Title

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Publication Date

2024-04-01

DOI

10.7922/G2PK0DH2

RESEARCH REPORT

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Report No: UCPRC-RR-2023-06 | April 2024

Partnered Pavement Research Center Strategic Plan Element (PPRC SPE) 2.9 (DRISI Task 3215): CalME Support

PREPARED FOR

California Department of Transportation
Division of Research, Innovation and System Information
Office of Materials and Infrastructure

PREPARED BY

University of California Pavement Research Center
UC Davis and UC Berkeley

TECHNICAL REPORT DOCUMENTATION PAGE

1. REPORT NUMBER
UCPRC-RR-2023-06

2. GOVERNMENT ASSOCIATION NUMBER

3. RECIPIENT'S CATALOG NUMBER

4. TITLE AND SUBTITLE
Analysis of Recycling Agent Effects on the Mechanical Properties of HMA with High Recycled Binder Ratios

5. REPORT PUBLICATION DATE
April 2024

6. PERFORMING ORGANIZATION CODE

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8. PERFORMING ORGANIZATION REPORT NUMBER
UCPRC-RR-2023-06
UCD-ITS-RR-23-81

9. PERFORMING ORGANIZATION NAME AND ADDRESS
University of California Pavement Research Center
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10. WORK UNIT NUMBER

11. CONTRACT OR GRANT NUMBER
65A0788

12. SPONSORING AGENCY AND ADDRESS
California Department of Transportation
Division of Research, Innovation, and System Information
P.O. Box 942873
Sacramento, CA 94273-0001

13. TYPE OF REPORT AND PERIOD COVERED
Research Report
September 2020 to June 2023

14. SPONSORING AGENCY CODE

15. SUPPLEMENTAL NOTES
doi:10.7922/G2PK0DH2

16. ABSTRACT
The goal of the research presented in this report is to study how the mechanical properties of hot mix asphalt change upon the addition of high contents of reclaimed asphalt pavement (RAP) and the inclusion of any amount of recycled asphalt shingles (RAS), with between 25% and 50% binder replacement and to consider the addition of recycling agents to reduce the increase in stiffness and corresponding decrease in fatigue resistance. To achieve this goal, 16 mixes and the corresponding binders were fabricated and tested in the laboratory. The mix factorial includes a control gradation, two virgin binders (PG 64-16 and PG 58-28, from different sources), two RAPs with different levels of aging (PG high temperatures of 102°C and 109°C), one RAS, and two recycling agents (a petroleum-derived aromatic and a tall oil). The testing of the binders included performance grade (PG), shear stiffness, and Fourier transform infrared spectroscopy. The testing of the mixes included stiffness, four-point flexural fatigue resistance, rutting resistance, and the IDEAL cracking tolerance (IDEAL-CT) test. The main conclusion from this study is that most of the increased stiffness effects of high RAP and/or RAS addition can be offset by using recycling agents and/or reducing the stiffness of the virgin binder by reducing the PG binder grade. Two approaches are proposed to determine an appropriate dosage of recycling agent. The first focuses on restoring the mechanical properties of the mix with high RAP/RAS content back to the properties of a control mix with either no RAP/RAS or a low RAP/RAS content. The second approach focuses on meeting the required performance-related specifications within the balanced mix design framework by using the minimum amount of recycling agent. It was found that restoring the PG high temperature of the binder blend, a commonly followed approach, may result in unnecessarily high recycling agent doses with a consequent increase in cost and greenhouse gas emissions and the over-softening of the mix at intermediate and low temperatures.

17. KEYWORDS
reclaimed asphalt pavement (RAP), recycled asphalt shingles (RAS), recycling agent, balanced mix design (BMD)

18. DISTRIBUTION STATEMENT

19. SECURITY CLASSIFICATION (of this report)
Unclassified

20. NUMBER OF PAGES
133

21. PRICE
None

UCPRC ADDITIONAL INFORMATION	
1. DRAFT STAGE Final	**2. VERSION NUMBER** 1
3. UCPRC STRATEGIC PLAN ELEMENT NUMBER 4.79	**4. CALTRANS TASK NUMBER** 3819
5. CALTRANS TECHNICAL LEAD AND REVIEWER(S) Kee Foo, Raghu Shrestha, and Saeed Pourtahmasb	**6. FHWA NUMBER** CA243819
7. PROPOSALS FOR IMPLEMENTATION This study proposes two approaches for determining the recycling agent dose. The approaches are ready for pilot implementation on the field.	
8. RELATED DOCUMENTS Alavi, M. Z., Jones, D., He, Y., Chavez, P., and Liang, Y. 2017. *Investigation of the Effect of Reclaimed Asphalt Pavement and Reclaimed Asphalt Shingles on the Performance Properties of Asphalt Binders: Phase 1 Laboratory Testing* (Research Report: UCPRC-RR-2016-06). UC Davis: University of California Pavement Research Center. Harvey, J., Buscheck, J., Brotschi, J., Rahman, M., Mateos, A., and Jones, D. 2023. *RAP and RAS in HMA Pilot Project on ELD 49: Material Testing, Observations, and Findings* (Research Report: UCPRC-TM-2022-04). UC Davis: University of California Pavement Research Center.	
9. VERSION UPDATES	
10. LABORATORY ACCREDITATION The UCPRC laboratory is accredited by AASHTO re:source and CCRL for the laboratory testing discussed in this report	AASHTO ACCREDITED CCRL Cement and Concrete Reference Laboratory
11. SIGNATURES	

A. Mateos	J.T. Harvey	C. Fink	J.T. Harvey	K. Foo	S. Mafi
FIRST AUTHOR	**TECHNICAL REVIEW**	**EDITOR**	**PRINCIPAL INVESTIGATOR**	**CALTRANS TECHNICAL LEAD(S)**	**CALTRANS CONTRACT MANAGER**

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ACKNOWLEDGMENTS

The University of California Pavement Research Center acknowledges the following individuals and organizations who contributed to the project: the Caltrans Office of Asphalt Pavement for support and technical lead of the project, in particular Cathrina Barros and Kee Foo; former DRISI project manager T. Joseph Holland; Vulcan Materials Company for providing the asphalt mix design, virgin aggregate, and reclaimed asphalt pavement (RAP) used as a reference in this research and technical expertise; Teichert Aggregates and Syar Industries for providing additional RAP sources; Valero and the San Joaquin refineries for providing the asphalt binder; Ingevity and the San Joaquin refinery for providing the recycling agents and technical expertise; Stonemont Solutions for proving the asphalt mix design management system; the UCPRC laboratory and field staff at UC Davis and UC Berkeley; and UCPRC publications manager Camille Fink.

PROJECT OBJECTIVES

This study is a continuation of PPRC Project 4.64 (Continued Development of Guidelines for Determining Binder Replacement in High RAP/RAS Content Mixes), completed under PPRC Project 4.79 (Guidance, Tests, and Specifications for High Reclaimed Asphalt Pavement/Recycled Asphalt Shingle Contents in HMA and RHMA Mixes). The objective of Project 4.79 is to develop guidelines for determining binder replacement rates in high recycled asphalt shingles/reclaimed asphalt pavement (RAS/RAP) content mixes without the need for binder extraction and performance-related tests for use in routine mix design and construction quality control/quality assurance. This will be achieved through the following tasks:

- Task 1: Update literature review to include recently completed research.
- Task 2: Complete testing of high RAP and RAP/RAS mixes to determine their performance properties.
- Task 3: Complete testing of extracted and recovered RAP, RAP/RAS, and RAP/RAS/virgin binder blends to assess the effectiveness of different recycling agents.
- Task 4: Complete investigation into the use of fine aggregate matrix mix testing to assess the fatigue performance of mixes and to predict binder properties.
- Task 5: Investigate long-term aging effects of high RAP and RAP/RAS mixes using different laboratory-aging protocols.
- Task 6: Monitor field performance of high RAP and RAP/RAS mixes, and use results to evaluate laboratory-aging protocols.
- Task 7: Prepare a research report with recommendations for use of RAP and RAP/RAS as a binder replacement, and, if applicable, recommendations for accelerated wheel-load testing.

The results presented in this research report complete the work of Task 2 and Task 3 by presenting the results of the laboratory investigation of the performance-related properties of binders and mixes containing different virgin binders, RAP materials, RAS, and recycling agents.

EXECUTIVE SUMMARY

The use of increased amounts of reclaimed asphalt pavement (RAP) and the use of recycled asphalt shingles (RAS) in hot mix asphalt (HMA) can considerably reduce the economic cost and the environmental impacts associated to HMA production. The use of RAP and/or RAS is expected to result in an increase in mix stiffness and rutting resistance, but previous research at the UCPRC working with Caltrans and industry has identified potential concerns regarding cracking resistance and similar concerns have been raised by other researchers. These concerns are addressed in PPRC Project SPE 4.79, "Guidance, Tests, and Specifications for High Reclaimed Asphalt Pavement/Recycled Asphalt Shingle Contents in HMA and RHMA Mixes" (2020-2023). The research presented in this report is part of the SPE 4.79 research project.

The goal of the research presented in this report is to study how the mechanical properties of HMA change with the addition of high RAP content and any amount of RAS, resulting in between 25% and 50% binder replacement, and how the resulting changes on stiffness and resistance to fatigue, rutting, and cracking can be engineered by using recycling agents and/or by changing the base binder stiffness. To achieve the goal, 16 mixes and the corresponding binders were fabricated and tested in the laboratory. The set of mixes included a control gradation (0.5 in. NMAS), two virgin binders (PG 64-16 and PG 58-28), two RAPs with different levels of aging (PG high of 102°C and 109°C), one RAS, and two recycling agents (a petroleum-derived aromatic and a tall oil).

The testing of the binders included PG grading, shear stiffness, and Fourier transform infrared (FTIR) spectroscopy. The mix testing included stiffness (asphalt mixture performance tester [AMPT] axial dynamic modulus and four-point bending [4PB] dynamic modulus), 4PB fatigue resistance, rutting resistance (AMPT repeated load testing and Hamburg Wheel-Tracking testing), and the IDEAL cracking tolerance (IDEAL-CT) test to determine the cracking tolerance index (CT_{Index}) and *Strength*.

The mixes included three RAP binder replacement levels: 0%, 25%, and 50%, where the binder replacement is defined as the sum of RAP and, if used, recycling agent, divided by the sum of virgin binder, RAP, and, if used, recycling agent. Two of the mixes included RAS in addition to RAP, and the binder replacement was around 35%, with around 15% coming from the RAS.

The recycling agent dose was determined with the goal of restoring the PG high of the binder blend back to that of the PG 64 grade control binder, based on binder blends prepared in the laboratory by blending the virgin binder, the binder extracted and recovered from the RAP/RAS, and the corresponding recycling agent. This approach has been included in the draft AASHTO standard developed in NCHRP 9-58, "Evaluating the Effects of Recycling Agents on Asphalt Mixtures with High RAS and RAP Binder Ratios."

The experiment was designed to address a number of questions, presented in the following discussion, and the conclusions obtained regarding each of the questions.

