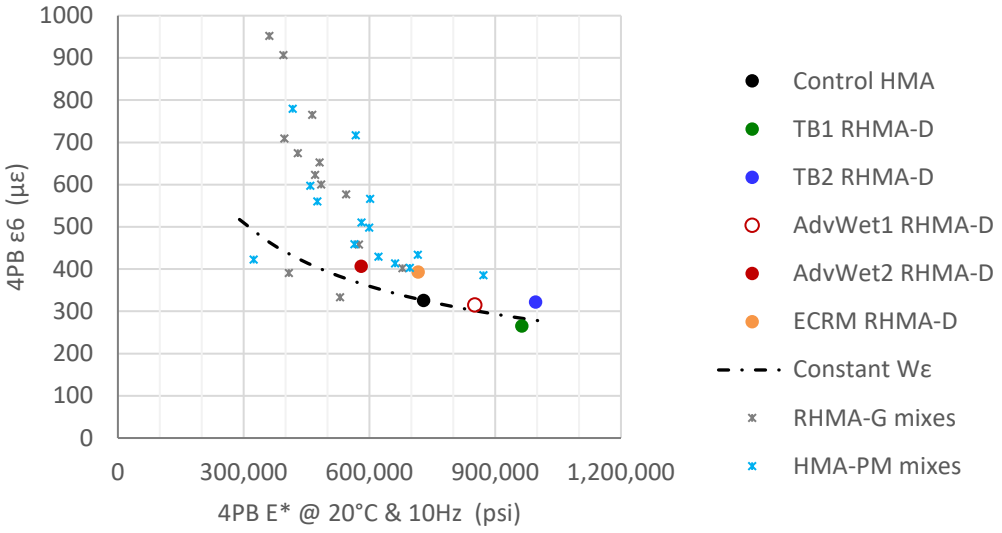


Figure 5.19: 4PB fatigue testing results of the Levee Road mixes: life–stiffness space.

6 LIFE CYCLE EVALUATION OF REHABILITATION WITH RHMA-D

This chapter discusses the potential life cycle benefits of using RHMA-D compared with the Control HMA. The potential benefits of RHMA-D are driven by improved performance and the resulting reduction in future maintenance and rehabilitation needs. The discussion is presented separately for age-related block cracking (Section 6.1) and for fatigue-related cracking (Section 6.2).

6.1 Benefits Associated with Improved Resistance to Age-Related Block Cracking

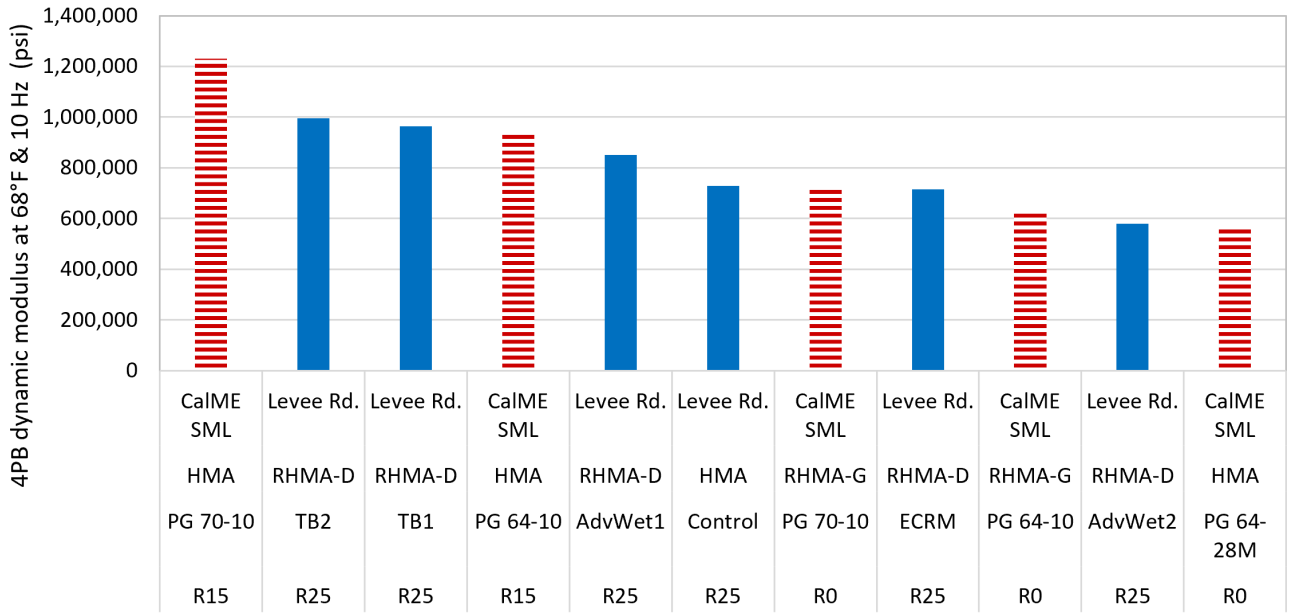
The benefits associated with improved resistance to age-related block cracking are evaluated based on a conceptual comparison of the costs and GWP of the frequency of preservation treatments needed to minimize age-related cracking for conventional HMA and RHMA-G mixes versus the RHMA-D mixes developed in this study. The comparison involves the conceptual estimation of the number of years to the appearance of age-related cracking. Age-related cracking consists initially of transverse cracking, followed by longitudinal cracking, leading to block cracking. As explained in Section 1.4, this approach assumes an unrealistic unrestricted-funding scenario. However, the results are expected to provide a very rough order-of-magnitude estimate of the potential long-term savings or additional costs associated with the use of RHMA-D compared with standard HMA.

The premise of the comparison is that the appearance of age-related cracking is related to the stiffness of the mix. Stiffer mixes will have higher stresses leading to age-related cracking for a given change in temperature and coefficient of thermal contraction (primarily a function of the aggregate source). This is a gross simplification because other factors will significantly affect the time to age-related cracking development:

- Depth below the surface, with mix aging less the deeper it is below the surface because of reduced air penetration into the mix, cooler temperatures in the summer slowing aging, and warmer temperatures in the winter reducing stresses, to the extent that age-related cracking can be considered to not be an issue for mixes below the surface layer.
- Extent of cracking in underlying asphalt layers, with faster appearance of transverse and longitudinal cracking on the surface when it is reflected up from existing cracking than when there is no existing cracking below the new surface and the cracking initiates at the pavement surface.
- Temperature susceptibility, the change of stiffness versus temperature, with higher temperature susceptibility resulting in higher stresses at lower temperatures.
- Ability to relax stress, as measured by phase angle at intermediate temperatures and creep modulus at lower temperatures, with greater phase angle and lower creep modulus resulting in lower stresses.
- Binder film thickness, a function of binder content and aggregate surface area, with thicker film thicknesses reducing stresses in the binder and also reducing mix stiffness.

- Aging susceptibility, with greater aging susceptibility resulting in increased stiffness, lower phase angles, and less stress relaxation from creep, resulting in greater stresses at lower temperatures over time.
- Climate region, which determines the range of lower temperatures in the winter and the range of high temperatures contributing to aging in the summer.
- Compaction of the mix, with greater compaction resulting in slower aging because of cooler temperatures.
- Potential for polymer-modified and rubberized mixes to better resist age-related cracking for a given set of conditions, compared with mixes with unmodified binders.

All of those factors being important, a rough comparison of unaged mix stiffnesses at 68°F (20°C) and 10 Hz (intermediate temperature, much faster loading than that causing age-related cracking) from flexural beam mix testing still provides a very first-order idea of potential for age-related cracking. Those stiffnesses are shown in Figure 6.1. The Levee Road control and RHMA-D mixes are shown compared with mixes in the UCPRC/Caltrans Standard Materials Library (SML) used by the *CalME* design program.



Note: Levee Road mixes shown in solid blue, *CalME* SML mixes shown in striped red.

Figure 6.1: Comparison of mix flexural stiffnesses at 68°F (20°C) and 10 Hz for Levee Road and *CalME* Standard Materials Library mixes.

CalME does not yet have an age-related cracking model, however, first-order estimates of ranges of time to first age-related cracking in the climate regions they are used in for the *CalME* SML mixes are shown below, all assuming typical construction compaction and no pavement preservation

treatments. These estimates are based on anecdotal observations and informal surveys of local governments.

- PG 70-10 with 15% RAP in the Desert region: approximately 3 to 12 years.
- PG 64-10 with 15% RAP in the Inland Valley region: approximately 5 to 18 years.
- PG 64-10 with 15% RAP in the Central and South Coast regions: approximately 10 to 22 years.
- PG 64-28M in the Mountain and High Desert regions: approximately 10 to 25 years.
- RHMA-G 70-10 with no RAP: approximately 2 to 5 years longer than PG 70-10 mixes.
- RHMA-G 64-10 with no RAP in coastal regions: approximately 2 to 5 years longer than PG 64-10 with 15% RAP.

The goal of pavement preservation treatments such as chip seals, slurry seals, microsurfacing seals, and cape seals is to slow aging. A general recommendation is to apply preservation seal coats before age-related cracking appears or at the latest when it first appears, because seal coats generally do not seal cracks for very long. Therefore, the earlier appearance of age-related cracking would be expected to require more frequent preservation treatments and therefore higher life cycle cost to manage the cracking.

Based on the first-order observations discussed above, and considering that the Levee Road mixes have similar binder contents and rubber contents, an initial estimate is that the Levee Road RHMA-D mixes with higher stiffnesses (TB2 and TB1) may exhibit age-related cracking sooner than those with lower stiffnesses. The TB2 and TB1 mixes may have similar performance as the HMA 64-10 R15 from the SML, whether the age-related cracking comes from the surface or from reflective cracking. The AdvWet1 RHMA-D mix would be expected to have age-related cracking performance between that of the HMA 64-10 R15 mix and the Levee Road Control HMA. The Levee Road HMA Control R25, an RHMA-G 70-10 from the SML, and the ECRM RHMA-D mixes would be expected to have similar performance. The AdvWet2 mix would be expected to have similar age-related cracking performance to an RHMA-G 64-10 or HMA 64-28M R0. The RHMA-D mixes may exhibit age-related cracking at later times than the Levee Road Control HMA despite having higher stiffnesses because of their lower temperature susceptibility, although those with greater increase in stiffness and reduction in CT_{Index} value after medium-term oven aging (Section 5.3) indicate potential for faster age-related cracking appearance. The experimental results from the Levee Road will provide better information than this first-order analysis.

6.2 Benefits Associated with Improved Resistance to Fatigue-Related Cracking

The benefits associated with improved resistance to fatigue-related cracking are evaluated based on the comparison of the costs and GWP of rehabilitating a pavement section using conventional HMA versus the RHMA-D mixes developed in this study. The comparison involves the estimation of the cost and GWP of rehabilitating the section each time it reaches a critical level of cracking over the analysis period. As explained in Section 1.4, this approach assumes an unrealistic unrestricted-funding

scenario. However, the results are expected to provide an order-of-magnitude estimate of the potential long-term savings or additional costs associated with the use of RHMA-D compared with standard HMA.

The evaluation methodology is detailed in Section 6.2.1. Then the methodology is applied to evaluate two different case studies where the RHMA-D is used either as surface layer (Case Study 1, Section 6.2.2) or as intermediate layer (Case Study 2, Section 6.2.3).

6.2.1 Evaluation Methodology

As explained above, the evaluation methodology requires the estimation of the cost and GWP of rehabilitating a pavement section each time it reaches a critical level of cracking over the analysis period. The methodology includes the following steps:

(1) Define case studies. Each case study represents a potential scenario in which the use of RHMA-D can be considered, which consists of a pavement section with a predefined existing structure and distress state, subjected to specific climate and traffic conditions. In this study, due to scope and report length limitations, a comprehensive set of case studies is not presented. Instead, one representative case study is defined for each of the two RHMA-D applications: as a surface layer and as an intermediate layer. The objective is to provide a first-level estimate of the potential cost and GWP savings associated with the use of RHMA-D compared with conventional HMA with plain binder.

(2) Design the treatment. This step consists of defining the pavement repairs and overlay materials and thicknesses that will be applied to the existing distressed section. The term "treatment" is a generic term used in this report to refer to this intervention. For example, a treatment may consist of milling 2.4 in. (61 mm) of old HMA and paving a 2.4 in. overlay of new HMA. The new HMA can be either the Control HMA or any of the RHMA-D mixes evaluated in this study. The same thickness is assumed for both the RHMA-D mixes and the Control HMA.

(3) Estimate cost and GWP of the treatment. Once the treatment is defined, its economic cost and GWP can be quantified. In this study, the costs of producing and placing asphalt mix are estimated based on the Caltrans Contract Cost Database *(15)* and Caltrans 2022 Crumb Rubber Report *(3)* for materials already available in the market (e.g., cost per ton of HMA), and based on direct surveys of suppliers for RTR-derived products. The GWP is estimated using the Caltrans Environmental Life Cycle Assessment for Pavement (*eLCAP*), version 1.0 *(9)*, and OpenLCA *(16)*.