1. What are the effects of the addition of high RAP content on the mechanical properties of the HMA?
   - As expected, the addition of RAP resulted in higher stiffness, particularly at high temperatures, and higher *Strength,* higher rutting resistance, and lower CT_{Index}.
   - Unexpectedly, the addition of RAP to the control mix with PG 64-16 virgin binder did not reduce, but instead improved, the 4PB fatigue resistance at a given tensile strain. This unexpected outcome was related to the poor fatigue performance of the binder source used in this study. In fact, the fatigue performance of the RAP and RAS (aged) binders was better than the fatigue performance of the PG 64-16 virgin binder. Since the control mix with PG 58-28 virgin binder (and no RAP) was not tested, the effect of the RAP addition could not be determined for this mix.
2. Can the RAP addition effects be predicted based on testing of the blended binder?
   - The effects of RAP addition on HMA stiffness, rutting resistance, and IDEAL *Strength* were strongly related to the effect on the PG of the binder blend at similar temperatures as the high performance grade (PGH) mix testing. Mix stiffness at high temperatures and rutting resistance were correlated to the PGH, mix stiffness at intermediate temperatures and *Strength* were correlated to PGI, and mix stiffness at low temperatures was correlated to PGL. PGH, PGI, and PGL are the PG high, intermediate, and low, respectively, of the binder blend, with the binder blend being virgin binder plus RAP binder and recycling agent, if used.
   - On the contrary, the effects of RAP and recycling agent on 4PB fatigue life and IDEAL CT_{Index} did not correlate well with any blended binder property.
3. What are the effects of the recycling agent addition on the mechanical properties of HMA with high RAP content?
   - As expected, the recycling agent produced an overall softening (decrease in stiffness and IDEAL *Strength* and increase in IDEAL CT_{Index}) of the mix. The effect was somewhat the opposite to the RAP addition.
   - The addition of the recycling agent did not consistently produce the same effect on the rutting resistance of the HMA with RAP.
   - As expected, the addition of the recycling agent resulted in an improvement in the 4PB fatigue life for the mix with PG 58-28 binder. Unexpectedly, the addition of the recycling agent did not improve the 4PB fatigue life for the mix with PG 64-16 binder. This unexpected outcome was believed to be related to the poor fatigue performance of the virgin base binder source used in this study.
   - The main difference between the two recycling agents was that the aromatic required a higher dose (around 60% higher) than the tall oil to produce similar effects on the HMA

mechanical properties. Another difference is that—for a similar effect on the PGH—the aromatic produced a higher improvement in ΔTc (more positive ΔTc) than the tall oil.

4. By using a recycling agent, can the mechanical properties of an HMA with high RAP content be restored back to the properties of the HMA with low RAP content?
   - The answer to this question is that, overall, yes. By using a recycling agent, the stiffness of the mix with high RAP content can be restored back to the stiffness of the mix with low or no RAP content, and the same applies to IDEAL *Strength*, CT_{Index}, and fatigue resistance.
5. Are there specific considerations required for the addition of RAS compared with the addition of RAP?
   - The effects of adding RAS on the mix mechanical properties was consistent with the higher stiffness (higher PG) of the RAS binder compared with the RAP binders. Further, the addition of a recycling agent produced similar effects on the mix with RAP and RAS as the effects on the mixes with only RAP.
   - No reason was found to treat mix designs with RAS differently from mix designs with RAP other than the facts that RAS PGH is typically much higher than RAP PGH and that RAS binder content is typically three to five times higher than RAP binder content. Because of the high binder content of the RAS compared with the RAP, the mass amount of RAS to achieve a similar binder replacement to RAP is three to five times lower.
6. Can mixes with 50% RAP content and/or RAS be engineered to have desired properties for different applications in the pavement structure?
   - It was demonstrated that mixes with both 25% and 50% RAP (or RAS and RAP) can be engineered to have generally the same properties for a surface mix as a mix with the same base binder and no RAP.
   - It was also demonstrated that the addition of RAP and/or RAS can be used to stiffen a mix used below the surface mix for use in thicker overlays and new pavement.
   - Mechanical properties for either application can be engineered using different binder replacement rates, different base binders, different RAP and/or RAS sources, and recycling agent.
7. What is the recommended approach to determine the recycling agent dose?
   - The approach followed in this research study, recommended based on NCHRP 9-58, which consists of restoring the PGH of the binder blend back to the PGH of the control binder, may result in unnecessarily high recycling agent doses and the consequent over-softening of the mix. The high recycling agent dose will increase cost and greenhouse gas emissions. Further, the soft mixes will underperform in many scenarios, particularly when used as layers below the surface in overlays or new pavements with more than one lift of new HMA.

- Two approaches have been proposed for dosing the recycling agent: Approach 1 and Approach 2:
    - Approach 1 focuses on engineering the mechanical properties of the mix with high RAP/RAS content to match the properties of a control mix with either no RAP/RAS or low/standard RAP/RAS content. The dosing goal is to match the stiffness of the HMA at intermediate temperatures, based on either binder or mix testing. The resulting mix and/or the extracted binder is then tested for low and high temperatures performance verification.
    - Approach 2 focuses on meeting the required performance-related specifications within the balanced mix design framework by changing the base binder and/or using the minimum amount of recycling agent.

Further research is recommended to address several topics not considered in this study. Two of the recommended topics are the evaluation of the long-term effectiveness of the recycling agent and the evaluation of the effect of RAP/RAS and recycling agent on the moisture sensitivity of the mix.

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LIST OF ABBREVIATIONS

AMPT	Asphalt mixture performance tester
BBR	Bending beam rheometer
BMD	Balanced mix design
BR	Binder replacement
CA	Carbonyl area
CAmod	Modified carbonyl area index
FTIR	Fourier transform infrared
FTIR-ATR	Fourier transform infrared spectroscopy with attenuated total reflection
Gmm	Theoretical maximum specific gravity
GR	Glover-Rowe
HMA	Hot mix asphalt
HWT	Hamburg Wheel-Tracking
IDEAL-CT	IDEAL cracking tolerance
LCA	Life cycle assessment
LCCA	Life cycle cost analysis
ME	Mechanistic-empirical
MTOA	Medium-term oven aging
NMAS	Nominal maximum aggregate size
OLTS	Online lab tracking system
PAV	Pressurized aging vessel
PG	Performance grade
PGH	Performance grade high
PGI	Performance grade intermediate
PGL	Performance grade low
PPRC	Partnered Pavement Research Center
QA	Quality assurance
QC	Quality control
RA	Recycling agent
RAP	Reclaimed asphalt pavement

RAS	Recycled asphalt shingles
RHMA	Rubberized hot mix asphalt
RLT	Repeated load test
RTFO	Rolling thin-film oven
SCB	Semicircular bending
SSD	Saturated surface-dry
STOA	Short-term oven aging
SUL	Sulfoxide
Superpave	Superior Performing Asphalt Pavement
TWM	Total weight of mix
VMA	Voids in mineral aggregate

LIST OF TEST METHODS AND SPECIFICATIONS

AASHTO M 320	Standard Specification for Performance-Graded Asphalt Binder
AASHTO M 323	Standard Specification for Superpave Volumetric Mix Design
AASHTO PP 3	Standard Practice for Preparing Hot Mix Asphalt (HMA) Specimens by Means of the Rolling Wheel Compactor
AASHTO R 28	Standard Practice for Accelerated Aging of Asphalt Binder Using a Pressurized Aging Vessel (PAV)
AASHTO R 30	Standard Practice for Mixture Conditioning of Hot Mix Asphalt (HMA)
AASHTO T 84	Standard Method of Test for Specific Gravity and Absorption of Fine Aggregate
AASHTO T 85	Standard Method of Test for Specific Gravity and Absorption of Coarse Aggregate
AASHTO T 164	Standard Method of Test for Quantitative Extraction of Asphalt Binder from Hot-Mix Asphalt (HMA)
AASHTO T 166	Standard Method of Test for Bulk Specific Gravity (Gmb) of Compacted Hot Mix-Asphalt (HMA) Using Saturated Surface-Dry Specimens
AASHTO T 209	Standard Method of Test for Theoretical Maximum Specific Gravity (Gmm) and Density of Hot-Mix Asphalt (HMA)
AASHTO T 240	Standard Method of Test for Effect of Heat and Air on a Moving Film of Asphalt Binder (Rolling Thin-Film Oven Test)
AASHTO T 283	Standard Method of Test for Resistance of Compacted Asphalt Mixtures to Moisture-Induced Damage
AASHTO T 308	Standard Method of Test for Determining the Asphalt Binder Content of Hot Mix-Asphalt (HMA) by the Ignition Method
AASHTO T 312	Standard Method of Test for Preparing and Determining the Density of Asphalt Mix Specimens by Means of the Superpave Gyratory Compactor
AASHTO T 313	Standard Method of Test for Determining the Flexural Creep Stiffness of Asphalt Binder Using the Bending Beam Rheometer
AASHTO T 315	Standard Method of Test for Determining the Rheological Properties of Asphalt Binder Using a Dynamic Shear Rheometer
AASHTO T 316	Standard Method of Test for Viscosity Determination of Asphalt Binder Using Rotational Viscometer

AASHTO T 321	Standard Method of Test for Determining the Fatigue Life of Compacted Asphalt Mixtures Subjected to Repeated Flexural Bending
AASHTO T 324	Standard Method of Test for Hamburg Wheel-Track Testing of Compacted Asphalt Mixtures
AASHTO T 331	Bulk Specific Gravity (Gmb) and Density of Compacted Hot Mix Asphalt (HMA) Using Automatic Vacuum Sealing Method
AASHTO T 378	Standard Method of Test for Determining the Dynamic Modulus and Flow Number for Asphalt Mixtures Using the Asphalt Mixture Performance Tester (AMPT)
ASTM D 8225	Standard Test Method for Determination of Cracking Tolerance Index of Asphalt Mixture Using the Indirect Tensile Cracking Test at Intermediate Temperature
ASTM D 4552	Standard Practice for Classifying Hot-Mix Recycling Agents
ASTM D 5404	Standard Practice for Recovery of Asphalt from Solution Using the Rotary Evaporator
ASTM D 8159	Standard Test Method for Automated Extraction of Asphalt Binder from Asphalt Mixtures
ASTM D 7643	Standard Practice for Determining the Continuous Grading Temperatures and Continuous Grades for PG Graded Asphalt Binders (DeltaTc)
ASTM E 168	Standard Practice for General Techniques of Infrared Quantitative Analysis
Asphalt Institute MS-2	Asphalt Mix Design Methods

CONVERSION FACTORS

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

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

1 INTRODUCTION

1.1 Background

The California Department of Transportation (Caltrans) is interested in finding, developing, and implementing approaches to reduce life cycle cost and improve the life cycle environmental performance of its pavements. Caltrans' goal includes achieving carbon neutrality by 2045 by building sustainable, resilient, and equitable communities, outlined in The California Climate Crisis Act (California Assembly Bill 1279) *(1)*. Two approaches under investigation that offer the potential to advance these goals are the use of increased amounts of reclaimed asphalt pavement (RAP) and the use of recycled asphalt shingles (RAS) in hot mix asphalt (HMA) materials. Caltrans is investigating the performance of high RAP content mixes, mixes containing more than 25% RAP. The University of California Pavement Research Center (UCPRC) has been contributing to the Caltrans investigation of the use of higher percentages of RAP in HMA through laboratory testing of laboratory-prepared and field-sampled materials, observations of construction and field performance, mechanistic-empirical simulations using the performance-related test properties for the mixes, strategic planning, and other support.

Previous and ongoing research at the UCPRC working with Caltrans and industry has identified potential concerns regarding using highly aged, stiff RAP *(2,3)*, and similar concerns have been raised by other researchers *(4,5)*. The addition of RAP to a mix is expected to result in an increase in mix stiffness and rutting resistance but also in a reduction of mix fatigue life at a given tensile strain under repeated loading and fracture cracking resistance under monotonic loading. The volumetric mix design method (SuperPave) and specifications currently used for HMA in California and most of the rest of the country do not provide much information regarding the effects of high RAP contents and/or the inclusion of RAS on mix performance-related mechanical properties.

A relatively simple approach to estimate the impacts of RAP addition on HMA mechanical properties (stiffness, fatigue, fracture, permanent deformation [rutting]) has not been developed yet. The current performance grade (PG) binder specification provides information regarding stiffness at two critical temperatures: high temperatures for rutting and low temperatures for low temperature cracking with aging. The PG specification also includes an intermediate temperature maximum stiffness specification limit that provides some information regarding stiffness at those temperatures where fatigue damage is primarily an issue, but it is only applicable for thin overlays and it does not directly address fatigue damage resistance. Sampling and specimen preparation methods for binder testing result in complete blending of the RAP and/or RAS binder and recycling agent (RA), if used, with the virgin binder, which may not be the case in the mix.

Limited work had been done on binder replacement from RAS in California by the UCPRC, Caltrans, and industry prior to the pilot study presented in this research report. Limited previous work by the

UCPRC indicated poor results because of the lack of blending of the RAS and virgin binders due to the very heavy oxidation of the single RAS source used in the initial work *(3)*.

Two main strategies have been used to offset the increased stiffness effects and potential for reduced fatigue life at a given strain and fracture of the aged RAP or RAS binder: (1) reducing the stiffness of the virgin binder by "stepping down" the base binder grade (e.g., using PG 58-22 instead of PG 64-16) and/or (2) adding recycling agents. The latter has been the topic of several research studies *(2–6)*, and the two strategies have been implemented in several Caltrans pilots in recent years, including ELD 49 (State Route 49 in El Dorado County) *(7)*, SJ 26 (State Route 26 in San Joaquin County), and SBD 215 (State Route 215 in San Bernardino County). Caltrans has several additional pilot studies planned.

The recycling agents, sometimes also referred to as "rejuvenating recycling agents," have been shown to soften the asphalt mix through the replacement of the maltene phase lost during its service life at least partially, and potentially completely, offsetting the aged binder effect on stiffness *(4,5)*. The expectation is that the softening will also restore—at least in part—the loss of fatigue and fracture cracking resistance associated with the high RAP and/or RAS addition (hereafter referred to as RAP/RAS) that is associated with the increased stiffness. Testing conducted in past studies, mainly based on monotonic loading fracture cracking tests, has shown that the expectation may be realistic. A National Center for Asphalt Technology (NCAT) study showed that the addition of recycling agents increased cracking resistance as measured by the Texas Overlay Tester (cyclic loading) and the University of Florida Energy Ratio approach *(4)*, while a National Cooperative Highway Research Program (NCHRP) study showed similar outcomes based on the Illinois Flexibility Index Test *(5)*. Preliminary results from Caltrans high RAP pilots, based on monotonic testing and four-point bending beam flexural fatigue testing, point in the same direction.

One of the main steps for designing HMA with high RAP/RAS content is determining the recycling agent dose. Texas A&M Transportation Institute researchers, as part of the NCHRP project, have proposed the use of the PG high (PGH) of the binder blend (base binder + recycled binder + recycling agent) as a measure of the recycling agent effect. These researchers have outlined the recycling agent dose determination approach in a draft AASHTO standard *(5)*. Based on this draft AASHTO standard, the amount of recycling agent shall be the one that restores the PGH of the binder blend to the PGH required for the project climate, and the PGH cannot be greater than that level. For example, if a PG 64 material is required for the climate region, then the combination of the virgin binder, the RAP binder, and the RA must not be greater than the minimum temperature allowed for a PG 64 binder, which is 69.99°C. This approach, conceived for surface mixes, was followed on the Caltrans ELD 49, SJ 26, and SBD 215 pilot projects, and it has been evaluated in the research presented in this report. Although PGH is intended to address rutting, and a higher PGH is better for rutting, the intent is that a reduced PGH will also result in a reduction in low and intermediate PG temperatures, which is beneficial for low temperature cracking and for thin overlay fatigue cracking.

Several performance-related tests have been identified to assess the performance of mixes with high RAP and RAS content, focused on rutting, stiffness, and fatigue. These performance-related tests include long-established tests such as the Hamburg Wheel-Tracking test, repeated load test (RLT), four-point bending flexural fatigue test, and flexural and axial dynamic modulus frequency sweep tests. Some of these tests are key inputs to mechanistic-empirical (ME) modeling of pavement performance. Other recently developed tests, such as the semicircular bending (SCB) test and the indirect tensile asphalt cracking test, also known as the IDEAL cracking tolerance (IDEAL-CT) test, are also being assessed for their potential to provide a quick and simple indicator of mix performance for mix design and quality control/quality assurance (QC/QA) purposes. During this study, additional rutting surrogate tests, namely the high temperature indirect tensile strength test (Hot-IDT) and rutting tolerance index using the rapid rutting test (IDEAL rutting test), were identified in the literature but not included in the study. They will be considered in future rutting validation studies. This research report presents the results of an experimental study, based on mixes produced in the laboratory, to analyze the impacts of high RAP and RAS additions to the mechanical properties of HMA and how the effects can be engineered by using recycling agents.

1.2 Problem Statement

The following problems have been identified:

- While the overall effect of RAP/RAS addition on the mechanical properties of the HMA has been identified before (increase in stiffness and rutting resistance, decrease in fatigue and cracking resistance), a relatively simple approach to quantify the effects has not been developed. Further, the range of effects on performance-related test results of mix design variables, including the properties of the virgin and recycled binders, in combination with high RAP/RAS addition, remains essentially unknown for the unique range of California crude sources.
- Little is known about the effects of the recycling agent on the mechanical properties of HMA with high RAP/RAS, other than the softening of the binder and the mix. The effects on mix stiffness at different temperatures and frequencies, rutting resistance, fatigue resistance, and monotonic cracking resistance deserve further research. The need for further research is particularly relevant for the recycling agent effect on fatigue cracking resistance (under repeated loading) as most studies conducted to date have tested cracking resistance based on monotonic loading (e.g., the Illinois Flexibility Index Test [I-FIT] or IDEAL-CT test).
- Selection of the recycling agent dose is one of the critical steps in the design of HMA with high RAP/RAS content. While some relatively simple approaches have been proposed to date (e.g., restore PGH of the binder blend), no approach focuses on optimizing the performance of the mix within a balanced mix design (BMD) framework. The performance optimization would require consideration of the pavement structure and the location and role of the HMA with high RAP/RAS in the pavement structure—in addition to HMA and RAP/RAS properties. The

development of an approach that allows recycling agent dose determination without the need for binder extraction and recovery would be desirable.

The study presented in this research report is intended to address the three problems stated above. Other relevant problems have been also identified, though they are not the goal of this research:

- The long-term effectiveness of the recycling agent remains unknown. The diffusion of the recycled binder in the new binder and recycling agent blend, or other processes between the new binder and RA, is known to take place during mixing, construction, and a period of time in the service life of the pavement. Consequently, the recycling agent effect as measured in short-term aged mixes (produced in either the laboratory or plant) will not represent the long-term conditions in the field. This will be further influenced by the location of those materials in the pavement structure (e.g., depth in the asphalt layers below the surface and resulting differences in exposure to heat and air).
- The effect of high RAP/RAS addition on the moisture sensitivity of the mix deserves further research as contradictory results to date exist. Further, the role of the recycling agent on the moisture sensitivity of the mix is essentially unknown for California aggregate and crude sources.

1.3 Goal and Questions to Answer

The goal of the research presented in this report is to study how the mechanical properties of the HMA change upon the addition of high RAP content and/or the addition of RAS resulting in 25% to 50% binder replacement and how the changes (e.g., increase in stiffness, decrease in monotonic cracking resistance, changes in fatigue and rutting resistance) can be engineered by using recycling agents for different applications of HMA in the pavement structure. The study was designed to address the following questions:

1. What are the effects of the addition of high RAP content on the mechanical properties of the HMA?
2. Can the RAP addition effects be predicted based on testing of the blended binder?
3. What are the effects of the recycling agent addition on the mechanical properties of HMA with high RAP content?
4. By using a recycling agent, can the mechanical properties of an HMA with high RAP content be restored back to the properties of the HMA with low RAP content?
5. Are there specific considerations required for the addition of RAS compared with the addition of RAP?
6. Can mixes with 50% RAP content and/or RAS be engineered to have desired properties for different applications in the pavement structure?
7. What is the recommended approach to determine the recycling agent dose?

1.4 Experimental Approach

The goal of this research will be addressed by the laboratory evaluation of a set of mixes in a factorial experiment design. The factorial has been designed to cover the range of variation of the most relevant variables to the performance of mixes with high RAP content, including binder type, RAP content and RAP aging condition, and recycling agent type. The evaluation includes the testing required to conduct the ME simulation of the performance of the mixes as part of an asphalt pavement. ME simulations were not part of the study.

The approach includes the following steps:

1. Select a reference HMA design.
2. Select and sample virgin aggregates and control virgin base binder with a PGH of 64°C (the most common in California).
3. Select and sample two RAP sources with different levels of aging.
4. Select and sample two recycling agents with different chemical approaches (made from petroleum and made from tall oil from pine trees).
5. Select and sample a second virgin binder that is softer than the control binder. The PGH of the second virgin binder must be 58°C (one high temperature grade lower than the PGH of the control binder). The goal of selecting a second virgin binder that is softer than the control binder is to evaluate one of the existing strategies to engineer the effects of the high RAP/RAS addition, stepping down the binder grade.
6. Evaluate the RAP and recycling agent effects based on binder testing:
    a. Test the virgin binder, the RAP binder, and the virgin and RAP binder blends in the laboratory following Superpave methods, with RAP binder replacement levels of 25% and 50%.
    b. For each binder blend, determine the amount of each of the two recycling agents required to restore the PGH of the blend to the PGH of the control binder (64°C).
    c. Test the binder blends, including each recycling agent at the required dose, following Superpave binder test methods.
7. Evaluate the RAP and recycling agent effects based on mix testing:
    a. Prepare the HMA in the laboratory, including different levels of each of the following variables: virgin binder type, RAP source, and binder replacement. Conduct mechanical characterization of the mixes in the laboratory.
    b. For each of the mixes in step 7.a, fabricate in the laboratory the corresponding mix with the required amount of each recycling agent (dose determined in step 6.b). Conduct mechanical characterization of the mixes in the laboratory.

8. Evaluate the effects of the RAS and recycling agent additions by mixing and testing one HMA with RAS and no recycling agent and the same mix with the recycling agent.
9. Analyze the tests results to address each of the questions stated in Section 1.3.

It should be noted that the mechanical characterization of the mixes in the laboratory includes the following:

- Axial stiffness, measured with the asphalt mix performance tester (AMPT)
- Flexural stiffness, measured with the four-point bending (4PB) flexural beam apparatus
- Rutting resistance following repeated load testing, measured with the AMPT
- Rutting and moisture resistance following the Hamburg Wheel-Tracking (HWT) test
- Flexural fatigue resistance, measured with the 4PB flexural beam apparatus
- Cracking resistance following the IDEAL-CT test

1.5 Scope of the Report

This study is exclusively based on binders and mixes produced in the laboratory. The mixes were short-term oven conditioned for four hours at 135°C for mechanical testing (following the former AASHTO R30), but they were not subjected to any further aging. Long-term effects of the recycling agent were not evaluated in this study.

Aggregate type effects, while important, were not evaluated in this study, as only one virgin aggregate source and gradation were used for mix fabrication. Aggregate type is not regarded as an important variable to address the questions to be answered in this study. The control binder selected for this study is PG 64-16, one of the most commonly used binders in California. A second binder, with a PGH of 58°C (step-down binder), was also selected for this study. The suppliers of the two binders are different from each other. While investigation of RAP addition is one of the goals of this study, limited testing was conducted for mixes with RAS.

1.6 Measurement Units

In this report, both US and metric units (provided in parentheses after the US units) are provided in the general discussion. There are two exceptions: (1) the PG of the asphalt binder is reported in metric units (°C), following AASHTO M 320-21 and (2) the load and displacement measured in the IDEAL-CT test are reported in metric units following ASTM D 8225-19. A conversion table (US versus metric) is provided on page xx.