(4) Estimate future rehabilitation schedule. The fatigue-cracking performance of the rehabilitated sections is predicted using *CalME* software. *CalME* accounts for the specific mechanical properties of the asphalt mixes used in the rehabilitation, with properties determined from the four-point bending (4PB) fatigue laboratory characterization presented in Chapter 5. An example of cracking performance prediction is shown in Figure 6.2. In this figure, cracking increases over time until it reaches an unacceptable level that triggers a new treatment (second, third, and fourth rehabilitations in the figure). For simplicity, it is assumed that all

treatments are identical to the first one; therefore, the same cracking history is repeated after each treatment. The predicted cracking is used to estimate the future rehabilitation schedule of each section, identified as years Y_2, Y_3, and Y_4 in Figure 6.2. It is assumed that rutting would not trigger rehabilitation of the sections.

One limitation of *CalME* is that it only models fatigue cracking—that is, cracking caused by repeated traffic loading, specifically bottom-up and reflective cracking. It does not account for age-related cracking, such as transverse and longitudinal cracking leading to block cracking caused by thermal cycling combined with aging of the surface mix. As a result, *CalME* may overpredict fatigue life under certain scenarios, particularly for pavements subjected to low traffic volumes.

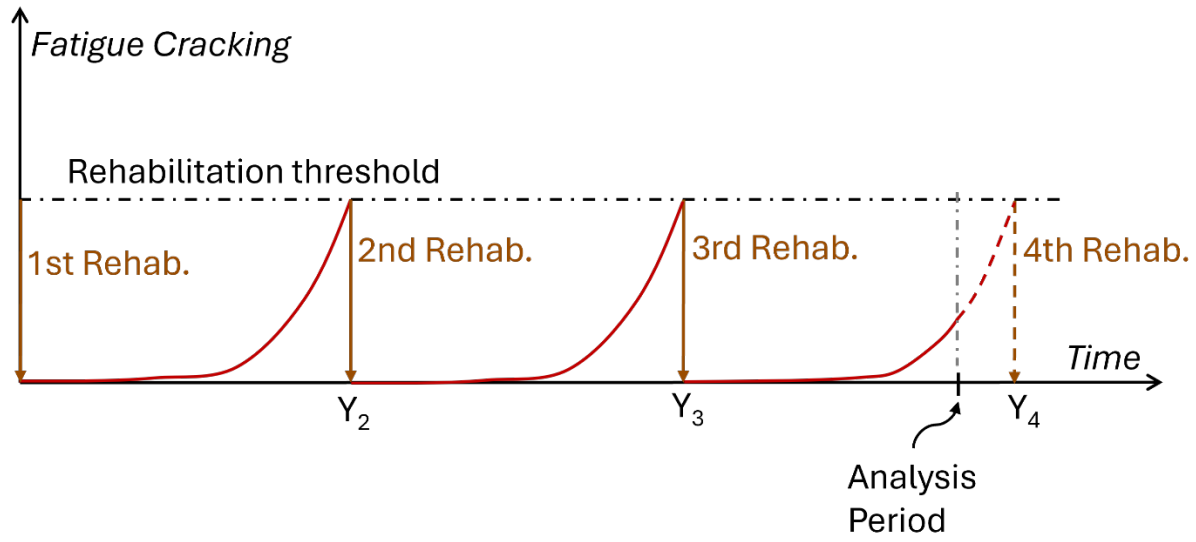


Figure 6.2: Rehabilitation scheme based on cracking performance.

(5) Quantify life cycle cost and GWP. Once the costs and GWP of the treatments are quantified and the future rehabilitation schedule is established, the life cycle cost and GWP can be calculated. The life cycle cost is defined as the sum of the present value of the costs of all treatments performed over the analysis period. This sum is referred to as net present value (NPV). Similarly, the life cycle GWP is the sum of the GWP of all treatments performed over the analysis period. For both the life cycle cost analysis (LCCA) and the life cycle assessment (LCA), a salvage value was deducted for the remaining service life (linear depreciation) of the last treatment at the end of the analysis period.

(6) Compare life cycle cost and GWP. For each of the two case studies—one considering RHMA-D used as the surface layer and the other as the intermediate layer—the life cycle cost and GWP were determined following the methodology outlined in the previous steps. These determinations assumed that the new HMA would consist of either the Control HMA or any of the RHMA-D mixes evaluated in this study. Consequently, for each case study, the mix that yields the lowest life cycle cost and/or GWP can be identified.

The methodology presented above does not account for preventive maintenance treatments that can help delay cracking. This simplification was adopted to support the main research objective, which is to estimate the order of magnitude of the potential cost and GWP savings that RHMA-D may provide compared with conventional HMA. Also, preservation seal coat treatments are primarily meant to extend age-related cracking life and do not have much influence on fatigue life.

6.2.1.1 Case Studies and Treatments

Two case studies are defined below: one for evaluating the use of RHMA-D as a surface layer and the other for evaluating its use as an intermediate layer.

Case Study 1: Evaluation of RHMA-D Use as a Surface Layer

The case study for evaluating RHMA-D use as a surface layer is defined by the features listed below. This case may correspond to a Caltrans secondary roadway or to a city or county arterial or truck route.

- Climate: California Inland Valley. Caltrans considers nine climate regions for pavement design and management *(12)*, with the Inland Valley extending through the Central Valley and adjacent inland valleys of California.
- Traffic:
    - 20-year Traffic Index (TI) = 8.5. A TI of 8.5 corresponds to 0.62 million 18-kip equivalent single axle loads (ESALs)[12].
    - Truck traffic characteristics: WIM Spectra 3. Caltrans considers five truck traffic groups for pavement design and management: WIM Spectra 1, WIM Spectra 2, WIM Spectra 3, WIM Spectra 4, and WIM Spectra 5 *(17)*. These WIM groups represent the range of truck traffic characteristics present on the Caltrans road network, with WIM Spectra 1 being the lightest and WIM Spectra 5 the heaviest. For WIM Spectra 3, the load equivalency factor of an average truck is 0.24; in other words, an average WIM Spectra 3 truck is equivalent to 0.24 ESALs.

    Note: A WIM Spectra 3 20-year TI of 8.5 is equivalent to an initial annual average daily truck traffic (AADTT) of 275 (per lane), assuming 3% AADTT annual increase.
- Existing section: 7.2 in. (183 mm) of old HMA on 7.8 in. (198 mm) aggregate base (Figure 6.3). The old HMA has alligator cracking that recommends a mill-and-fill (mill and overlay) treatment.
- Treatment: Milling 2.4 in. (61 mm) of the existing HMA and placing a new asphalt concrete (AC) overlay of the same thickness (Figure 6.3). The overlay can consist of the Control HMA, any of four RHMA-D mixes—TB1, TB2, AdvWet2, or ECRM—or a conventional RHMA-G. The

[12] The TI is an index that Caltrans uses for quantifying cumulative traffic. The TI is a function of the 18-kip ESALs:

$$TI = 9.0 \times \left(\frac{ESALs}{10^6}\right)^{0.119}$$

RHMA-G is added for comparison purposes as it is Caltrans' preferred surface mix for projects below 3,000 ft. elevation. The AdvWet1 RHMA-D, produced at 5.20% $P_{b;\,ARNMA}$ (TMM), is not considered in this case study because it is better suited for use as an intermediate layer rather than a surface layer.

Note: The overlay thickness was not determined using mechanistic-empirical design principles. Instead, a standard routine maintenance approach was assumed, in which a minimum thickness is milled to remove surface distresses and the same thickness of new asphalt mix is then placed.

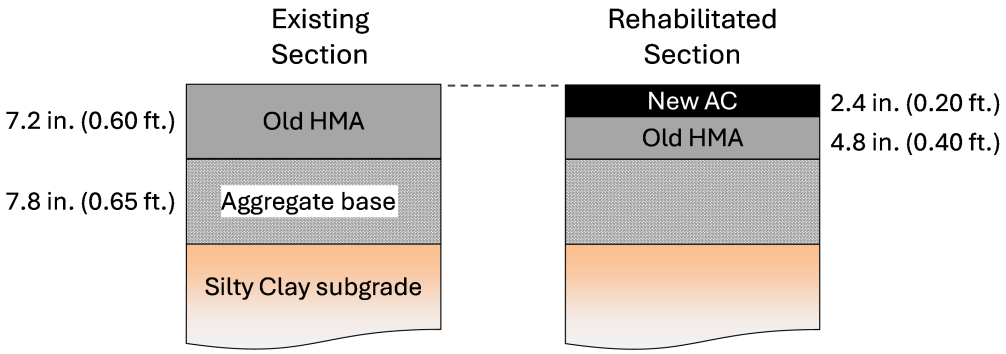


Figure 6.3: Section for evaluation of RHMA-D as surface layer.

Case Study 2: Evaluation of RHMA-D Use as an Intermediate Layer

The case study for evaluating RHMA-D use as an intermediate layer is defined by the features listed below. It may correspond to a Caltrans roadway or to a city or county truck route.

- Climate: California Inland Valley *(12)*.
- Traffic:
    - 20-year Traffic Index (TI) = 11. A TI of 11 corresponds to 5.4 million ESALs.
    - Truck traffic characteristics: WIM Spectra 3.
    - A WIM Spectra 3 20-year TI of 11 is equivalent to an initial annual average daily truck traffic (AADTT) of 2,398 (per lane), assuming 3% AADTT annual increase.
- Existing section: 12 in. (305 mm) of old RHMA-G and HMA on 7.8 in. (198 mm) aggregate base (Figure 6.4). The existing RHMA-G exhibits alligator cracking, which extends into and affects the underlying HMA layer. This condition supports the use of a mill-and-fill rehabilitation treatment.
- Treatment: Milling 9 in. (229 mm) of the existing RHMA-G and HMA and placing an intermediate HMA layer followed by an RHMA-G surface layer (Figure 6.4). The intermediate layer can consist of the Control HMA or any of four RHMA-D mixes—TB1, TB2, AdvWet1, or ECRM. The AdvWet2 RHMA-D, produced at 6.25% $P_{b;\,ARNMA}$ (TMM), is not considered in this case study because it is better suited for use as a surface layer rather than an intermediate

layer. The RHMA-G surface-layer thickness is fixed at 1.8 in. (46 mm), while the intermediate layer thickness of 7.2 in. (183 mm) was determined using *CalME*, assuming the Control HMA as the intermediate layer. The same intermediate layer thickness is applied when the Control HMA is replaced with any of the four RHMA-D mixes.

It should be noted that the TB1, TB2, and ECRM RHMA-D mixes were originally engineered for use as surface layers rather than intermediate layers. However, they are considered as intermediate layers in this case study. TB1 and TB2 were included because, as discussed in Chapter 5, these two RHMA-D mixes were stiffer than the Control HMA and, based on IDEAL-CT and 4PB test results, were expected to perform adequately as intermediate layers. The ECRM RHMA-D mix was included for simplicity.

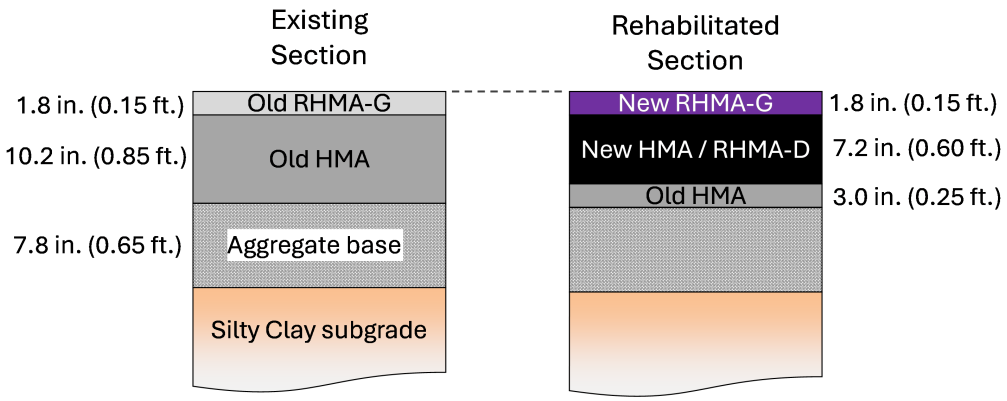


Figure 6.4: Section for evaluation of RHMA-D as intermediate layer.

6.2.1.2 Functional Unit

The functional unit of the LCCA and LCA is one lane-mile of pavement.

6.2.1.3 Goal and Scope

Comparative cradle-to-grave LCCA and LCA were conducted over the analysis period, including the product stage (raw material extraction through factory gate), the construction stage (materials transport to the construction site and placement), and the end-of-life stage that—in the two case studies evaluated in this report—includes milling the existing pavement and transport of the RAP to an asphalt plant. Following ISO 21930 terminology, the LCA includes stages A1–A3 (collectively referred to as the product stage), stages A4–A5 (collectively referred to as the construction stage), and stages C1–C4 (collectively referred to as end-of-life stage). Only agency costs are included in the LCCA; road user costs are not considered. Similarly, the impacts of the construction work zone on the fuel consumption are not included in the LCA.

6.2.1.4 Analysis Period and Salvage Value

The analysis period (life cycle) selected for this study depends on the case study. An analysis period of 20 years is selected for Case Study 1 (RHMA-D use as surface layer) while an analysis period of 40 years

is selected for Case Study 2 (RHMA-D use as intermediate layer). The same analysis period applies to both LCCA and LCA.