2 EXPERIMENT DESIGN

The design of the experiment, the methods used for specimen preparation, and the testing methods used for binder and asphalt mix are described in this chapter.

2.1 Experimental Framework

2.1.1 Mix Designs and Materials

2.1.1.1 Reference Mix Design

The mix design used as a reference in this study was developed by Vulcan Materials for the City of Los Angeles. The mix is a Marshall dense-graded HMA with 50% RAP and 1/2 in. nominal maximum aggregate size. Some of the features of the mix design were adopted for this study while others were modified:

- The virgin binder in the reference mix design was PG 64-10. For this study, another virgin binder type (PG 64-16) was selected for the control mix (Section 2.1.1.2).
- The virgin aggregates in the reference mix design came from the Vulcan Irwindale plant alluvial deposit. The same virgin aggregates were used in this study (Section 2.1.1.3).
- The aggregate gradation of the reference mix design was maintained in this study. For each of the mixes fabricated in this study, the proportions of the different virgin aggregate bins were adjusted to match the gradation of the reference mix design (Section 2.1.1.3).
- The RAP in the reference mix design was not fractionated, but it was fractionated for this study (only pass 3/8 in. RAP fraction was used in this study). The two RAPs used in this study are described in the following discussion (Section 2.1.1.4).
- The recycling agent in the reference mix design was an aromatic extract (RA 5 according to the ASTM D4552-20 denomination) used at 10% dose (% weight of binder). Two recycling agents were selected for this study: the same aromatic extract and a tall oil (Section 2.1.1.5).
- The total binder content of the reference mix design was 5.1% (by total weight of mix [TWM]). For this study, the binder content for each of the mixes was determined following Superpave specifications to obtain 4% air voids at 85 gyrations (N_{Design}).

Two of the mixes tested in this study include RAS in addition to RAP. The mixes with 3% RAS were based on a commercially available mix from a Sacramento-region HMA plant that included 20% RAP and 3% RAS. The RAS used in this study is described in the following discussion (Section 2.1.1.4).

2.1.1.2 Virgin Binders

The control binder selected for this study is PG 64-16, sampled from a binder producer in Southern California. In addition to the PG 64-16 control binder, a second virgin binder with a PGH of 58°C was selected for this study. The goal of selecting a second virgin binder softer than the control binder is the evaluation of one of the strategies to engineer the effects of the high RAP/RAS addition: stepping down the binder grade. As previously explained, the second asphalt binder was sampled from a different binder producer than the first one. Consequently, the binder grade stepping-down strategy in this study includes a confounding variable, which is the binder source. The binder source within California is known historically to play an important role in HMA performance *(8)*.

2.1.1.3 Aggregate and Gradations

The target gradation of the reference mix, shown in Figure 2.1, meets the Caltrans 1/2 in. nominal maximum aggregate size specification. The gradation was reconstituted in the laboratory by using the corresponding RAP/RAS and the following virgin aggregate bins (bin gradations are shown in Figure 2.2):

- 1/2” virgin aggregate
- 3/8” virgin aggregate
- 1/4” x dust virgin aggregate
- 1/4” x dust virgin aggregate (washed)
- 1/4” x dust virgin aggregate (washed), fraction passing #50
- 1/4” x dust virgin aggregate (washed), fraction passing #100

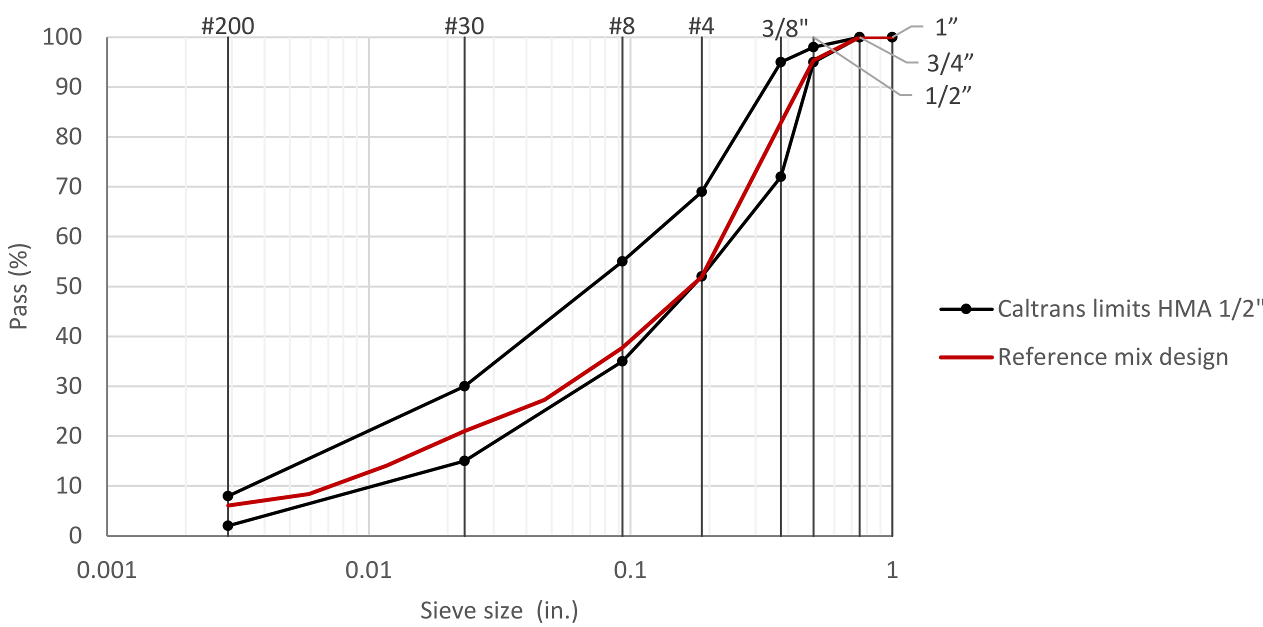


Figure 2.1: Target gradation of the reference mix design.

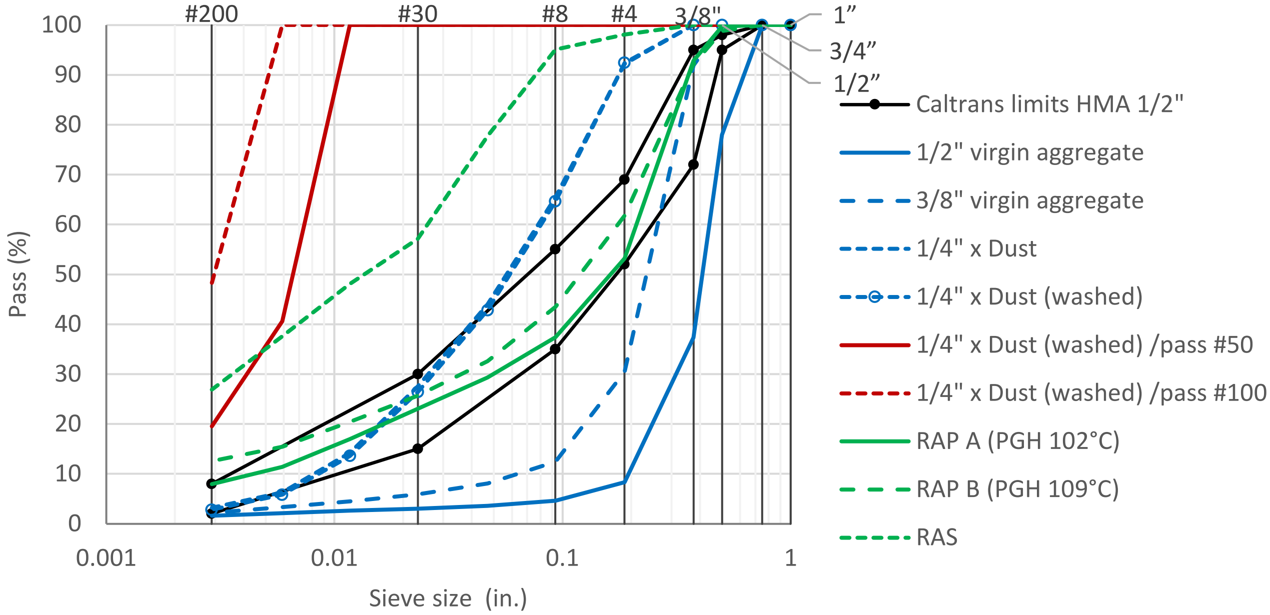


Figure 2.2: Virgin aggregate bins, RAP, and RAS gradations.

The virgin aggregates were sampled from Vulcan's Irwindale plant alluvial deposit in the Los Angeles area of Southern California.

2.1.1.4 RAP and RAS

Two RAP materials were sampled for this study, referred to as RAP A and RAP B. RAP A was sampled from an HMA plant in Irwindale in Southern California. The RAP A binder PGH was 102°C. RAP B was sampled from an HMA plant near Sacramento, in the California Inland Valley. The RAP B binder PGH was 109°C, indicating that it was likely more aged than the RAP A binder and may include stiffer base binders.

The RAP was processed by each asphalt plant following Caltrans specifications. Only the passing 3/8 in. fraction was used in this study. The RAP binder content, determined by automatic solvent extraction (ASTM D 8159), was 4.3% by TWM for RAP A and 4.7% by TWM for RAP B. RAP A and RAP B gradations are shown in Figure 2.2.

One RAS material was sampled for this study. The RAS was sampled from an HMA plant near Sacramento in the California Inland Valley. The RAS had a nominal maximum aggregate size of #4 (4.26 mm) and was classified as post-consumer waste, sometimes referred to as "tear offs." The RAS binder PGH exceeded the temperature range of the testing equipment (118°C maximum) so the PGH could not be determined. Nonetheless, the RAS PGH was back-calculated using binder data from the extracted blended binder of one of the RAS mixes (Mix 23), and it was estimated to be between 130°C and 140°C. The RAS binder content, determined by automatic solvent extraction, was 22.8% by TWM. The RAS gradation is shown in Figure 2.2.

2.1.1.5 Recycling Agents

A number of recycling agents have been used in the United States to date, including paraffinic and naphthenic oils, aromatic extracts from crude oil refining, triglycerides and fatty acids like treated wasted vegetable oils, and tall oils from paper manufacturing using certain species of pine trees *(9)*. Due to time and resource availability, only two recycling agents were selected for this study, an aromatic extract and a tall oil. The two types of recycling agents have already been used extensively in different Caltrans pilot projects or by local agencies. The aromatic extract recycling agent was sourced from a California refinery and the tall oil was sourced from a South Carolina manufacturer. Following the ASTM D 4552-20 (Standard Classification for Hot-Mix Recycling Agents) classification, based on a kinematic viscosity at 140°F (60°C), the aromatic extract would be classified as RA 5 and the tall oil as RA 0.

2.1.1.6 Definition of Total Binder Content, Binder Replacement, and Binder Blend

The total binder content by total weight of the mix is demoted as P_B in this study. P_B is assumed to include virgin binder, recycled binder, and recycling agent, shown in Equation 2.1:

$$P_B = P_{VB} + P_{RB} + P_{RA} \qquad \textbf{(2.1)}$$

where P_{VB} is virgin binder content (TWM), P_{RB} is recycled binder content (TWM from RAP and RAS), and P_{RA} is recycling agent content (TWM).

In this study, the binder replacement (*BR*) is defined as the percentage of virgin binder replaced, and it is determined based on the sum of the recycled binder and the recycling agent, shown in Equation 2.2:

$$BR = (P_{RB} + P_{RA}) / (P_{VB} + P_{RB} + P_{RA}) \qquad \textbf{(2.2)}$$

The combination of virgin binder, recycled binder, and recycling agent (if present) is referred in this report as the “binder blend.”