A salvage value was deducted for the last treatment prior to the end of the analysis period. The deduction, applicable to both cost and GWP, assumes a linear depreciation over the treatment's life. For example: a treatment is conducted in year 37, expected to last for 12 years; if the treatment cost is C, the deducted value in year 40 would be C×(12-3)/12. The deducted value is a reimbursement in the NPV cost calculation. Similarly, if the treatment GWP is X kg carbon dioxide equivalent (CO_2e), the deducted value would be X×(12-3)/12 kg CO_2e.

6.2.1.5 Cracking Failure Level

The cracking failure level is the amount of cracking that triggers the need for a rehabilitation intervention, shown as "rehabilitation threshold" in Figure **6.2**. For this study, the selected level is 10% Alligator B cracking[13], which, according to the Caltrans Pavement Management System (PMS) decision trees, triggers a minor rehabilitation.

While Alligator B cracking is a convenient variable for Caltrans pavement management, it is not the cracking metric predicted by *CalME*. Instead, *CalME* predicts the percentage of the total pavement length exhibiting either Alligator A or Alligator B cracking in any of the wheel paths. This length corresponds to the variable L_T in Figure 6.5.

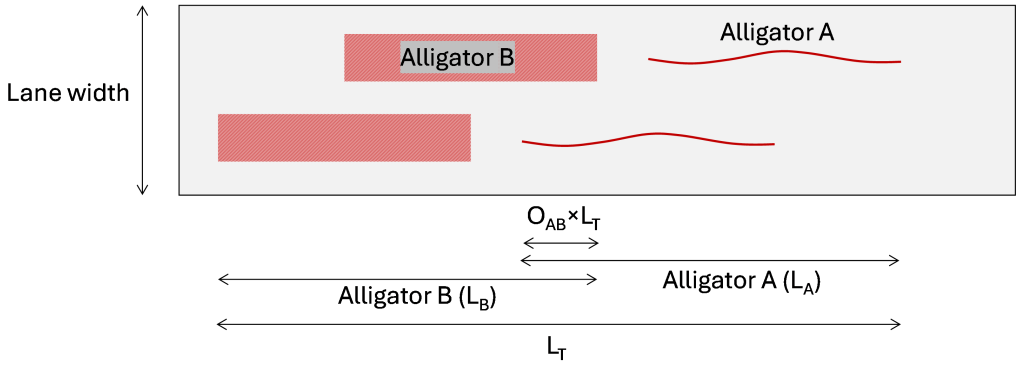


Figure 6.5: Cracking definition by CalME and Caltrans PMS.

Since *CalME* predicts total cracking while the rehabilitation threshold is defined by Alligator B cracking, a correspondence between the two metrics is required. For an Alligator B cracking level of 10%, assuming Alligator A cracking is also 10% and that the overlap between the two types is 33% (O_{AB} in Figure 6.5), the total pavement length affected by either cracking type (A or B) would be 15%. In other words, a *CalME*-predicted cracking level of 15% can be considered roughly equivalent to 10% Alligator B cracking and would therefore trigger the need for pavement rehabilitation.

[13] Alligator B cracking is defined as a series of interconnected cracks forming a pattern similar to alligator skin within the wheel path. It indicates a pavement that is structurally distressed and approaching the need for rehabilitation. Alligator A cracking represents early (low-severity) fatigue cracking in the asphalt surface and consists of fine, hairline cracks that are not fully interconnected. These definitions follow Caltrans classifications of asphalt cracking.

While the correspondence between 10% Alligator B cracking and 15% *CalME*-predicted cracking is debatable, it must be considered that the main output of the *CalME* modeling is the time to reach the rehabilitation threshold, and this time is relatively insensitive to the selected threshold value itself. For example, very similar time to rehabilitation would be obtained if the rehabilitation threshold was 25% instead of 15%. The reason is that the cracking progresses relatively rapidly once it appears in the section, so the time to reach 25% cracking would be only slightly higher than the time to reach 15% cracking.

Alligator B cracking is not the metric typically used by local agencies either. Local agencies (like cities and counties) generally quantify pavement distresses using a composite index known as the (PCI), which is determined in accordance with ASTM D6433-24. Asphalt surface cracking contributes to the PCI based on the percentage of the pavement area affected by cracking. Under certain assumptions, it can be established that 10% Alligator B cracking is roughly equivalent to a PCI of 50–60 *(5)*. This PCI would typically trigger pavement rehabilitation by local agencies only in main arterials or truck routes. The thresholds for pavement rehabilitation are summarized in Table 6.1.

Table 6.1: Thresholds for Pavement Rehabilitation

CalME Prediction	Caltrans PMS	Local Agencies
15% total cracking (Alligator A and B)	10% Alligator B cracking	50-60 pavement condition index

6.2.1.6 Performance Modeling and Rehabilitation Schedule

The rehabilitated sections for the two case studies are shown in Figure 6.3 (evaluation of RHMA-D as surface layer) and Figure 6.4 (evaluation of RHMA-D as intermediate layer) respectively. In each of the two case studies, the new asphalt mix can consist of the Control HMA, any of four RHMA-D mixes, or—in Case Study 1—a conventional RHMA-G. For each case study, once the new asphalt mix is selected, *CalME* is used to predict cracking. An example of *CalME* cracking prediction is shown in Figure 6.6 below. According to *CalME,* the rehabilitated section reaches the failure level of 15% cracking after 5.4 years of service. A second rehabilitation is therefore required at that time to prevent the pavement from reaching a terminal condition. As noted earlier, it is assumed that all rehabilitations performed during the analysis period are identical to the initial rehabilitation; consequently, the cracking history is assumed to repeat every 5.4 years.

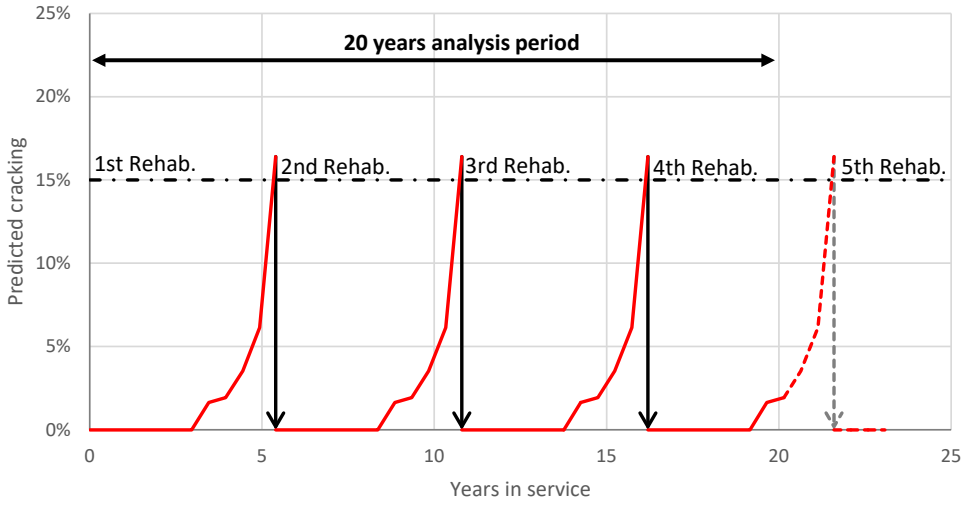


Figure 6.6: Fatigue-cracking prediction by CalME and rehabilitation schedule example.

The actual *CalME* output that is used in the LCCA and LCA is not the predicted cracking but the time it takes for the rehabilitated section to reach the cracking threshold that triggers a new rehabilitation, i.e., the useful life of the rehabilitation (5.4 years in the example illustrated in Figure 6.6).

Some features of the *CalME* modeling are listed below:

- Subgrade and aggregate base are default *CalME* database materials referred to as "2020 Standard SC" and "2020 Standard AB-Class 2" respectively.
- The material "2020 Standard Old HMA" in *CalME* database was chosen to model the existing asphalt pavement in the first case study (evaluation of RHMA-D use as a surface layer). This material enables the reflective cracking action on the layers above. In the second case study (evaluation of RHMA-D use as an intermediate layer), the structural contribution of the 3.0 in. of old HMA remaining after milling (Figure 6.4) is not considered in the *CalME* modeling.
- The material "2020 Standard RHMA-G with PG 64-16 base binder for non-PRS Projects" was chosen to model the new RHMA-G. This material represents the average performance of RHMA-G with PG 64-16 base binder in California. The RHMA-G is only considered for use as surface layer (Case Study 1).
- The Control HMA and the five RHMA-D mixes were added to *CalME* database and used in the corresponding modeling. The mix parameters entered into the *CalME* database were determined based on 4PB stiffness and fatigue resistance testing conducted on the plant-produced mixes. For the AdvWet, two materials were modeled: (1) AdvWet1 produced at 5.20% $P_{b;\,ARNMA}$ (TMM); and (2) AdvWet2 produced at 6.25% $P_{b;\,ARNMA}$ (TMM). The AdvWet2 is only considered for use as surface layer (Case Study 1), while the AdvWet1 is only considered for use as intermediate layer (Case Study 2).
- Truck traffic characteristics are defined as WIM Spectra 3, referred to as "WIM-2022 medium" in *CalME*.

6.2.1.7 LCCA Assumptions, Data, and Sources

The cost estimation for the different rehabilitation treatments includes two components. The first component, referred to in this study as direct cost, is the sum of the unit cost multiplied by the quantity of units for all construction items required to complete the treatment. The second component, referred to in this study as indirect cost, is a lump sum that compiles the cost of engineering, traffic handling, headquarters support, project management, and contingency costs and is calculated as a percentage of the direct cost. The unit costs for the direct cost calculation are listed below:

- Mill and remove existing asphalt pavement: The cost of this unit has been estimated at $44/yd^3$ based on Caltrans Contract Cost Database *(15)* for the past five years. Because the unit cost depends on the number of units, a project size of 5 lane-miles was assumed for this estimate.
- Asphalt overlay using Control HMA: The cost of the Control HMA has been estimated at $95/ton ($105/metric ton) based on Caltrans 2022 Crumb Rubber Report *(3)*.
- Asphalt overlay using RHMA-G: The cost of the RHMA-G has been estimated at $112/ton ($123/metric ton) based on Caltrans 2022 Crumb Rubber Report *(3)*.
- Asphalt overlay using RHMA-D: Based on the Levee Road pilot experience, the production, transport, placement, and compaction of the RHMA-D is very similar to a conventional HMA with plain binder. Consequently, it was assumed that the difference in cost between each of the RHMA-D mixes and the Control HMA would be the additional cost of the raw materials. The unit costs of the raw materials were obtained through inquiries with asphalt mix producers and suppliers of RTR-derived products and are shown in Table 6.2. This table also presents the mass composition of the Control HMA and the five RHMA-D mixes. The last column of Table 6.2 provides the estimated cost of the raw materials for each mix. The differential cost of the raw materials (versus the Control HMA) is added to the cost of the Control HMA ($95/ton) to estimate the cost of the different RHMA-D mixes, as shown in Table 6.3.

Table 6.2: Cost of Raw Materials in the Mixes (1 ton of asphalt mix)

Mix Type	Mix	Composition by Mass (%)							Cost of Raw Materials ($)
		Virgin Aggregates ($30 /ton)	Virgin Binder (Plain) ($500 /ton)	Virgin Binder (TB) ($580 /ton)	CRM #40 ($400 /ton)	ECRM ($1,000 /ton)	RAP ($25 /ton)	Total	
HMA	Control	71.47	3.52	—	—	—	25.01	100	45.29
RHMA-D	TB1	71.10	—	4.03	—	—	24.87	100	50.92
RHMA-D	TB2	71.10	—	4.03	—	—	24.87	100	50.92
RHMA-D	AdvWet1	71.10	3.55	—	0.48	—	24.87	100	47.22
RHMA-D	AdvWet2	70.31	4.49	—	0.60	—	24.60	100	52.09
RHMA-D	ECRM	70.16	4.29	—	—	1.00	24.55	100	58.64

Table 6.3: Cost Estimation of the RHMA-D Mixes (1 ton of asphalt mix)

Mix Type	Mix	Cost of Raw Materials ($)	Differential Cost of Raw Materials ($)	Estimated Cost of the Mixes ($/ton)
HMA	Control	45.29	—	95
RHMA-D	TB1	50.92	5.63 ≈ 6	95 + 6 = 101
RHMA-D	TB2	50.92	5.63 ≈ 6	95 + 6 = 101
RHMA-D	AdvWet1	47.22	1.93 ≈ 2	95 + 2 = 97
RHMA-D	AdvWet2	52.09	6.80 ≈ 7	95 + 7 = 102
RHMA-D	ECRM	58.64	13.35 ≈ 13	95 + 13 = 108

The indirect cost lump sum is estimated at 50% of the direct cost of the rehabilitation using the Control HMA. This assumption implies that indirect costs—including engineering, traffic handling, headquarters support, project management, and contingency—are the same regardless of whether the Control HMA or any of the RHMA-D mixes are used.

An annual discount rate of 3.2% was assumed for the calculation of the life cycle cost NPV. This value corresponds to the discount rate used by Caltrans for LCCA in early 2026.

6.2.1.8 LCA Assumptions, Data, and Sources

The LCA was performed using *eLCAP*, with the corresponding life cycle inventory (LCI) data documented in Caltrans LCI Report *(18)*. However, the GWP of the plain asphalt binder and the two terminal blend (TB) binders were modeled separately in OpenLCA using LCI data from the Federal LCA Commons dataset *(19)*.

The GWP is quantified in kg of carbon dioxide equivalent (CO_2e) following the US EPA's Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI) *(20)*.

Hypotheses followed in the LCA are described below:

- Transport distances:
    - Millings (RAP), from construction site to asphalt plant: 10 miles
    - Virgin aggregates, from quarry to asphalt plant: 50 miles
    - Asphalt binder, from refinery to asphalt plant: 250 miles
    - CRM and ECRM, from processing facility to asphalt plant: 250 miles
    - Asphalt mix, from asphalt plant to construction site (gate-to-site): 25 miles
- Standard CRM: The cut-off method was applied to estimate the GWP associated with CRM manufacturing. Under this approach, only the CRM processing stage is included, and its associated GWP is quantified. Scrap tires are assumed to have zero upstream environmental impacts, as the burdens from their production and use are allocated to the original tire

manufacturing and vehicle use. The system boundary, therefore, includes the grinding, crushing, and pulverization of scrap tires to produce CRM. The LCI developed by Corti and Lombardi *(21)* was used to determine the GWP of CRM production. The Corti and Lombardi data correspond to the production of CRM with particle sizes smaller than 0.08 in. (2 mm), which is considered appropriate for the standard CRM used in the production of the RHMA-G mix. According to the information provided by the CRM manufacturers, waste tire processing yields three co-products: CRM, iron scrap, and fibers. CRM and iron scrap have economic value, while fibers are considered waste. Consequently, GWP allocation in CRM modeling was performed using mass-based allocation between CRM and iron scrap only. The California electricity grid mix of 2024 was used to calculate the GWP of CRM production.

- CRM #40: The CRM #40 used in the production of the AdvWet RHMA-D has a maximum particle size of 0.016 in. (0.4 mm; passing the #40 sieve), which is significantly finer than conventional CRM. Due to the lack of specific life cycle inventory (LCI) data for CRM #40, its GWP was estimated using the GWP of standard CRM, scaled by a cost-based factor. Based on information provided by CRM manufacturers, the cost of CRM #40 is approximately 1.33 times that of standard CRM. Accordingly, the GWP of CRM #40 was assumed to be 33% higher than that of standard CRM, with the assumption that the additional cost and handling are associated with energy use.
- ECRM: The ECRM used in the Levee Road pilot project consists of 60% CRM, 20% asphalt binder, and 20% limestone and slaked lime powder, with percentages by mass. In the ECRM modeling, the GWP of the CRM component is assumed to be equal to that of CRM #40, the GWP of the limestone and slaked lime production and transportation are obtained from the Caltrans LCI Report, and the virgin binder GWP is extracted from the Federal LCA Commons dataset. Because ECRM production typically occurs at temperatures comparable to those used in conventional asphalt mixing, the natural gas consumption associated with ECRM production was assumed to be equivalent to that of conventional HMA production.
- Asphalt mixing energy requirements:
    - HMA and RHMA-D (1 kg): 1.32E-02 MJ of electric energy and 8.75E-03 m^3 of natural gas (natural gas use estimated from mixing temperatures).
    - RHMA-G (1 kg): 1.32E-02 MJ of electric energy and 9.43E-03 m^3 of natural gas.
    - California electricity grid: The California electricity mix was modeled in *eLCAP* using the 2024 grid mix data acquired from the California Energy Commission, shown in Table 6.4, with a grid loss of 5%.

Table 6.4: California 2024 Electricity Grid Mix

Sources	Generation (GWh)	Contribution to Grid Mix (%)
Coal	6,162	2.214
Waste Heat	220	0.079
Biomass	5,394	1.938
Geothermal	12,803	4.600
Nuclear	27,613	9.921
Natural Gas	94,655	34.007
Large Hydro	30,780	11.058
Small Hydro	4,240	1.523
Solar PV	59,283	21.299
Wind	33,102	11.893
Unspecified	4,051	1.455
Oil	36	0.013
Total	278,339	100

Source: California Energy Commission, 2024 Total System Electric Generation: https://www.energy.ca.gov/data-reports/energy-almanac/california-electricity-data/2024-total-system-electric-generation

- GWP of asphalt mixes: The raw materials used in the asphalt mixes evaluated in Case Studies 1 and 2—including the Control HMA, RHMA-D mixes, and RHMA-G—are listed in Table 6.5, together with the GWP associated with their production and transportation to the asphalt plant. Using the data in Table 6.5 and the mass composition of each mix, the contribution of the raw materials to the GWP of each asphalt mix was calculated, as reported in Table 6.6. In addition to raw material production and transport, energy consumption during mixing was considered to determine the cradle-to-gate GWP of the asphalt mixes; these results are summarized in Table 6.7.

Table 6.5: Global Warming Potential of Raw Materials in the Mixes

Source	GWP (kg CO_2e per ton of raw material)								
	Virgin Aggregate	Virgin Binder (Plain)	Virgin Binder (TB1)[a]	Virgin Binder (TB2)[b]	Std. CRM	CRM #40	ECRM	Ext. Oil	RAP
Production	2.44	573	601	632	83.7	112	407	11,225	0.0437
Transport	8.52	168	168	168	42.6	42.6	42.6	168	0
Total	10.96	741	769	800	126.3	154.6	449.6	11,393	0.0437

[a] TB1 contains 14.5% recycled tire rubber.
[b] TB2 contains 30.0% recycled tire rubber.
Note: Ext. Oil = Extender oil

Table 6.6: Mix Composition and Global Warming Potential of Raw Materials

Mix Type	Mix	Virgin Aggregate	Virgin Binder (Plain)	Virgin Binder (TB1)	Virgin Binder (TB2)	Std. CRM	CRM #40	ECRM	Ext. Oil	RAP	Total Mix
		Composition of Mixes by Mass (%)									
HMA	Control	71.47	3.52	—	—	—	—	—	—	25.01	100
RHMA-D	TB1	71.10	—	4.03	—	—	—	—	—	24.87	100
RHMA-D	TB2	71.10	—	—	4.03	—	—	—	—	24.87	100
RHMA-D	AdvWet1	71.10	3.55	—	—	—	0.48	—	—	24.87	100
RHMA-D	AdvWet2	70.31	4.49	—	—	—	0.60	—	—	24.60	100
RHMA-D	ECRM	70.16	4.29	—	—	—	—	1.00	—	24.55	100
RHMA-G	—	92.50	6.00	—	—	1.35	—	—	0.15	—	100
Mix Type	**Mix**	**GWP of Raw Materials Production and Transport to Asphalt Plant (kg CO_2e per ton of mix)**									
HMA	Control	7.8	26.1	—	—	—	—	—	—	≈ 0	33.9
RHMA-D	TB1	7.8	—	31.0	—	—	—	—	—	≈ 0	38.8
RHMA-D	TB2	7.8	—	—	32.2	—	—	—	—	≈ 0	40.0
RHMA-D	AdvWet1	7.8	26.3	—	—	—	0.7	—	—	≈ 0	34.8
RHMA-D	AdvWet2	7.7	33.3	—	—	—	0.9	—	—	≈ 0	41.9
RHMA-D	ECRM	7.7	31.8	—	—	—	—	4.5	—	≈ 0	44.0
RHMA-G	—	10.1	44.5	—	—	1.7	—	—	17.1	—	73.4

Note: Ext. Oil = Extender oil

Table 6.7: ISO 21930 A1-A3 (Cradle-to-Gate) Global Warming Potential for the Mixes

Mix Type	Mix	GWP (kg CO_2e per ton of mix)			
		Raw Materials	Plant Mixing (electricity)	Plant Mixing (natural gas)	Total
HMA	Control	33.9	0.8	19.1	53.9
RHMA-D	TB1	38.8	0.8	19.1	58.7
RHMA-D	TB2	40.0	0.8	19.1	60.0
RHMA-D	AdvWet1	34.8	0.8	19.1	54.8
RHMA-D	AdvWet2	41.9	0.8	19.1	61.8
RHMA-D	ECRM	44.0	0.8	19.1	63.9
RHMA-G	—	73.4	0.8	20.6	94.8

- Construction: Emissions from construction used the standard order of work in *eLCAP* for asphalt construction and were the same for all mixes.

6.2.2 Case Study 1: Evaluation of RHMA-D Use as Surface Layer

The case study evaluating the use of RHMA-D as a surface layer, described in Section 6.2.1.1 and illustrated in Figure 6.3, consists of a mill-and-fill rehabilitation in which 2.4 in. (61 mm) of the existing asphalt pavement are milled and replaced with a new asphalt concrete overlay of the same thickness. The new overlay can be constructed using the Control HMA with plain binder, an RHMA-D, or conventional RHMA-G. The AdvWet mix selected for the evaluation is the one produced with a binder content of 6.25% ($P_{b;\,ARNMA}$, TMM), identified as AdvWet2. The fatigue cracking predicted by *CalME* for each of the six mixes is presented in Figure 6.7.

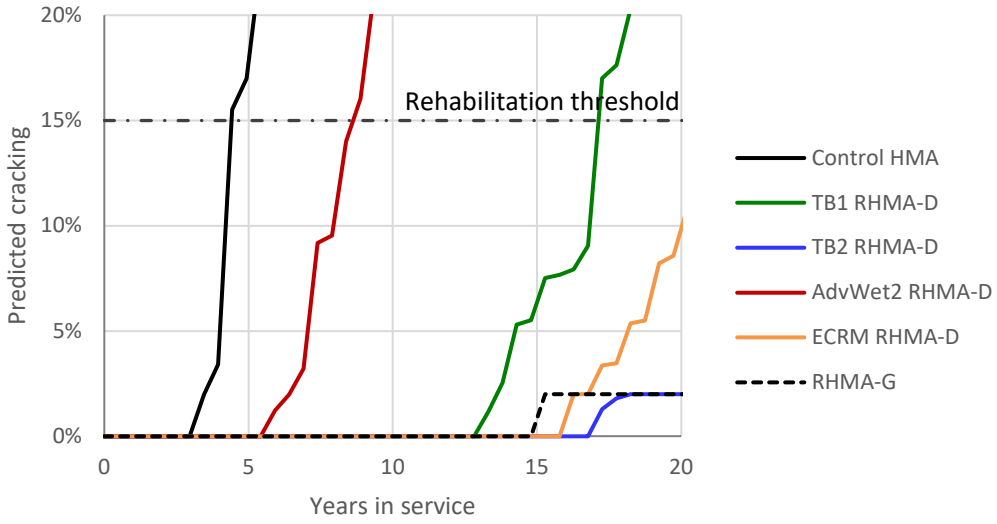


Figure 6.7: Fatigue-cracking prediction by *CalME*.

As shown in Figure 6.7, all RHMA-D mixes significantly improve the cracking performance relative to the Control HMA, and most achieve performance comparable to the RHMA-G. The estimated fatigue-cracking life of the rehabilitation is summarized in Table 6.8. The corresponding rehabilitation schedule for each of the six mixes during the 20-year analysis period is presented in Table 6.9.

Table 6.8: Estimated Fatigue-Cracking Life of Rehabilitation (Years)

Mix					
Control HMA	RHMA-D				Std. RHMA-G
	TB1	TB2	AdvWet2	ECRM	
4.4	17.1	>20	8.6	>20	>20

Table 6.9: Rehabilitation Schedule Relative to Initial Rehabilitation (Years)

Rehabilitation	Mix					
	Control HMA	RHMA-D				Std. RHMA-G
		TB1	TB2	AdvWet2	ECRM	
First rehabilitation	0	0	0	0	0	0
Second rehabilitation	4.4	17.1	>20	8.6	>20	>20
Third rehabilitation	8.8	>20	—	17.2	—	—
Fourth rehabilitation	13.2	—	—	>20	—	—
Fifth rehabilitation	17.6	—	—	—	—	—
Sixth rehabilitation	>20	—	—	—	—	—

6.2.2.1 LCCA Results

The calculation of the cost of the first rehabilitation for each of the six mixes is outlined in Table 6.10 while the life cycle cost net present value (NPV) is shown in Table 6.11. The life cycle NPV cost is calculated as the sum of the cost of the first rehabilitation and the net present value of all subsequent rehabilitations performed over the 20-year analysis period, subtracting the salvage value of the last rehabilitation. Figure 6.8 illustrates the initial (first rehabilitation) and life cycle NPV costs, and Figure 6.9 presents the same costs relative to the Control HMA alternative. As shown in Figure 6.9, the use of the RHMA-D mixes results in around 40% to 70% reduction in life cycle cost compared to the Control HMA. Furthermore, the use of the RHMA-D mixes provides life cycle cost savings comparable to those achieved with RHMA-G.