2.1.1.7 Experiment Mix Designs

Sixteen mixes with different virgin binder types, RAP/RAS sources and contents, and recycling agent types were fabricated and tested in this study. For each of the mixes, the mix design had to be adjusted—as explained in the following discussion—to accommodate the different levels of RAP/RAS and recycling agent added. In all cases, the virgin binder content of the mix was determined with the goal of obtaining 4% air voids at 85 gyrations (N_{Design}).

Mix design adjustments for mixes without RAP or RAS were the following:

- The optimum binder content was determined with the goal of obtaining 4% air voids at 85 gyrations.

- The different virgin aggregate bin proportions were adjusted to match the target gradation of the reference mix as closely as possible (Figure 2.1).

Mix design adjustments for mixes with RAP and no RAS were the following:

- The binder replacement is predefined for each mix: 0%, 25%, or 50%.
- For each binder replacement level, the ratio between recycling agent and recycled binder contents (P_{RA}/P_{RB}) is determined to match the PGH of the binder blend to the PGH of the control base PG 64-16 binder (the PGH target value was 67.5°C, which is around the midpoint between 64°C and the next PGH level of 70°C). For mixes without a recycling agent, P_{RA}/P_{RB} equals 0. An upper limit of 10% binder replacement from the recycling agent was set based on the recommendation from previous work that focused on use of aromatic extract recycling agent *(5)*.
- Once the ratio P_{RA}/P_{RB} is determined, the proportions of the total binder can be determined as follows:
    a. $P_{VB}/P_B = 1- BR$
    b. $P_{RB}/P_B = BR \times 1 / (1 + P_{RA}/P_{RB})$
    c. $P_{RA}/P_B = BR \times P_{RA}/P_{RB} / (1 + P_{RA}/P_{RB})$
- The total binder content (P_B) is determined with the goal of obtaining 4% air voids at 85 gyrations.
- The amount of RAP (aggregate and binder) for laboratory mixing is determined based on the RAP binder content (P_{RB}) determined previously.
- The different virgin aggregate bin proportions are adjusted to fit the target gradation of the reference mix (Figure 2.1) after considering the contribution from the RAP aggregates.

The design of the two mixes with RAS is similar to the design of the mixes with only RAP except that the recycling agent dose is predefined and it is not enough to restore the PGH of the binder blend back to the target PGH.

2.1.1.8 Mix Design Nomenclature

Each mix in this study is referred by a composite name that includes the components and proportions of the binder blend ingredients. The mix name includes the following information:

- R_{VB}: ratio of virgin binder versus total binder [i.e., $P_{VB} / (P_{VB} + P_{RB} + P_{RA})$]
- Virgin binder PGH, preceded by the letters "PG"
- R_{RB}: ratio of recycled binder versus total binder [i.e., $P_{RB} / (P_{VB} + P_{RB} + P_{RA})$]
- RAP binder PGH, preceded by the letters "RPG"

- R_{RA}: ratio of recycling agent versus total binder [i.e., P_{RA} / (P_{VB} + P_{RB} + P_{RA})]
- Recycling agent type

Note that R_{VB} + R_{RB} + R_{RA} must equal 100%.

For example:

- The binder blend (total binder) of the mix "75% PG64, 19% RPG102, 6% Aromatic" includes:
  - 75% virgin base binder PGH 64 (25% binder replacement)
  - 19% RAP binder with PGH of 102 (RAP A)
  - 6% aromatic recycling agent
- The binder blend (total binder) of the mix "75% PG58, 25% RPG109, 0% Rej" includes:
  - 75% virgin binder PGH 58 (25% binder replacement)
  - 25% RAP binder with PGH of 109 (RAP B)
  - No recycling agent

The names of the mixes with RAS also include the ratio of recycled binder from each of RAP and RAS versus total binder. For example:

- The binder blend (total binder) of the mix "66.1% PG64, 13.3% RPG102, 14.6% RAS, 6% Aromatic" includes:
  - 66.1% virgin binder PGH 64 (33.9% binder replacement)
  - 13.3% RAP binder with PGH of 102 (RAP A)
  - 14.6% RAS binder
  - 6% aromatics as recycling agent

2.1.2 Experimental Factorial

This study was designed to address the questions formulated in Section 1.3. The first question, repeated below, was addressed by the experiment factorial shown in Table 2.1.

✓ What are the effects of the addition of high RAP content on the mechanical properties of the HMA?

Table 2.1: Experiment Factorial to Study RAP Effects on HMA Mechanical Properties

PGH	No RAP	25% Binder Replacement	
		RAP A (PGH = 102)	RAP B (PGH = 109)
64	Tested mix (control mix)	Tested mix	Tested mix[a]
58	Tested mix[a]	Tested mix	Tested mix[a]

[a] Except four-point bending stiffness and fatigue.

The second question, repeated below, was addressed by testing the virgin binders and the binder blends (virgin plus RAP) for the cases shown in Table 2.1, in addition to the RAP binders.

- ✓ Can the RAP addition effects be predicted based on testing of the blended binder?

The third and fourth questions, repeated below, were addressed by the experiment factorial shown in Table 2.2.

- ✓ What are the effects of the recycling agent addition on the mechanical properties of HMA with high RAP content?
- ✓ By using a recycling agent, can the mechanical properties of an HMA with high RAP content be restored back to the properties of the HMA with low RAP content?

Table 2.2: Experiment Factorial to Study Recycling Agent Effects on HMA Mechanical Properties

PGH	No RAP	25% Binder Replacement (RAP A)			50% Binder Replacement (RAP A)		
		No Recycling Agent	Recycling Agent: Aromatic	Recycling Agent: Tall Oil	No Recycling Agent	Recycling Agent: Aromatic	Recycling Agent: Tall Oil
64	Tested mix (control mix)	Tested mix	Tested mix	Tested mix	—[a]	Tested mix	Tested mix
58	—[a]	Tested mix	Tested mix	Tested mix	—[a]	Tested mix[b]	Tested mix[b]

[a] Mix not tested.
[b] Except four-point bending stiffness and fatigue.

The fifth of the questions, repeated below, was addressed by testing a mix with a relatively high RAS content (around 15% binder replacement in total binder) and no recycling agent and the same mix with recycling agent.

- ✓ Are there specific considerations required for the addition of RAS compared with the addition of RAP?

The sixth of the questions, repeated below, was addressed by analyzing the results of all mix and binder testing and the answers to the previous questions.

- ✓ Can mixes with 50% RAP content and/or RAS be engineered to have desired properties for different applications in the pavement structure?

The seventh and last of the questions, repeated below, was addressed by analyzing the results of all mix and binder testing and the answers to the previous questions.

- ✓ What is the recommended approach to determine the recycling agent dose?

2.2 Specimen Preparation

All constituent raw materials (virgin aggregates, RAP, RAS, virgin asphalt binder, and recycling agent) were collected from Caltrans-approved suppliers and prepared per the manufacturers' recommendations. The applicable ASTM or AASHTO standards were followed for the binder and loose mixture sampling and preparation. Two database and calculation systems, StonemontQC and the UCPRC online lab tracking system (OLTS), were used to assist in the production of the mixes and test specimens and for later access to data for analysis.

2.3 Test Methods

2.3.1 Binder Testing

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

- Performance grade (PG)
- Frequency sweep tests to evaluate binder stiffness
- Fourier transform infrared (FTIR) spectroscopy tests to track changes in binder chemistry after aging

These tests were all performed on virgin binders, binders extracted from the RAP samples, and binder blends (virgin, recycled, and, if applicable, recycling agent) blended in the laboratory.

2.3.1.1 Performance Grading

A dynamic shear rheometer was used to determine the binder high and intermediate temperature PGs. Short-term aging of the binders was simulated in the rolling thin-film oven (RTFO) at 325°F (163°C) for 85 minutes, following AASHTO T 240. Long-term aging of the binder was simulated in a pressure aging vessel (PAV) at 212°F (100°C) and 310 psi (2.07 Mpa) pressure following the AASHTO R 28 method for 20 hours. The low temperature PGs were determined on PAV-aged binders using a bending beam rheometer (BBR), following AASHTO T 313.

2.3.1.2 Frequency Sweep

A symmetric sigmoidal fit function was used to convert the frequency sweep data into a master curve at the reference temperature using the fit function in Equation 2.3. The midpoint of the temperature testing range (40°C) was selected as the reference temperature.

$$log|G^*| = \delta + \frac{\alpha}{1+e^{\beta+\gamma log\omega f_r}} \quad \textbf{(2.3)}$$

Where:

$|G^*|$: magnitude of complex shear modulus (kPa)

α: fitting parameter (the high asymptote of the master curve)

δ: fitting parameter (the lower asymptote of the master curve)

β, γ: fitting parameters (the slope of the transition region of the master curve)

ω: frequency (Hz)

f_r: reduced frequency, which is the shifted frequency at the reference temperature from the frequency at the test temperature (Hz)

The reduced frequency in Equation 2.3 can be calculated using the time-temperature superposition (Equation 2.4) and the Arrhenius equation (Equation 2.5).

$$logf_r = logf + log\alpha_T \quad \textbf{(2.4)}$$

$$log\alpha_T = \frac{E_a}{R(ln10)}\left(\frac{1}{T} - \frac{1}{T_r}\right) \quad \textbf{(2.5)}$$

Where:

f: frequency sweep test loading frequency (Hz)

α_T: shift factor as a function of temperature in Kelvin (°K)

E_α: activation energy (J/mol)

T: test temperature (°K)

T_r: reference temperature (°K)

R: ideal gas constant, 8.314 J/(°K mol)

Measured dynamic moduli can be horizontally shifted into a single master curve at the reference temperature using the above equations. The shift factor (αT) can be determined using the solver function in Excel by minimizing the sum of squares error between the predicted and measured dynamic moduli. Figure 2.3 and Figure 2.4 show examples of the fitting procedure.

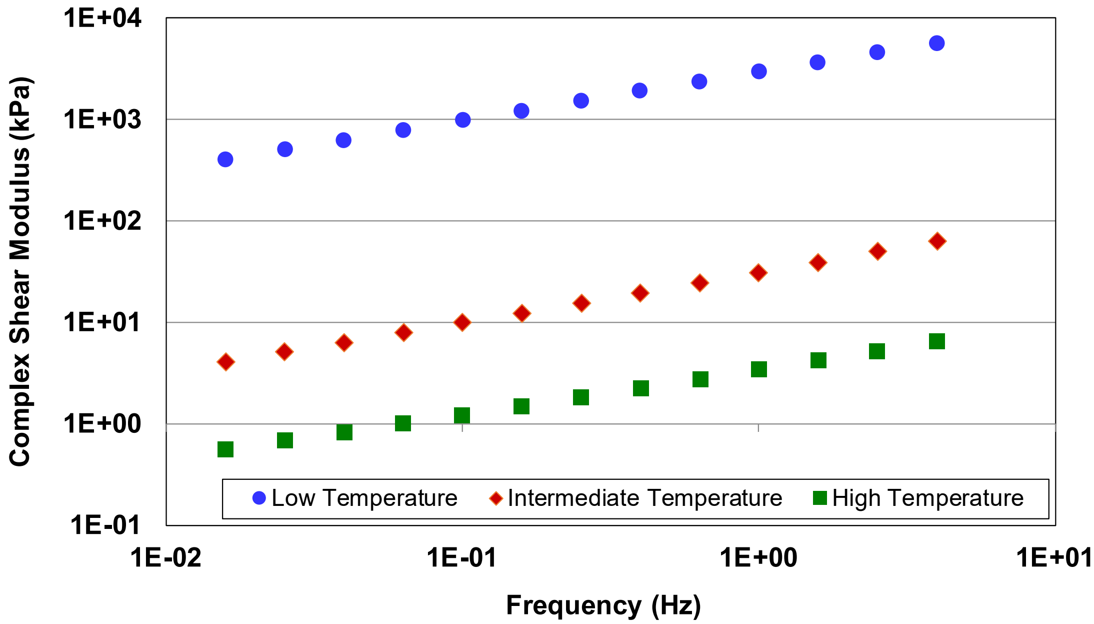


Figure 2.3: Example of modulus master curves (plotted by frequency at tested temperature).

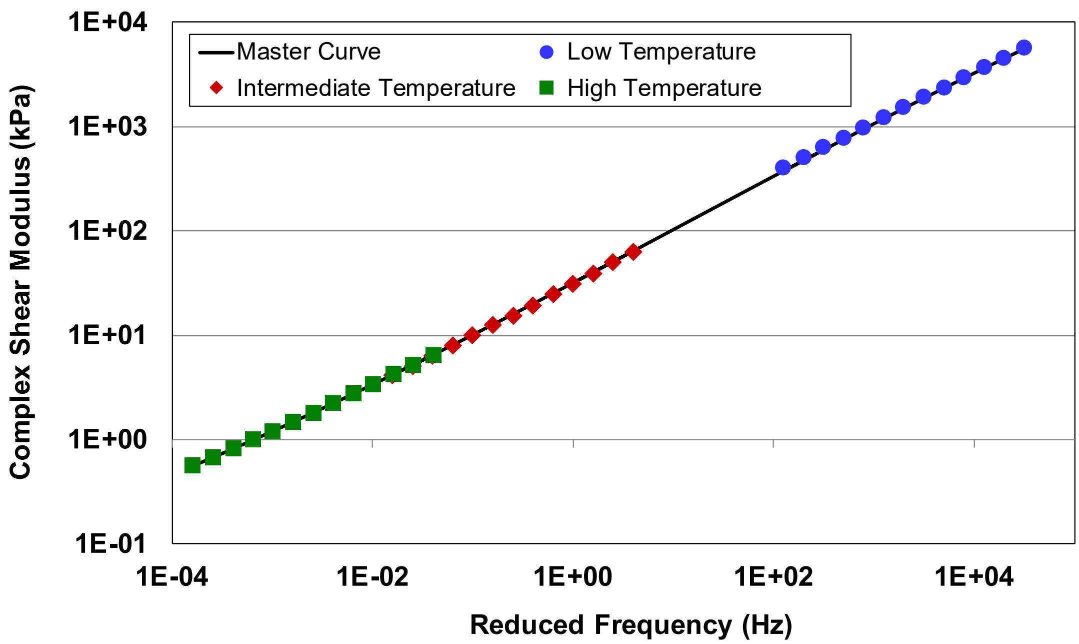


Figure 2.4: Example of modulus master curves (plotted by shifted frequency).

Several other aging parameters were calculated using the G* and δ values, shown in Table 2.3.

Table 2.3: Summary of Rheological Aging Parameters

Parameters	Definition/Source	Expected Effect of Aging
Glover-Rowe (GR)	$GR = \frac{G^* cos^2\delta}{sin\delta}$ at 15°C and 0.005 rad/sec	Increase
Complex modulus (G*)	At 64°C and 10 Hz	Increase
Crossover modulus (Gc)	Complex modulus value (G*) at $\delta = 45°$	Decrease

2.3.1.3 Fourier Transform Infrared Spectroscopy

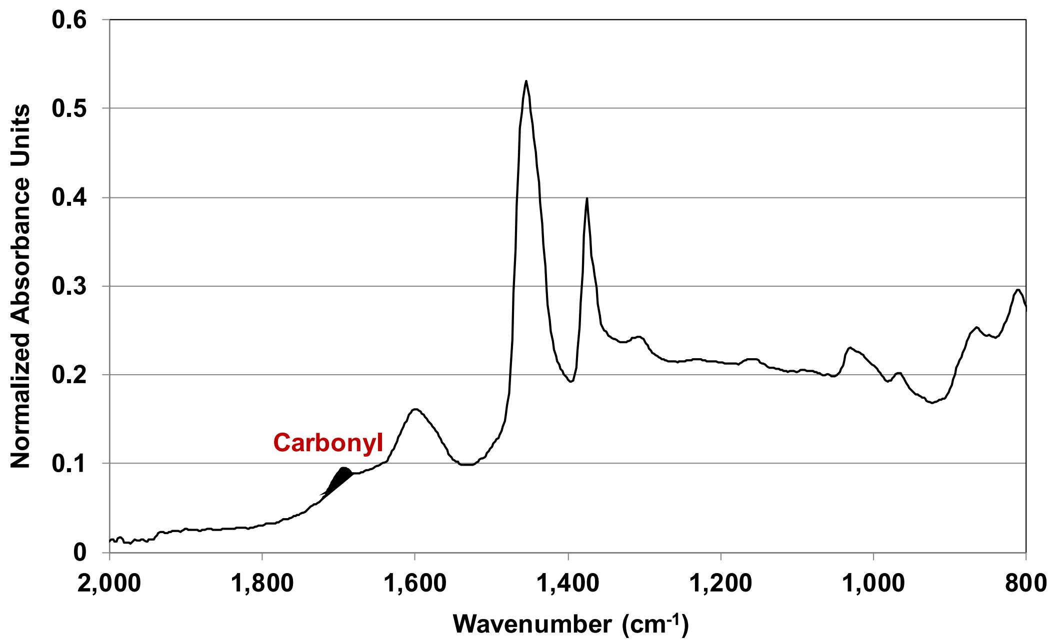
Chemical component changes in the control and blended binders were evaluated using Fourier transform infrared spectroscopy with attenuated total reflection (FTIR-ATR). The spectra measured by the FTIR were recorded in a reflective mode, from 4,000 to 400 cm^{-1}, at a resolution of 4 cm^{-1}. Each measurement included 24 scans, and an average value was recorded. Nine replicate measurements were taken to ensure that representative measurements were collected for each binder sample. The carbonyl component was used to track oxidative aging, which is usually defined by the peak at 1,680 cm^{-1} *(10)*. The tangential integration of the component area index was calculated between the upper and lower wavenumbers (1,675 and 1,750 cm^{-1}).

The spectra were normalized using the aliphatic band at 2,923 cm^{-1} to eliminate any variability introduced by the operator and any background impacts between repeat measurements. This aliphatic band structure is not affected by aging over time *(10)*. The chemical component area index was then integrated from the normalized spectra using Equation 2.6. Figure 2.5 shows an example of a spectrum and the respective component.

$$I_i = \int_{w_{l,i}}^{w_{u,i}} a(w)dw - \frac{a(w_{u,i})+a(w_{l,i})}{2} \times (w_{u,i} - w_{l,i}) \quad \textbf{(2.6)}$$

Where:

- I_i: index of area i
- $w_{l,i}$: lower wavenumber integral limit of area i
- $w_{u,i}$: upper wave number integral limit of area i
- $a(w)$: absorbance as a function of wavenumber



Note: Plot shows tangential integration with carbonyl areas.

Figure 2.5: Example of normalized FTIR absorbance spectrum.

2.3.2 Mix Testing

Mix testing included the following (the following discussion includes an overview of the methods and data interpretation):

- Axial dynamic modulus test (AASHTO T 378; specimens prepared in a gyratory compactor)
- Flexural dynamic modulus test (AASHTO T 321; specimens prepared using a rolling wheel compactor)
- Flexural fatigue cracking test (AASHTO T 321; specimens prepared using a rolling wheel compactor)
- Indirect tensile cracking test (ASTM D 8225; specimens prepared in a gyratory compactor)
- Repeated load test (AASHTO T 378; specimens prepared in a gyratory compactor)
- Hamburg Wheel-Tracking test (AASHTO T 324; specimens prepared in a gyratory compactor)

2.3.2.1 Test Specimen Air Void Contents

The bulk densities of the IDEAL-CT and HWT test specimens were determined according to AASHTO T 166 (saturated surface-dry [SSD] method). The bulk densities of the beams and AMPT specimens were determined according to AASHTO T 331 (CoreLok). Theoretical maximum specific gravity (Gmm) was determined according to AASHTO T 209. All specimens for all tests were compacted to 7% air voids with a 0.5% tolerance around that target.

2.3.2.2 Axial Dynamic Modulus Test

Axial dynamic modulus testing followed AASHTO T 378 using an AMPT with specimens prepared in a gyratory compactor. Specimens were tested at 39°F, 70°F, 100°F, and 129°F (4°C, 21°C, 38°C, and 54°C) and at frequencies between 25 and 0.1 Hz. Measured dynamic moduli were horizontally shifted into a master curve at 20°C using Equation 2.2 and Equation 2.3 and the Williams-Landel-Ferry shift function, shown in Equation 2.7.

$$log(\alpha_T) = \frac{-C_1(T-T_r)}{C_2+(T-T_r)} \quad \textbf{(2.7)}$$

Where:

- α_T: shift factor as a function of temperature T
- T: test temperature in Kelvin (°K)
- T_r: reference temperature in Kelvin (°K)
- C_1 and C_2: fitting parameters

2.3.2.3 Flexural Dynamic Modulus Test

Flexural beam frequency sweep testing followed AASHTO T 321 using a beam fatigue apparatus and beams prepared using a rolling wheel compactor. Specimens were tested at 50°F, 68°F, and 86°F (10°C, 20°C, and 30°C) and at frequencies between 15 and 0.01 Hz. A sinewave function was applied to produce a tensile strain of 100 µstrain on the longitudinal surface of the beam. The measured stiffnesses were horizontally shifted into master curves at 68°F (20°C) using Equations 2.2, 2.3, and 2.5.

2.3.2.4 Flexural Fatigue Cracking Resistance Test

Fatigue cracking resistance testing followed AASHTO T 321 on beams prepared using a rolling wheel compactor. Beam specimens were subjected to four-point bending by applying sinusoidal loading at three different strain levels (high, intermediate, and low) at a frequency of 10 Hz and temperature of 68°F (20°C). The fatigue life for each strain level was selected at the maximum of the stiffness times number of cycles, following AASHTO T 321.

In this study, the testing approach currently specified in AASHTO T 321 was modified to optimize the quantity and quality of the data collected. Replicate specimens were first tested at high and medium strain levels to develop an initial regression relationship between fatigue life and strain (Equation 2.8). Strain levels were selected, based on experience, to achieve fatigue lives between 10,000 and 100,000 load cycles for high strains and between 300,000 and 500,000 load cycles for medium strains. Additional specimens were then tested at lower strain levels, selected based on the results of the initial linear regression relationship to achieve a fatigue life of about 1 million load repetitions. The final regression relationship was then refined to accommodate the measured stiffness at the lower strain level.

$$Log(N) = A + B \; x \; log(\varepsilon) \quad \textbf{(2.8)}$$

Where:

N: fatigue life (number of cycles)

ε: strain level (μstrain)

A and *B:* model parameters

Test results can also be used to generate the material fatigue response in the *CalME* simulations when used with flexural stiffness master curves to calculate estimated strains in the pavement. Flexural fatigue results can be directly compared without *CalME* simulations when taking into consideration the fact that laboratory test results will generally correspond with field fatigue or reflective cracking performance for overlays thinner than about 0.2 ft. (62 mm) but may not correspond with expected field performance for thicker layers of asphalt. For thicker layers, the interaction of the pavement structure, traffic loading, temperature, and mix stiffness with the controlled-strain beam fatigue results needs to be simulated using mechanistic analysis to rank mixes for expected field performance.