Table 6.10: Initial Rehabilitation Cost, Surface-Layer Application ($ per lane-mile)

Construction Item	Unit Cost	Mix					
		Control HMA	RHMA-D				Std. RHMA-G
			TB1	TB2	AdvWet2	ECRM	
Mill and remove existing asphalt pavement (2.4 in.)	$44/yd^3	$20,700	$20,700	$20,700	$20,700	$20,700	$20,700
Asphalt overlay (2.4 in.)	$95 to $112/ton (see 6.2.1.7)	$86,400	$91,800	$91,800	$92,800	$98,200	$101,800
Indirect cost	50% of Control HMA Direct Cost (see 6.2.1.7)	$53,600	$53,600	$53,600	$53,600	$53,600	$53,600
Total		$160,700	$166,100	$166,100	$167,100	$172,500	$176,100

Table 6.11: Initial and Life cycle Cost, Surface-Layer Application ($ per lane-mile)

Cost Period	Mix					
	Control HMA	RHMA-D				Std. RHMA-G
		TB1	TB2	AdvWet2	ECRM	
Initial (relative to Control HMA)	$160,700 (100%)	$166,100 (103.4%)	$166,100 (103.4%)	$167,100 (104.0%)	$172,500 (107.3%)	$176,100 (109.6%)
Life cycle NPV (relative to Control HMA)	$581,800 (100%)	$189,600 (32.6%)	$166,100 (28.5%)	$331,700 (57.0%)	$172,500 (29.6%)	$176,100 (30.3%)

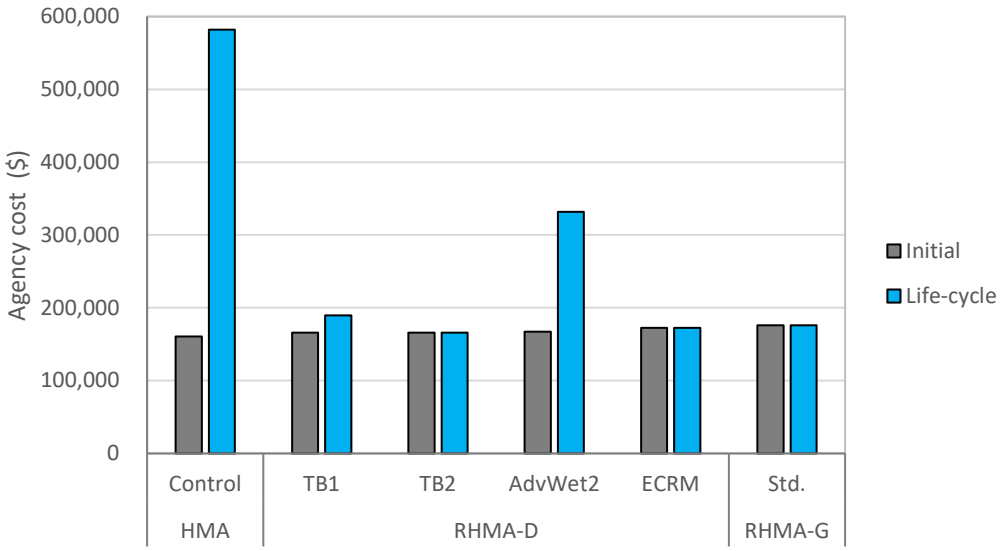


Figure 6.8: Initial and life cycle agency cost (1 lane-mile) over 20 years.

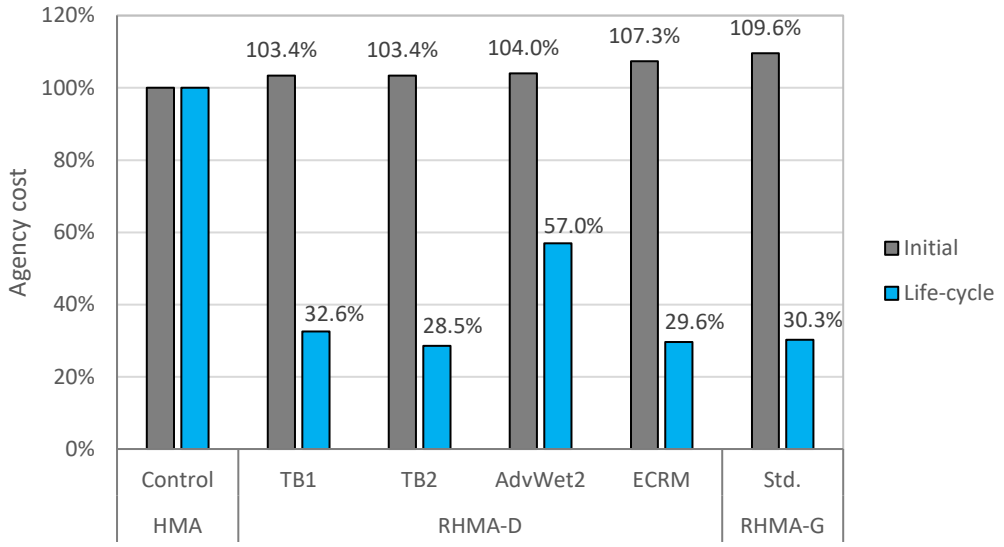


Figure 6.9: Normalized initial and life cycle agency cost (1 lane-mile) over 20 years relative to Control HMA.

6.2.2.2 LCA Results

The calculation of the GWP of the first rehabilitation for each of the six mixes is outlined in Table 6.12 while the life cycle GWP is shown in Table 6.13. The life cycle GWP is calculated as the sum of the GWP of all rehabilitations performed over the 20-year analysis period, subtracting the salvage value of the last rehabilitation. Figure 6.10 illustrates the initial (first rehabilitation) and life cycle GWP, and Figure 6.11 presents the GWP relative to the Control HMA alternative. As shown in Figure 6.11, the use of the RHMA-D mixes results in around 40% to 75% reduction in life cycle GWP compared to the Control HMA. Furthermore, the use of the RHMA-D mixes provides life cycle GWP savings comparable to those achieved with RHMA-G.

Table 6.12: Initial Rehabilitation Global Warming Potential, Surface-Layer Application

Construction Item	Mix (kg CO_2e per lane-mile)					
	Control HMA	RHMA-D				Std. RHMA-G
		TB1	TB2	AdvWet2	ECRM	
Milling and RAP transport	2,800	2,800	2,800	2,800	2,800	2,800
Mixes (cradle-to-gate)	49,500	54,000	55,100	56,800	58,700	87,100
Plant-to-site transport	6,200	6,200	6,200	6,200	6,200	6,200
Construction/paving	800	800	800	800	800	800
Total initial GWP	59,300	63,800	64,900	66,600	68,500	96,900

Table 6.13: Initial and Life Cycle Global Warming Potential, Surface-Layer Application

GWP Period	Mix (kg CO_2e per lane-mile)					
	Control HMA	RHMA-D				Std. RHMA-G
		TB1	TB2	AdvWet2	ECRM	
Initial (Relative to Control HMA)	59,300 (100%)	63,800 (107.6%)	64,900 (109.4%)	66,600 (112.3%)	68,500 (115.5%)	96,900 (163.4%)
Life cycle (Relative to Control HMA)	269,500 (100%)	74,600 (27.7%)	64,900 (24.1%)	154,900 (57.5%)	68,500 (25.4%)	96,900 (36.0%)

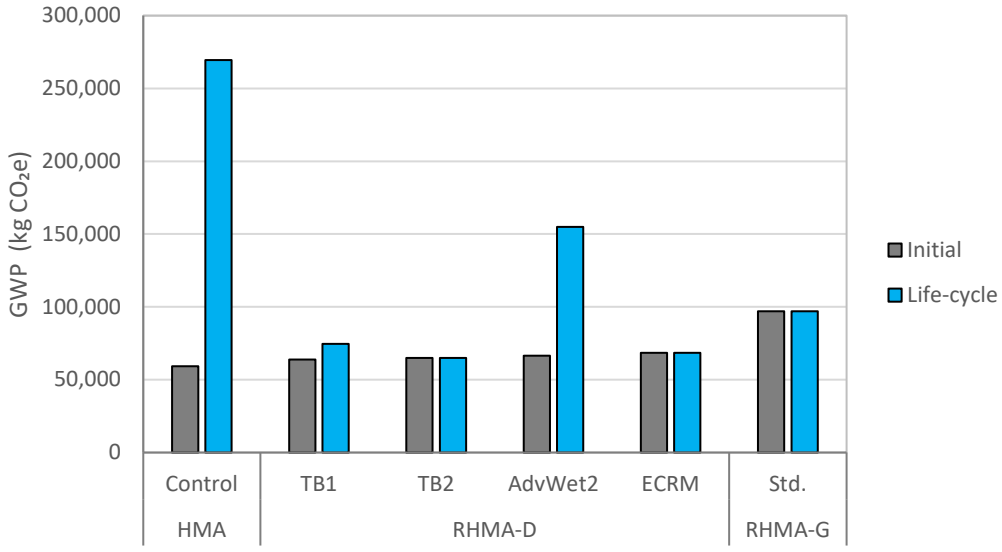


Figure 6.10: Initial and life cycle GWP over 20 years.

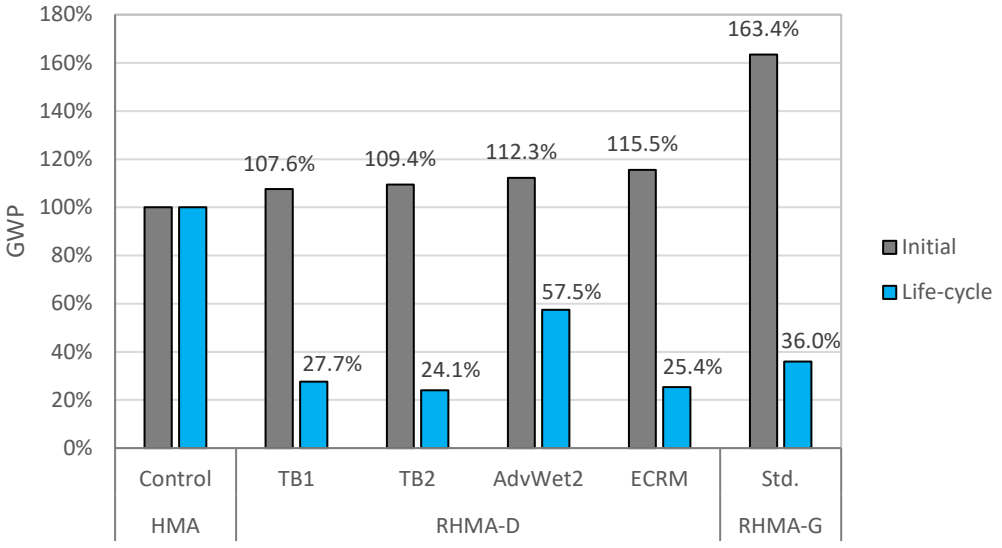


Figure 6.11: Normalized initial and life cycle GWP over 20 years relative to Control HMA.

6.2.3 Case Study 2: Evaluation of RHMA-D Use as Intermediate Layer

The case study evaluating the use of RHMA-D as an intermediate layer, described in Section 6.2.1.1 and illustrated in Figure 6.4, considers a rehabilitation scenario in which 9 in. (229 mm) of the existing asphalt pavement are milled and replaced with a new asphalt structure. The new structure consists of a 7.2 in. (183 mm) thick intermediate layer and a 1.8 in. (46 mm) thick RHMA-G surface layer. The intermediate layer may be constructed using either the Control HMA with plain binder or an RHMA-D. The AdvWet mix selected for the evaluation is the one produced with a binder content of 5.20% ($P_{b;\,ARNMA}$, TMM), referred to as AdvWet1. The fatigue cracking predicted by *CalME* for each of the five mixes is presented in Figure 6.12.

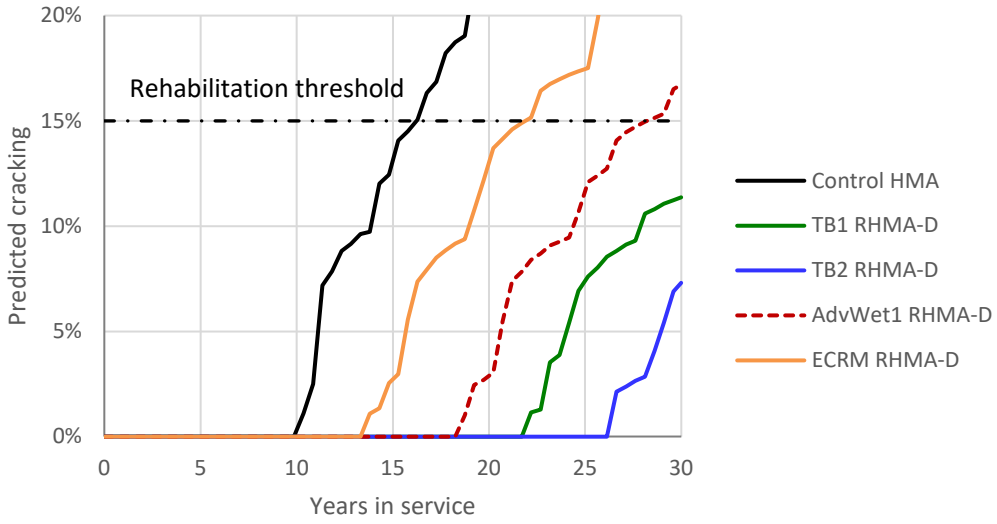


Figure 6.12: Fatigue cracking predicted by *CalME*.

As shown in Figure 6.12, all RHMA-D mixes considerably improve the cracking performance relative to the Control HMA. The estimated fatigue-cracking life of the rehabilitation is summarized in Table 6.14. The corresponding rehabilitation schedule for each of the five mixes during the 40-year analysis period is presented in Table 6.15.

Table 6.14: Estimated Fatigue-Cracking Life of Rehabilitation, Intermediate-Layer Application

Mix				
Control HMA (Years)	RHMA-D			
	TB1 (Years)	TB2 (Years)	AdvWet1 (Years)	ECRM (Years)
16.2	31.1	38.2	28.2	21.9

Table 6.15: Rehabilitation Schedule Relative to Initial Rehabilitation, Intermediate-Layer Application

Rehabilitation	Mix				
	Control HMA (Years)	RHMA-D			
		TB1 (Years)	TB2 (Years)	AdvWet1 (Years)	ECRM (Years)
First rehabilitation	0	0	0	0	0
Second rehabilitation	16.2	31.1	38.2	28.2	21.9
Third rehabilitation	32.4	>40	>40	>40	>40
Fourth rehabilitation	>40	—	—	—	—

6.2.3.1 LCCA Results

The calculation of the cost of the initial (first) rehabilitation for each of the five mixes is outlined in Table 6.16, while the life cycle cost net present value (NPV) is shown in Table 6.17. The life cycle NPV cost is calculated as the sum of the cost of the first rehabilitation and the net present value of all subsequent rehabilitations performed over the 40-year analysis period, subtracting the salvage value of the last rehabilitation. Figure 6.13 illustrates the initial (first rehabilitation) and life cycle NPV costs, and Figure 6.14 presents the same costs relative to the Control HMA. As shown in Figure 6.14, the use of the RHMA-D mixes results in around 15% to 40% reduction in life cycle cost compared to the Control HMA.

Table 6.16: Initial Rehabilitation Cost, Intermediate-Layer Application

Construction Item	Unit Cost	Mix ($ per lane-mile)				
		Control HMA	RHMA-D			
			TB1	TB2	AdvWet1	ECRM
Mill and remove existing asphalt pavement (9 in.)	$44/yd^3	77,400	77,400	77,400	77,400	77,400
Asphalt (RHMA-G) surface (1.8 in.)	$112/ton (see 6.2.1.7)	76,400	76,400	76,400	76,400	76,400
Asphalt intermediate layer (7.2 in.)	$95–$108/ton (see 6.2.1.7)	259,200	275,500	275,500	264,600	294,600
Indirect cost	50% of Control HMA Direct Cost (see 6.2.1.7)	206,500	206,500	206,500	206,500	206,500
Total		619,500	635,800	635,800	624,900	654,900

Table 6.17: Initial and Life Cycle Cost, Intermediate-Layer Application

Cost Period	Mix ($ per lane-mile)				
	Control HMA	RHMA-D			
		TB1	TB2	AdvWet1	ECRM
Initial (relative to Control HMA)	619,500 (100%)	635,800 (102.6%)	635,800 (102.6%)	624,900 (100.9%)	654,900 (105.7%)
Life cycle NPV (relative to Control HMA)	1,121,400 (100%)	745,800 (66.5%)	654,800 (58.4%)	778,900 (69.5%)	951,200 (84.8%)

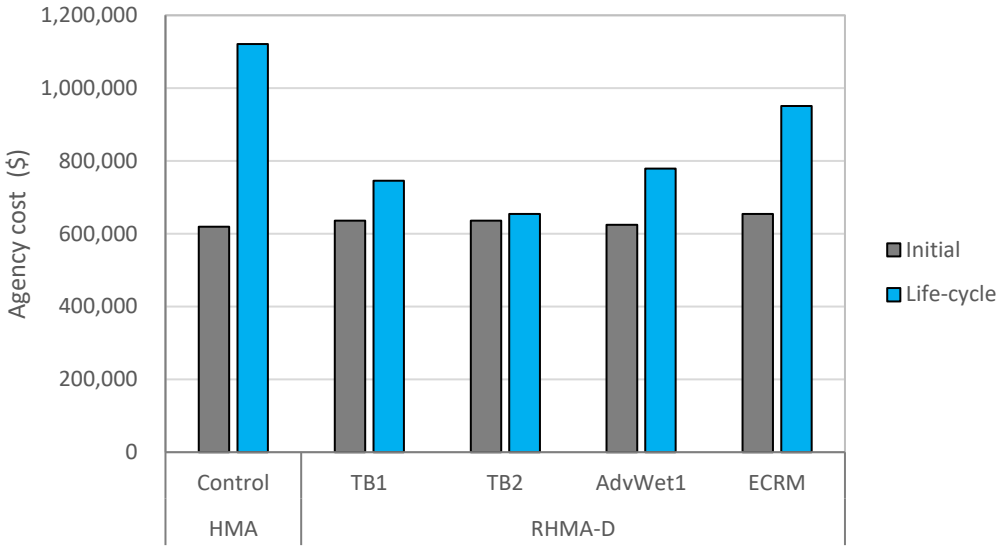


Figure 6.13: Initial and life cycle agency cost over 40 years.

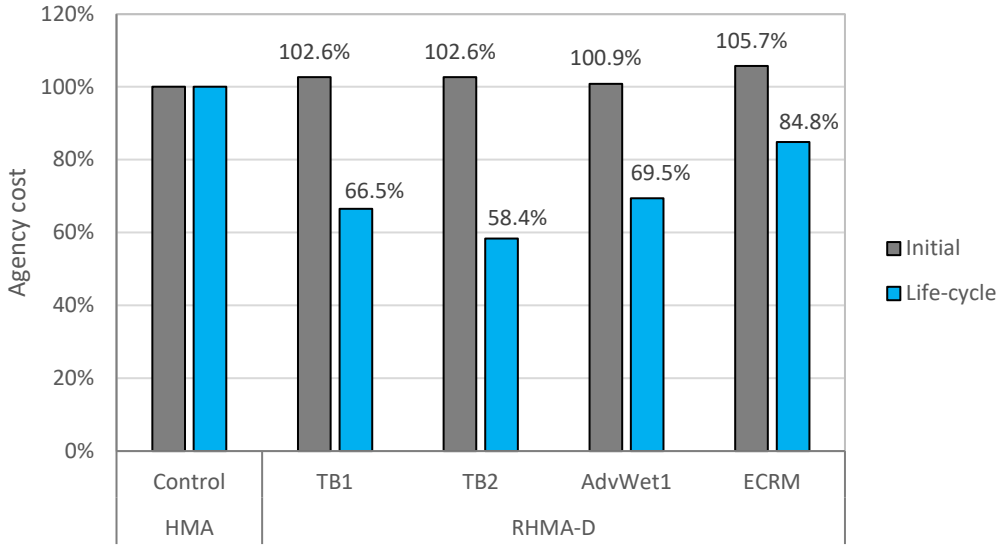


Figure 6.14: Normalized initial and life cycle agency cost over 40 years relative to Control HMA.

6.2.3.2 LCA Results

The calculation of the GWP of the first rehabilitation for each of the five mixes is outlined in Table 6.18, while the life cycle GWP is shown in Table 6.19. The life cycle GWP is calculated as the sum of the GWP of all rehabilitations performed over the 40-year analysis period, subtracting the salvage value of the last rehabilitation. Figure 6.15 illustrates the initial (first rehabilitation) and life cycle GWP, and Figure 6.16 presents the GWP relative to the Control HMA alternative. As shown in Figure 6.16, the use of any of the RHMA-D mixes results in around 20% to 55% reduction in life cycle GWP compared to the Control HMA.

Table 6.18: Initial Rehabilitation Global Warming Potential, Intermediate-Layer Application

Construction Item	Mix (kg CO_2e per lane-mile)				
	Control HMA	RHMA-D			
		TB1	TB2	AdvWet1	ECRM
Milling and RAP transport	10,600	10,600	10,600	10,600	10,600
Mixes (cradle-to-gate)	148,400	161,900	165,300	151,000	176,200
Plant-to-site transport	18,500	18,500	18,500	18,500	18,500
RHMA-G overlay	70,800	70,800	70,800	70,800	70,800
Construction/paving	2,400	2,400	2,400	2,400	2,400
Total initial GWP	250,700	264,200	267,600	253,300	278,500

Table 6.19: Initial and Life Cycle Global Warming Potential, Intermediate-Layer Application

GWP Period	Mix (kg CO_2e per lane-mile)				
	Control HMA	RHMA-D			
		TB1	TB2	AdvWet1	ECRM
Initial (Relative to Control HMA)	250,700 (100%)	264,200 (105.4%)	267,600 (106.7%)	253,300 (101.0%)	278,500 (111.1%)
Life cycle (Relative to Control HMA)	619,000 (100%)	339,800 (54.9%)	280,200 (45.3%)	359,300 (58.0%)	508,700 (82.2%)

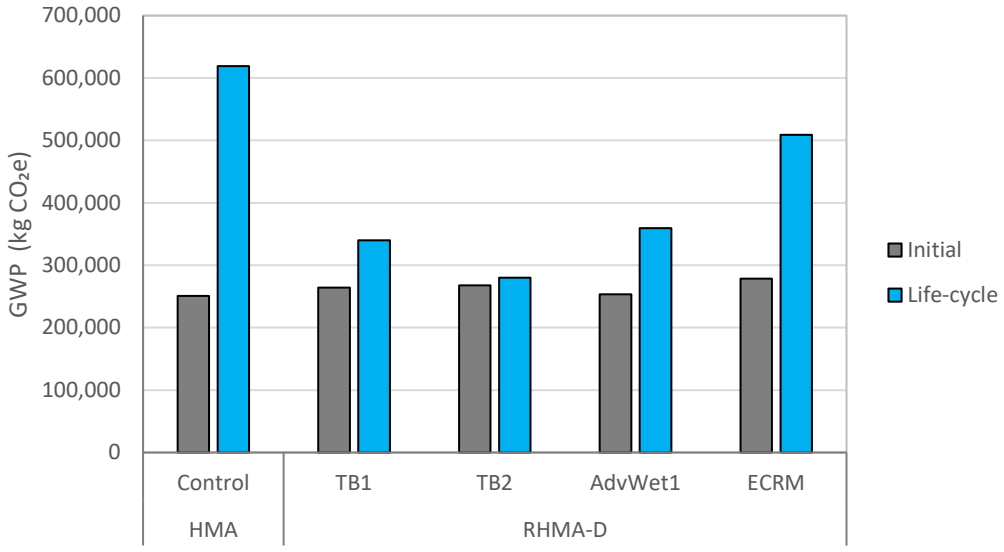


Figure 6.15: Initial and life cycle GWP over 40 years.

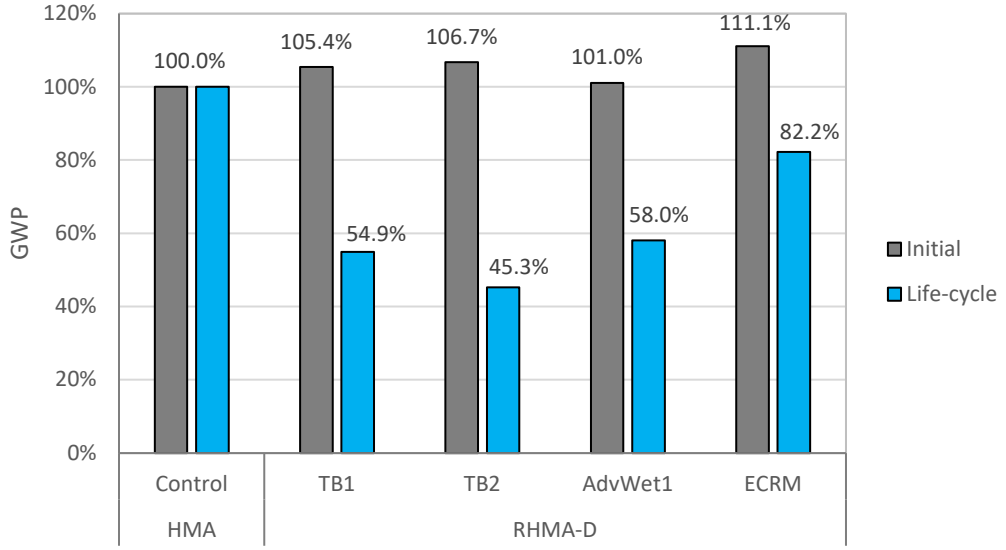


Figure 6.16: Normalized initial and life cycle GWP over 40 years relative to Control HMA.

7 DISCUSSION

The results of the testing of the asphalt mixes, the monitoring of the pilot project construction, and the LCCA and LCA analyses are discussed below. The discussion is organized around the different questions this research study was expected to answer (listed in Section 1.3).

7.1 What Is the Appropriate Approach for Conducting RHMA-D Mix Designs?

Based on the research conducted, the following steps are recommended to adapt an existing HMA design to incorporate RTR and optimize the mix for surface or intermediate-layer applications.

The first step depends on the technology used to introduce the RTR:

- For mixes with TB binder: Replace the original virgin binder with a TB binder that meets or exceeds the applicable PG requirements of the original virgin binder. "Meet or exceed" means that the TB binder has a high-temperature PG (PGH) equal to or higher than the required PGH, while its intermediate- and low-temperature PGs (PGI and PGL) are equal to or lower than the corresponding required values. The required PGH used as the reference needs to consider the RAP content.
- For mixes with discrete CRM particles (AdvWet and ECRM): Establish the CRM content of the mix. The AdvWet and ECRM RHMA-D mixes used in the Levee Road pilot project contained approximately 10% CRM by total binder weight, including binder contributed by the RAP. At present, due to limited experience with higher CRM contents in RHMA-D, caution is recommended when considering higher CRM levels.

The second step is to determine an initial estimate of the binder content for the new mix. For surface-layer applications, a BMD approach is recommended, in which the binder content is gradually increased while maintaining compliance with rutting performance requirements (e.g., maximum rut depth from the Hamburg Wheel-Tracking test). For intermediate-layer applications, as a first approximation, the binder content of the new mix may be set equal to that of the original HMA.