2.3.2.5 Indirect Tensile Cracking Test (IDEAL-CT Test)

The IDEAL-CT test uses a loading apparatus and specimen fixture, shown in Figure 2.6. A loading rate of 50 mm/min was applied until the tested specimen reached failure. An example of a test result from the IDEAL-CT test is shown in Figure 2.7.

Figure 2.6: Testing machine for IDEAL cracking test with a specimen.

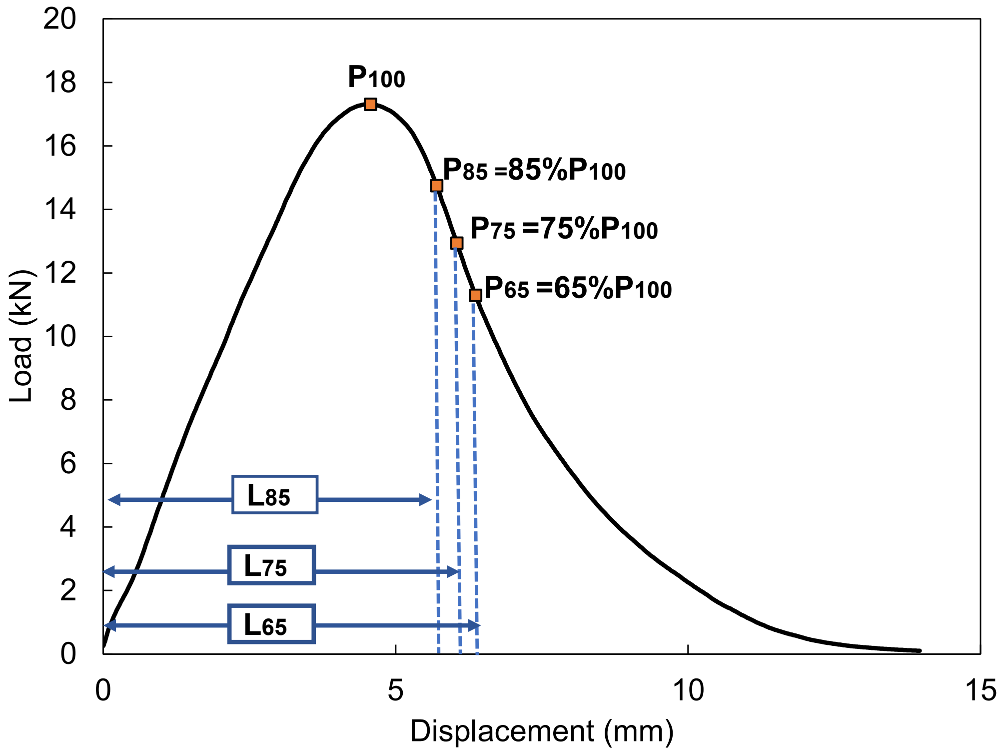


Figure 2.7: Example load-displacement curve from IDEAL-CT test.

Fracture parameters obtained from the IDEAL-CT test are shown in Table 2.4, along with definitions. The two parameters of primary interest are the *Cracking Tolerance Index* (CT_{Index}), which is intended to relate to cracking and which the UCPRC has found correlates very well with flexural stiffness at 10 Hz and 68°F (20°C), and the *Strength* parameter, which has also been found to have a strong correlation with flexural stiffness but half the test variability of the CT_{Index}.

Table 2.4: Fracture Parameters from IDEAL-CT Test

Parameters	Equations
$\|m_{75}\|$: post-peak slope (N/m)	$\|m_{75}\| = \left\|\frac{P_{85} - P_{65}}{l_{85} - l_{65}}\right\|$ Where: P_{85} = 85% of peak load P_{65} = 65% of peak load l_{85} = deformation at P_{85} l_{65} = deformation at P_{65}
l_{75} (mm)	Displacement at 75% of the peak load after the peak
G_f: failure energy (J/m^2)	$G_f = \frac{W_f}{D \times t} \times 10^6$ Where: W_f = area under load-displacement curve (J) $t = thickness\ (mm)$ $D = diameter\ (mm)$
CT_{Index}: *Cracking Tolerance Index*	$CT_{Index} = \frac{t}{62} \times \frac{l_{75}}{D} \times \frac{G_f}{\|m_{75}\|} \times 10^6$
Strength	$Strength = \frac{Peak\ load}{2rt}$

2.3.2.6 Repeated Load Test

Permanent deformation resistance testing followed AASHTO T 378 using an AMPT with specimens prepared in a gyratory compactor. The RLT parameters assessed included flow number and the number of cycles to reach 5% permanent axial strain. Specimens were tested with no confinement and with 5 psi (35 kPa) confinement under a deviator stress of 70 psi (483 kPa) at 122°F (50°C).

2.3.2.7 Hamburg Wheel-Tracking Test

Permanent deformation and moisture resistance testing with the Hamburg Wheel-Tracking (HWT) apparatus followed AASHTO T 324 with specimens prepared in a gyratory compactor. The HWT parameters assessed included the number of cycles to 0.5 in. (12.5 mm) and the rutting after 15,000 cycles. Specimens were tested at 122°F (50°C).

3 EXPERIMENT MIX DESIGNS

This study is based on the reference mix design described in Section 2.1.1.1, corresponding to an HMA with a ½ in. nominal maximum aggregate size. This reference mix design was adjusted to fabricate each of the different mixes evaluated in this research. The mix design adjustment included changes to the virgin aggregate bin proportions to accommodate the different levels of RAP/RAS and changes to the asphalt binder content, as explained in Chapter 2, with details in the following discussion.

The target gradation of the combined aggregate blend (virgin aggregates + RAP/RAS aggregates) is kept constant for the different mixes that were evaluated in this research. The target gradation is shown in Figure 2.1. As the different mixes included different percentages of RAP and RAS, the proportions of the different virgin aggregate bins had to be adjusted to match the target gradation. The resulting bin proportions for the different mixes that were evaluated in this research are shown in Table 3.1, and the corresponding aggregate gradations are shown in Figure 3.1 (mixes with PGH 64 and no RAS), Figure 3.2 (mixes with PGH 64 and RAS), and Figure 3.3 (mixes with PGH 58). All mixes fall within Caltrans specification limits and mix-to-mix differences are relatively small and expected to have very small effects on the test results.

Table 3.1: Aggregate Bin Combinations

Mix #	Mix ID	Aggregate Bins							
		1/2" (%)	3/8" (%)	1/4" × Dust Washed (%)	1/4" × Dust (%)	Washed Passing #50 (%)	Washed Passing #100 (%)	3/8" RAP (%)	RAS (%)
1	100% PG64, 0% RAP, 0% Rej	16.5	31.4	45.7	0.0	2.4	4.0	0.0	0.0
2	100% PG58, 0% RAP, 0% Rej	20.8	22.2	0.0	57.0	0.0	0.0	0.0	0.0
3	75% PG64, 25% RPG102, 0% Rej	18.1	13.9	32.0	0.0	4.0	0.0	32.0	0.0
4	75% PG58, 25% RPG102, 0% Rej	25.3	5.9	0.0	35.5	0.0	0.0	33.3	0.0
5	75% PG64, 25% RPG109, 0% Rej	23.6	14.0	0.0	34.1	0.3	0.0	28.0	0.0
6	75% PG58, 25% RPG109, 0% Rej	23.6	14.0	0.0	34.1	0.3	0.0	28.0	0.0
7	75% PG64, 19% RPG102, 6% Aromatic	18.6	15.7	35.7	0.0	4.0	0.0	26.0	0.0
8	75% PG58, 21% RPG102, 4% Aromatic	25.2	11.8	0.0	33.7	0.3	0.0	29.0	0.0
9	75% PG64, 21.8% RPG102, 3.2% TallOil	24.1	4.8	0.0	0.0	0.0	0.0	32.1	0.0
10	75% PG58, 22.5% RPG102, 2.5% TallOil	26.9	0.3	39.7	0.0	0.0	0.0	33.1	0.0

Mix #	Mix ID	Aggregate Bins							
		1/2" (%)	3/8" (%)	1/4" × Dust Washed (%)	1/4" × Dust (%)	Washed Passing #50 (%)	Washed Passing #100 (%)	3/8" RAP (%)	RAS (%)
15	50% PG64, 40% RPG102, 10% Aromatic	16.4	4.5	27.1	0.0	0.0	0.0	52.0	0.0
16	50% PG58, 40% RPG102, 10% Aromatic	14.3	4.5	0.0	26.8	0.0	0.0	58.9	0.0
17	50% PG64, 41.9% RPG102, 8.1% TallOil	8.0	3.2	0.0	20.6	0.0	0.0	68.2	0.0
18	50% PG58, 41.7% RPG102, 8.3% TallOil	15.9	0.0	0.0	22.7	0.0	0.0	61.4	0.0
23	65.7% PG64, 19.1% RPG102, 15.2% RAS	16.5	20.8	29.1	0.0	5.6	0.0	25.0	3.0
24	66.1% PG64, 13.3% RPG102, 14.6% RAS, 6% Aromatic	16.4	24.4	31.6	0.0	6.7	0.0	18.0	3.0

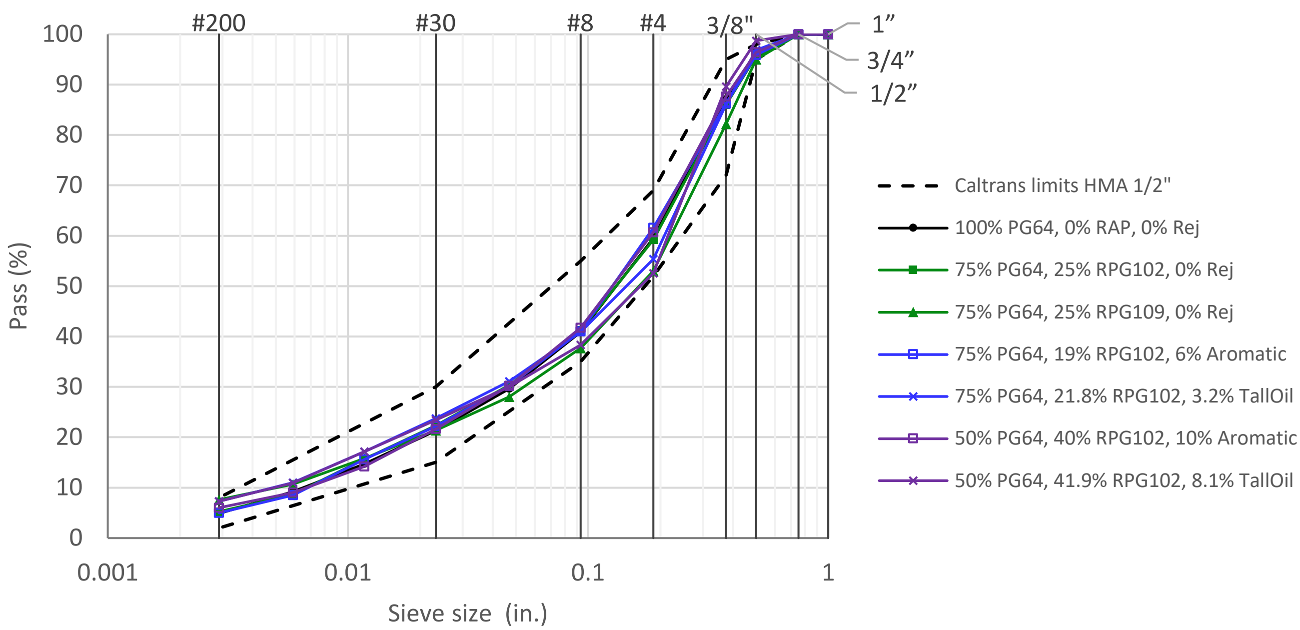


Figure 3.1: Aggregate gradations – Mixes with PGH 64 and no RAS.