The third step is to assess the changes in the mix mechanical properties based on the IDEAL-CT results, plotted in the CT_{Index}–Strength space (as in Figure 5.3). Optimization for surface-layer applications requires shifting the mix toward lower strength (leftward), whereas optimization for intermediate-layer applications requires shifting the mix toward higher strength (rightward); in both cases, the mix results must remain above the constant fracture energy (Wf) line.

The fourth step is to reassess the binder content and the PG grade of the virgin binder based on the location of the new mix IDEAL-CT results in CT_{Index}–Strength space. Shifting the mix toward lower strength may be achieved by increasing the binder content or by using a softer virgin binder, while still meeting rutting performance requirements. Shifting the mix toward higher strength may be achieved by using a harder virgin binder. If the mix plots below the constant Wf line, an increase in binder content may be required. The application of these ideas to the Levee Road pilot RHMA-D mixes is discussed below.

The IDEAL-CT testing results of the Levee Road mixes are shown in the CT_{Index}–Strength space in Figure 7.1. For both terminal blend binders—TB1 and TB2—the results plot to the right of the Control HMA, indicating that the mixes are better optimized for intermediate-layer application than for surface-layer use because of the higher stiffness (higher IDEAL-CT strength indicates higher stiffness). This explains the clear fatigue-cracking performance improvement compared to the Control HMA when these mixes were modeled with *CalME* as intermediate layer (Section 6.2.3). Although both mixes also outperformed the Control HMA when used as surface layer, the use of softer TB binders and higher binder content than were included in these RHMA-D mixes would likely have been more appropriate for surface-layer use.

The results of the AdvWet2 RHMA-D mix, produced with a binder content of 6.25% ($P_{b;\,ARNMA}$, TMM), plot to the left of the Control HMA in Figure 7.1, whereas the results of the AdvWet1 RHMA-D mix, produced with a binder content of 5.20% ($P_{b;\,ARNMA}$, TMM) plot to the right. Accordingly, the AdvWet2 mix is optimized for surface-layer applications, while the AdvWet1 mix is optimized for intermediate-layer applications. As shown in Figure 7.1, the ECRM mix is well optimized for surface-layer application; nevertheless, it also outperformed the Control HMA when used as an intermediate layer, based on *CalME* modeling as discussed in Section 6.2.3.

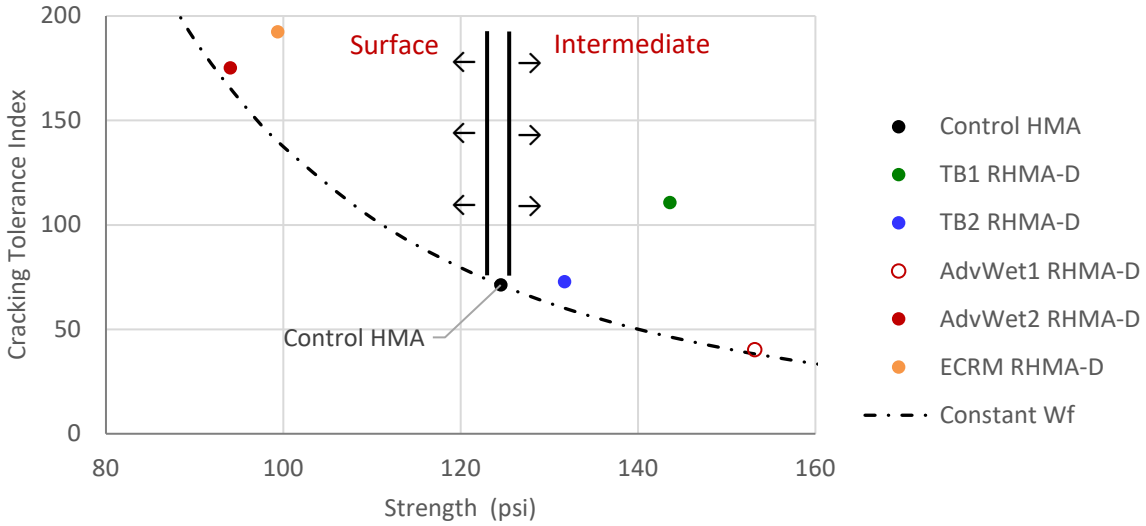


Figure 7.1: IDEAL-CT testing results of the Levee Road mixes: CT_{Index}–Strength space.

The approach outlined above is based on IDEAL-CT test results. However, for relevant rehabilitation projects, it is recommended to perform a verification using 4PB fatigue testing on plant-produced mixes sampled during job mix formula (JMF) approval. Experimental evidence indicates a weak correlation between the IDEAL-CT test cracking index (CT_{Index}) and mix fatigue resistance (ε_6). As a result, a mix may exhibit a high CT_{Index} yet still have poor fatigue performance, leading to premature bottom-up or reflective cracking. The 4PB-based verification follows the same principles described above but is conducted in the Fatigue Life–Stiffness space rather than the CT_{Index}–Strength space.

7.2 Do the Fabrication and Placement of RHMA-D Mixes Present Any Major Challenges?

The Levee Road construction monitoring and QC/QA testing results indicate that the fabrication and placement of the RHMA-D mixes do not differ from those of standard HMA produced with a plain binder, as discussed below.

First, the RHMA-D mixes were mixed and placed at the same temperatures as the Control HMA. Temperatures monitored during construction followed the typical trends observed for conventional HMA, reaching approximately 325°F (163°C) at the discharge of the mixing unit, 300–315°F (149–157°C) at the windrow ahead of the paver, and 260–290°F (127–143°C) behind the paver. Roller compaction procedures were the same as those used for the Control HMA.

Second, the in-place densities achieved in the field were, for all but one RHMA-D mix, higher than those of the Control HMA. The Control HMA achieved an average density of 94.5% (5.5% air-voids), whereas four of the five RHMA-D mixes achieved densities ranging from 94.7% to 97.2% (2.8% to 5.3% air-voids). The only RHMA-D mix with a lower density than the Control HMA was the AdvWet1 mix. Nevertheless, this mix achieved a density of 93.3% (6.7% air-voids), which is well above Caltrans minimum compaction threshold of 91%.

Third, plant and paving personnel did not observe any noticeable rubber odor, in contrast with RHMA-G fabrication and placement. This outcome is attributed to the lower mixing and compaction temperatures (relative to RHMA-G) and the absence of extender oil.

Finally, as noted in Section 4.4.1, the paving machine operator and roller operators reported very positive impressions regarding the compactability of all RHMA-D mixes. Overall, they indicated that the compactability of the RHMA-D mixes was comparable to that of conventional HMA produced with a plain binder and considerably better than that of RHMA-G.

7.3 Are There Significant Differences Between Plant-Produced and Laboratory-Produced RHMA-D?

A comparison of the IDEAL-CT and HWT test results obtained from RHMA-D mixes fabricated in the laboratory during the mix design process with those obtained from RHMA-D mixes produced at the plant during the Levee Road pilot construction shows no meaningful differences between the laboratory-produced and plant-produced mixes, other than those attributable to differences in binder content (Section 4.4.1; Figure 4.21 and Figure 4.22).

7.4 What Are the Performance-Related Properties of the RHMA-D Compared to Conventional Dense-Graded HMA with Plain Binder?

This fourth question is addressed separately for each of the asphalt mix mechanical properties important to asphalt pavement performance that were evaluated in this research (Chapter 5).

Mix stiffness is considered first. This property was measured using dynamic modulus testing in the AMPT and the 4PB apparatus. In addition, the strength measured in the IDEAL-CT test provides an indirect measure of mix stiffness at intermediate temperature. As shown in this research (e.g., Figure 5.3 and Figure 5.19), the introduction of RTR does not necessarily change the stiffness at intermediate temperatures in a single direction; rather, its effect depends on how the RHMA-D design

is engineered. In practice, the design should be adjusted according to the intended application of the RHMA-D: typically toward a softer mix for surface-layer use and a stiffer mix for intermediate-layer use.

Regardless of its effect on stiffness at intermediate temperatures, the addition of RTR in the form of discrete CRM particles (AdvWet and ECRM) substantially reduces the temperature susceptibility of the mix. This behavior is evident in the dynamic modulus master curves obtained from 4PB (Figure 5.10) and AMPT (Figure 5.13) testing. At high reduced frequencies (corresponding to low temperatures), the stiffness of the AdvWet1, AdvWet2, and ECRM RHMA-D mixes is lower than that of the Control HMA, whereas at low reduced frequencies (corresponding to high temperatures), the opposite trend is observed. This reduced temperature susceptibility is beneficial for pavement performance, as it lowers the susceptibility of the RHMA-D mixes to age-related block cracking and fatigue cracking while simultaneously reducing their susceptibility to rutting.

The reduced temperature susceptibility of the RHMA-D mixes containing discrete CRM particles is supported by the PG test results of the rubberized binder used for the AdvWet mix fabrication, which contained 11.8% CRM (Figure 4.23). The rubberized binder achieved a high-temperature PG that was 12.6°C higher than that of the control binder, while simultaneously reducing the intermediate- and low-temperature PGs by 5.7°C and 2.9°C, respectively.

The cracking resistance of the mixes was evaluated using the IDEAL-CT and the 4PB tests. The IDEAL-CT test provides the CT_{Index}, which quantifies the mix's capacity to deform without cracking. When considered together with the mix's aging susceptibility, the CT_{Index} can be regarded as an indicator of the mix's resistance to age-related cracking, which leads to block cracking. The 4PB test provides the Wöhler curve of the mix, which characterizes its ability to withstand repeated loading. One parameter derived from the Wöhler curve is ε_6, defined as the strain level at which the mix sustains 1 million (10^6) load repetitions to failure. Both CT_{Index} and ε_6 are highly sensitive to mix stiffness (or strength), decreasing as mix stiffness (or strength) increases, as shown in Figure 5.3 and Figure 5.19. However, overall, the RHMA-D mixes' CT_{Index} and ε_6 were relatively high considering their stiffness (or strength).

When plotted in the CT_{Index}–Strength space (Figure 5.3), the RHMA-D mixes fall above the constant fracture energy (Wf) line and achieve CT_{Index} values comparable to those of RHMA-G and higher than typical HMA mixes with polymer-modified binders. When plotted in the Fatigue Life–Stiffness space (Figure 5.19), the RHMA-D mixes fall above the constant deformation energy (Wε) line and achieve ε_6 values at the lower end of the range observed for RHMA-G and HMA mixes with polymer-modified binders.

The rutting resistance of the mixes was evaluated using the Hamburg Wheel-Tracking (HWT) test (Figure 5.15) and the AMPT repeated load testing (RLT) (Figure 5.17). With the exception of the AdvWet mixes, the rutting resistance of the RHMA-D mixes changed little relative to the Control HMA, despite their higher binder contents. The AdvWet1 mix, produced with a binder content of 5.20% ($P_{b;\,ARNMA}$, TMM), exhibited reduced rutting relative to the Control HMA, while the AdvWet2 mix, produced with a binder content of 6.25% ($P_{b;\,ARNMA}$, TMM), exhibited increased rutting.

The moisture damage resistance of the mixes was evaluated by determining the retained strength after wet conditioning at high temperature and under repeated water pressure cycles in the MiST device, as shown in Section 5.4 and summarized in Table 5.1. The Control HMA exhibited an average retained strength of approximately 87% (range: 83–91%). Comparable retained strength values were obtained for the RHMA-D mixes with 5.20% $P_{b;\,ARNMA}$ (TB1, TB2, and AdvWet1; 75–90%), while somewhat higher retained strengths were observed for the mixes with 6.25% $P_{b;\,ARNMA}$ (AdvWet2 and ECRM; 87–97%). Overall, the introduction of RTR does not appear to have an important effect on the moisture damage resistance of the mixes; instead, observed differences in retained strength are primarily attributable to differences in binder content between the RHMA-D mixes and the Control HMA.

The aging susceptibility of the mixes was evaluated by determining the change in strength and CT_{Index} after Caltrans MTOA conditioning, which consists of maintaining the loose mix in an oven at 212°F (100°C) for 20 hours. Overall, the introduction of RTR does not appear to have much effect on the aging susceptibility of the mixes. The results of this research show that incorporating RTR within a BMD framework allows cracking resistance to be enhanced without jeopardizing rutting performance.

7.5 What Are the Life Cycle Cost and Environmental Impacts of RHMA-D Use Compared to Conventional Dense-Graded HMA with Plain Binder?

The cost of the RHMA-D mixes used in the Levee Road pilot project was only slightly higher than that of the Control HMA produced with plain binder (Table 6.3). Estimated cost premiums ranged from $2 to $13 per ton, depending on the technology used to introduce the RTR and on how the RHMA-D mix design was engineered. For the two case studies evaluated in this research, the cost increase represented approximately 3% to 7% of the initial agency cost when the RHMA-D was used as a surface layer, and 1% to 6% when the RHMA-D was used as an intermediate layer.

Despite the slight increase in initial agency cost, the use of RHMA-D resulted in considerable life cycle cost and GWP savings compared to the Control HMA, driven by improved fatigue-cracking performance and the associated reduction in future maintenance and rehabilitation needs. For the two case studies evaluated in this research, life cycle agency cost savings were approximately 40% to 70% over a 20-year analysis period when RHMA-D was used as a surface layer, and approximately 15% to 40% over a 40-year analysis period when RHMA-D was used as an intermediate layer. GWP reductions followed a similar trend, with savings of roughly 40% to 75% for surface applications and approximately 20% to 55% for intermediate-layer applications. The savings based on fatigue-cracking performance are applicable to pavement where there is heavy truck and bus traffic.

The RHMA-D mixes achieved life cycle cost and GWP savings comparable to those of RHMA-G in Case Study 1, where the mixes were evaluated as surface layers. This finding is particularly noteworthy because the RHMA-D mixes also exhibited lower initial costs than the RHMA-G.

Among the RHMA-D alternatives evaluated as intermediate layers, the AdvWet mix produced with a binder content of 5.20% ($P_{b;\,ARNMA}$, TMM), referred to as AdvWet1, achieved a very low life cycle cost and GWP based on fatigue-cracking performance. Relative to the Control HMA, the use of AdvWet1 RHMA-D in Case Study 2 led to around 30% reduction in life cycle cost and around 40% reduction in

life cycle GWP. This finding is particularly noteworthy given that the initial cost premium of the AdvWet1 RHMA-D is only $2 per ton compared to the Control HMA.

Regarding age-related cracking, a mechanistic-empirical analysis could not be done because there is no validated model for age-related cracking. However, a simplistic first-order analysis of time to initiation of age-related cracking based on comparison of flexural stiffness at 68°F (20°C) indicated that the stiffer TB RHMA-D mixes and especially the AdvWet1 mix with the low binder content would be more susceptible to age-related cracking than the Control HMA mix when used in surface applications, while the softer AdvWet2 and ECRM mixes would likely have later age-related crack initiation than the Control mix. The mixes with longer time to initiation of age-related cracking would require less frequent preservation seal coats, which would reduce life cycle costs.

8 SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

8.1 Summary

Rubberized hot mix asphalt–dense-graded (RHMA-D) is a dense-graded hot mix asphalt (HMA) that incorporates rubber derived from recycled tires. This research report documents the pilot implementation of RHMA-D in an asphalt rehabilitation/reconstruction project carried out on Levee Road at the University of California, Davis campus in summer 2025.

The project consisted of a 1.7-mile pavement rehabilitation and reconstruction. The westbound lane was surfaced with a Control HMA fabricated with plain binder, while the eastbound lane was surfaced with five different RHMA-D mixes: two incorporating terminal blend (TB) binders, referred to as TB1 and TB2, respectively; two incorporating crumb rubber modifier (CRM) added through the advanced wet process, referred to as AdvWet1 and AdvWet2, respectively; and one incorporating engineered crumb rubber modifier (ECRM) added through the dry process, referred to as ECRM. The surface-layer thickness was 2.4 in. (61 mm) for all mixes.

The design of each of the RHMA-D mixes used in the Levee Road pilot was based on the design of the Control HMA, which was adapted to introduce recycled tire rubber (RTR) following balanced mix design (BMD) principles. The RHMA-D mixes had a total rubberized binder content, $P_{b;\,ARNMA}$ (TMM), of either 5.20% or 6.25%, where the term ARNMA stands for "asphalt, rubber, and non-mineral admixtures" and refers collectively to all components that bind the aggregate in any mix containing RTR. The ratio of RTR to total binder in the mix was about 10% for all mixes except TB2, for which it was 23%. Mixing and compaction temperatures for all RHMA-D mixes were the same as those used for the Control HMA.

Construction of the pilot project was monitored throughout mix production, placement, and compaction. During construction, all mixes were sampled at the plant and transported to the University of California Pavement Research Center (UCPRC) laboratory. There, the mixes were evaluated using a comprehensive battery of laboratory tests targeting mechanical properties considered critical to asphalt pavement performance.

The initial cost of each RHMA-D mix was estimated based on the cost of the Control HMA plus the additional cost of the RHMA-D raw materials relative to the Control HMA, acknowledging that fabrication, placement, and compaction procedures for the RHMA-D mixes do not differ from those of standard HMA. Similarly, the environmental impacts of the RHMA-D mixes were estimated using the Control HMA as the baseline, with adjustments accounting for differences in raw material inputs.

Two asphalt pavement rehabilitation case studies are presented in this report: one evaluating the use of RHMA-D as a surface layer and the other evaluating its use as an intermediate layer. Life cycle costs and environmental impacts were quantified following standard life cycle cost analysis (LCCA) and environmental life cycle assessment (LCA) procedures. Each case study was analyzed considering the use of the Control HMA and, alternatively, each of the RHMA-D mixes used in the Levee Road pilot project.

8.2 Conclusions

The following conclusions are based on asphalt mix testing results, observations during pilot project construction, and the LCCA and LCA analyses. The conclusions are organized according to the main research questions addressed in this study.

(1) What is the appropriate approach for conducting RHMA-D mix designs?

- An existing HMA design can be successfully adapted to incorporate recycled tire rubber (RTR) using any of the three technologies evaluated in this research.
- Mix design adjustments should follow BMD principles; however, the specific adjustments depend on both the RTR technology and the intended application of the RHMA-D.
- The mix design should be adjusted according to the intended application of the RHMA-D: typically toward a softer mix for surface-layer use and a stiffer mix for intermediate-layer use. Adjustments to binder content, the base virgin binder PG, and RAP content are effective tools for engineering the stiffness of RHMA-D mix.
- IDEAL-CT testing is recommended during the mix design process, with results evaluated in the CT_{Index}–Strength space. RHMA-D mixes should remain above the constant fracture energy (Wf) line, indicating fracture energy greater than that of the Control HMA on which the design is based.
- For relevant rehabilitation projects, verification using four-point bending (4PB) fatigue and stiffness testing on plant-produced mixes sampled during job mix formula (JMF) approval is recommended.

(2) Do the fabrication and placement of RHMA-D present any major challenges?

- The fabrication and placement of the RHMA-D mixes do not differ from those of standard HMA produced with plain binder.
- Field densities of all RHMA-D mixes in the Levee Road pilot met the Caltrans minimum compaction threshold of 91% and, overall, exceeded the density achieved with the Control HMA.
- Plant and paving personnel did not perceive any noticeable rubber smoke or odor, and roller operators reported very positive impressions regarding the compactability of all RHMA-D mixes.

(3) Are there significant differences between plant-produced and laboratory-produced RHMA-D?

- No meaningful differences were observed between the laboratory-produced and plant-produced RHMA-D mixes, other than those attributable to differences in binder content.

(4) What are the performance-related properties of the RHMA-D compared to conventional dense-graded HMA with plain binder?

- The introduction of RTR does not necessarily change the mechanical properties of the mix in a single direction; rather, its effect depends on how the RHMA-D design is engineered.
- The addition of RTR in the form of discrete CRM particles (AdvWet and ECRM) substantially reduces the temperature susceptibility of the mix.
- The RHMA-D mixes used in the Levee Road pilot exhibited CT_{Index} values comparable to those of RHMA-G and higher than those typically observed for HMA mixes with polymer-modified binders. Their fatigue-cracking resistance fell toward the lower end of the range observed for RHMA-G and polymer-modified HMA mixes.
- With the exception of the AdvWet mix dosed at 6.25% $P_{b;\,ARNMA}$ (TMM), the rutting resistance of the RHMA-D mixes changed little relative to the Control HMA, despite their higher binder contents. The AdvWet mix dosed at 6.25% nevertheless met Caltrans rutting requirements based on Hamburg Wheel-Tracking (HWT) test results.
- The incorporation of RTR did not have a significant effect on the moisture damage resistance of the mixes.
- The incorporation of RTR did not have a significant effect on the aging susceptibility of the mixes.
- The stiffnesses at intermediate temperatures of the TB1, TB2, and AdvWet1 mixes were greater than those of the Control HMA, potentially indicating the potential for earlier initiation of age-related cracking. The stiffnesses of the AdvWet2 and ECRM mixes were lower than those of the Control mix, potentially indicating later age-related cracking initiation. The analysis for age-related cracking was simplistic and did not consider any effects on mix properties other than stiffness.
- Overall, the results of this research show that incorporating RTR within a BMD framework allows fatigue-cracking resistance to be enhanced without jeopardizing rutting performance.

(5) What are the life cycle cost and environmental impacts of RHMA-D use compared to conventional dense-graded HMA with plain binder?

- The initial agency cost of the RHMA-D mixes used in the Levee Road pilot project was only slightly higher than that of the Control HMA produced with plain binder, with estimated cost premiums ranging from $2 to $13 per ton compared to standard HMA with plain binder.
- Despite the slight increase in initial agency cost, the use of RHMA-D resulted in substantial life cycle cost and global warming potential (GWP) savings compared to the Control HMA, driven by improved fatigue-cracking performance and the associated reduction in future maintenance and rehabilitation needs.
- The two case studies evaluated in this research indicated that the improved fatigue-cracking performance of the RHMA-D results in considerable savings driven by delays in future rehabilitation needs. In the case study evaluating the use of RHMA-D as surface layer, life cycle

agency cost savings were approximately 40% to 70% over a 20-year analysis period. In the case study evaluating the use of RHMA-D as intermediate layer, life cycle agency cost savings were approximately 15% to 40% over a 40-year analysis period. GWP reductions followed a similar trend, with savings of roughly 40% to 75% for surface applications and approximately 20% to 55% for intermediate-layer applications.

- The RHMA-D mixes achieved life cycle cost and GWP savings comparable to those of RHMA-G when evaluated as surface layers. This finding is particularly noteworthy because the RHMA-D mixes also exhibited lower initial costs than RHMA-G.
- Among the RHMA-D alternatives evaluated as intermediate layers, the AdvWet mix produced with a binder content of 5.20% ($P_{b;\ ARNMA}$, TMM) achieved 30% reduction in agency life cycle cost and 40% reduction in life cycle GWP, compared to the Control HMA. The initial cost premium of this mix is only $2 per ton compared to the Control HMA.
- The potential for earlier age-related cracking initiation for the RHMA-D mixes that were stiffer at intermediate temperatures than the Control HMA may result in life cycle costs from the need for more frequent seal coats to slow aging, when these mixes are used as a surface layer.

8.3 Recommendations

The following recommendations are made:

- It is recommended that the Levee Road pilot project continue to be monitored in the coming years, with particular attention paid to the potential for reflective cracking originating from the cement-stabilized base.
- In the Levee Road project, the RHMA-D mixes were placed as a surface layer. A new pilot project is recommended in which the RHMA-D is used as an intermediate layer.
- The terminal blend (TB) binders used in the Levee Road project contained no polymers other than recycled tire rubber (RTR), with the objective of isolating the effect of the RTR addition. However, combining RTR with other elastomeric modifiers, such as styrene-butadiene-styrene (SBS), is recommended, as this is expected to reduce temperature susceptibility and improve cracking resistance. The addition of polymer modifier will likely increase the initial cost and global warming potential (GWP) of the TB binders somewhat.
- The advanced wet technology, owing to its small crumb rubber modifier (CRM) particle size, offers several advantages over the conventional wet process used to produce asphalt rubber binder for RHMA-G and RHMA-O in California, including lower mixing temperatures, shorter interaction times, and the elimination of extender oil. It is recommended that the use of advanced wet technology be explored for the production of standard RHMA-G and RHMA-O mixes.

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APPENDIX A: RECOMMENDATIONS FOR THE USE OF RHMA-D MIXES

Note: The recommendations in these tables are based on the laboratory testing and constructability of a limited number of plant-produced RHMA-D mixes. The mid- and long-term field performance of the mixes has not been validated yet.

Definitions of acronyms:

- AdvWet: Advanced wet technology (asphalt rubber binder with CRM#40 and no extender oil)
- BMD: Balanced mix design
- ECRM: Engineered crumb rubber modifier
- HD: High Desert
- HM: High Mountain
- JMF: Job mix formula
- PM: Polymer-modified
- PRT: Performance-related testing
- SBS: Styrene-butadiene-styrene
- TB: Terminal blend

Layer	RHMA-D Type		Use	Expected Performance versus Conventional HMA (HMA Type A with plain binder)
	High Traffic Highways	Lower Traffic Highways		
Surface	Not yet recommended	• TB with SBS • AdvWet • ECRM	Alternative where RHMA-G is not feasible or practical (availability, perceived risk, etc.), potential alternative for HMA with PM binder	Improved cracking performance
Below surface	• AdvWet • ECRM	• AdvWet • ECRM	Can be used in place of conventional HMA (HMA Type A with plain binder)	Improved cracking and rutting performance

Layer	Expected Performance versus RHMA-G	Mix Design Approach	Cost Premium (rough estimate)
Surface	• Lower cracking performance than RHMA-G under high truck traffic • Comparable cracking performance (somewhat lower) to RHMA-G under low truck traffic • Same or better rutting performance than RHMA-G if correctly engineered	BMD: maximize cracking resistance while meeting minimum rutting resistance	Around 5–10% versus conventional HMA (HMA Type A with plain binder)
Below surface	Not applicable	BMD: maximize stiffness while meeting minimum cracking resistance	Around 5% versus conventional HMA

Layer	NSSPs	Climate	Thickness Design
Surface	Include PRT in JMF approval, production start-up, and production	Not yet recommended in HM and HD	Replace RHMA-G on a 1:1 basis
Below surface	Include PRT in JMF approval, production start-up, and production	All climates, including HM and HD	Replace HMA Type A on a 1:1 basis


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