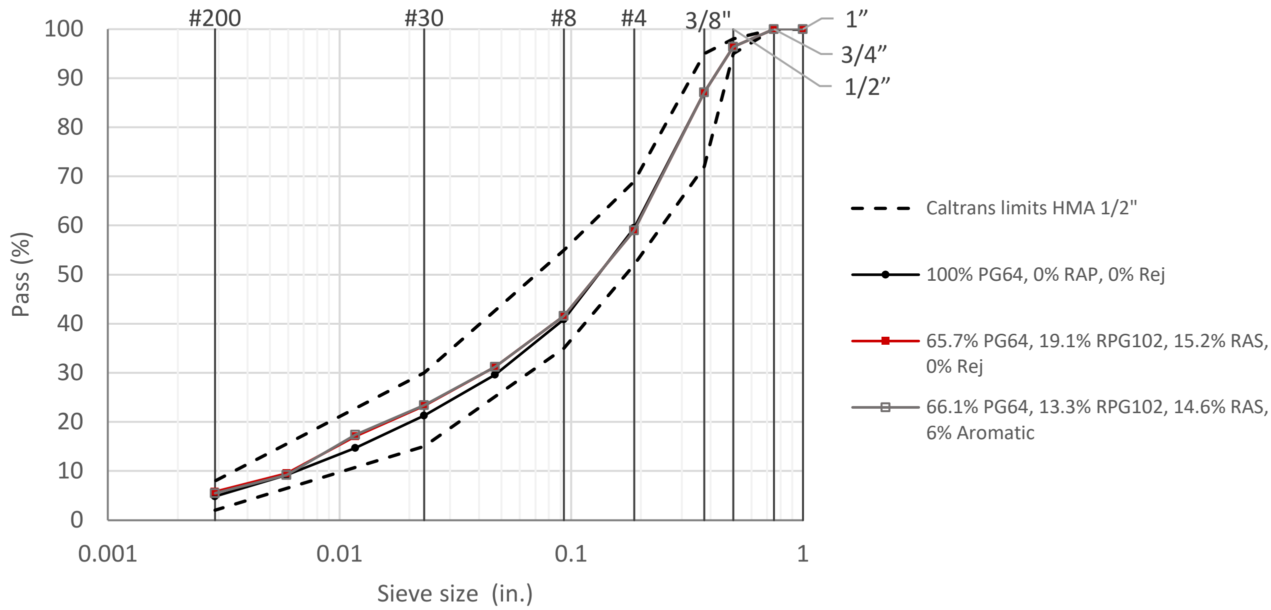


Figure 3.2: Aggregate gradations—mixes with PGH 64 and RAS.

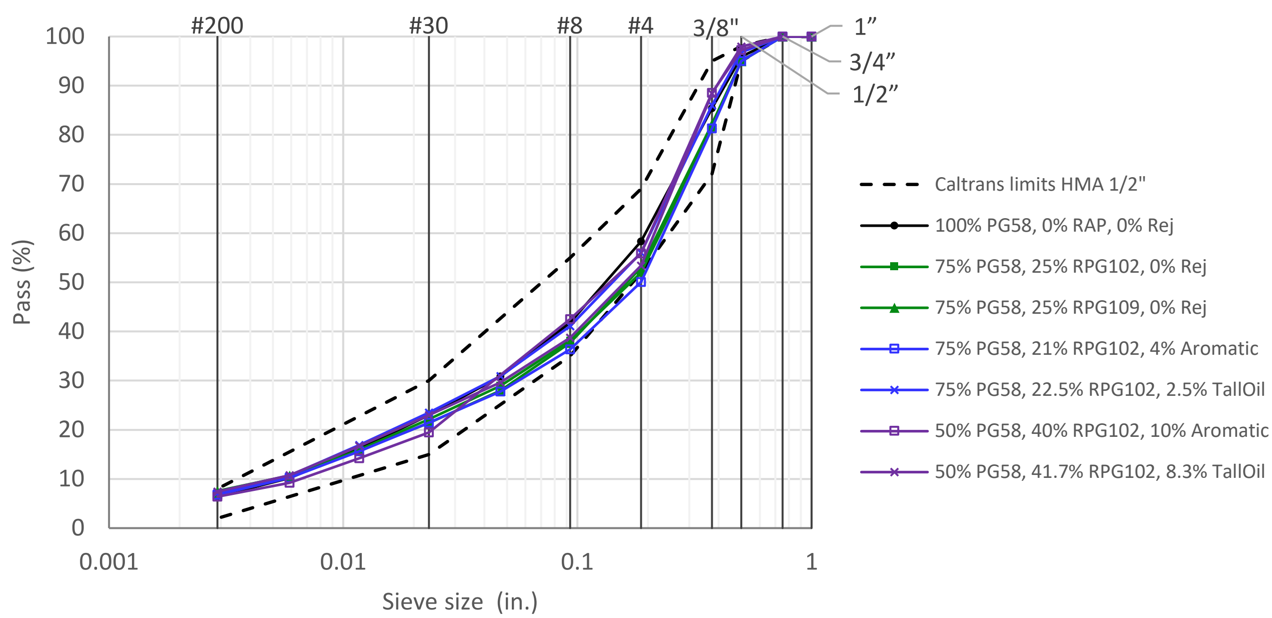


Figure 3.3: Aggregate gradations—mixes with PGH 58.

As explained in Chapter 2 (Section 2.1.1.7), the total binder content of each mix (P_B) was determined with the goal of obtaining 4% air voids at 85 gyrations (N_{Design}). The total binder (P_B) includes the virgin binder and, if applicable, the binder from the RAP/RAS and the recycling agent. The resulting P_B values, shown in Table 3.2, were approximately 0.4% (TWM) higher than the reference plant mix. This difference can be attributed to reduced RAP and virgin aggregate breakdown in the laboratory mixing process compared with the plant mixing, which affected the gyratory compaction results. Table 3.2 also shows some Superpave mix design information, including air voids (Va) under laboratory compaction, voids in mineral aggregate (VMA), and the percent passing the #200 (0.075 mm) sieve.

As explained in Section 2.1.1.7, the recycling agent dose was determined with the goal of restoring the PGH of the binder blend back to that of the PG 64 grade control binder, based on binder blends prepared in the laboratory, by blending the virgin binder, the binder extracted and recovered from the RAP/RAS, and the corresponding recycling agent. In practice, the recycling agent dose was such that the PGH of the binder blend was 67.5°C. For example, Mix #7 (75% PG 64, 19% RPG 102, 6% Aromatic)—a blend of 75% PG 64-16 virgin binder, 19% binder extracted from RAP A (Southern California with PGH of 102°C), and 6% aromatic recycling agent—will have a PGH of 67.5°C. Consequently, the high temperature PG grade of the binder blend will be PG 64.

Table 3.2: Mix Design Information

Mix #	Mix Id	Virgin Agg. (%)	RAP/ RAS Agg. (%)	Mixture		Volumetrics @ 85 Gyrations				Pass #200 (%)
				P_B (%)	Gmm	Va, SSD (%)	Va, Paraffin (%)	VMA, SSD (%)	VMA, Paraffin (%)	
1	100% PG64, 0% RAP, 0% Rej	100.0	0.0	5.4	2.471	4.4	—	15.0	—	4.8
2	100% PG58, 0% RAP, 0% Rej	100.0	0.0	5.4	2.482	1.2	1.2	12.6	12.6	6.5
3	75% PG64, 25% RPG102, 0% Rej	68.0	32.0	5.5	2.490	3.5	—	14.5	—	5.3
4	75% PG58, 25% RPG102, 0% Rej	66.7	33.3	5.5	2.490	1.3	1.3	11.5	11.5	6.8
5	75% PG64, 25% RPG109, 0% Rej	72.0	28.0	5.5	2.472	0.9	0.8	13.3	13.2	7.6
6	75% PG58, 25% RPG109, 0% Rej	72.0	28.0	5.5	2.474	1.2	1.0	13.5	13.3	7.6
7	75% PG64, 19% RPG102, 6% Aromatic	74.0	26.0	5.7	2.470	3.7	—	15.9	—	5.0
8	75% PG58, 21% RPG102, 4% Aromatic	71.0	29.0	5.7	2.483	—	—	—	—	6.8
9	75% PG64, 21.8% RPG102, 3.2% TallOil	67.9	32.1	5.7	2.476	—	—	—	—	7.3
10	75% PG58, 22.5% RPG102, 2.5% TallOil	66.9	33.1	5.7	2.484	1.3	1.2	12.0	11.9	7.2
15	50% PG64, 40% RPG102, 10% Aromatic	48.0	52.0	5.5	2.484	3.1	—	13.9	—	6.0
16	50% PG58, 40% RPG102, 10% Aromatic	41.1	58.9	5.5	2.473	1.1	1.5	11.2	11.5	6.4
17	50% PG64, 41.9% RPG102, 8.1% TallOil	31.8	68.2	5.5	2.476	0.8	0.7	10.4	10.4	7.3
18	50% PG58, 41.7% RPG102, 8.3% TallOil	38.6	61.4	5.5	2.474	0.5	0.6	10.5	10.5	7.4
23	65.7% PG64, 19.1% RPG102, 15.2% RAS	72.0	28.0	5.5	2.480	1.9	—	14.8	—	5.8
24	66.1% PG64, 13.3% RPG102, 14.6% RAS, 6% Aromatic	79.0	21.0	5.7	2.465	1.1	—	14.8	—	5.5

4 BLENDED BINDER TESTING RESULTS

This chapter discusses the binder testing results from virgin base binders, the RAP binders, and the blended binders produced in the laboratory following the same ratio of virgin binder, RAP binder, and recycling agent as was present in the mix, assuming complete blending in the mix. It should be noted that, in the binder blends, complete blending of the virgin binder, RAP binder, and recycling agent is expected and that this complete diffusion may not have occurred in the mix at the time of testing. For this chapter, the 'R', 'RAS', and 'RJ' represent the % of RAP, % of RAS, and % of recycling agent, respectively. As discussed earlier, two different RAP sources were considered for this study and are denoted as RAP(A) and RAP(B). The aromatic and tall oil-based recycling agents are denoted as RJ(a) and RJ(b), respectively. For example, "PG64+R13.3(A)+RAS14.6+RJ6(a)" represents the binder blend with the virgin binder 1 (PG 64-16) containing 13.3% RAP(A), 14.6% RAS, and 6% aromatic-based recycling agent.

4.1 PG Grading

Table 4.1 summarizes the true grades of the control binders, RAP and RAS binders, and blended binders at high, intermediate, and low temperatures, as specified in AASHTO M 320. The continuous high temperature grade is defined as the lowest temperature at which the unaged binder's G*/sin(δ) value equals 1.00 kPa and the temperature at which the RTFO-aged binder's G*/sin(δ) value equals 2.20 kPa. Intermediate temperature grading is defined as the temperature where the 20-hour PAV-aged binder's G*×sin(δ) values equal the maximum allowable stiffness of 5,000 kPa. Low temperature grading is defined as the highest of the following two temperatures using 20-hour PAV-aged binder: (1) the temperature where the creep stiffness of 300 MPa occurs or (2) the temperature where an m-value of 0.300 occurs.

Table 4.1 and the plots for high temperature grades (Figure 4.1 and Figure 4.2) show that an increase in RAP/RAS content increased the continuous grade for all cases. For example, the continuous high temperature grade for PG64 Virgin was 65.3°C. An increase of about 9°C in high temperature was observed due to the addition of 25% RAP(A) to PG64 Virgin (the PG64+R25(A) blend). Also, the extracted binder from RAP(B) showed higher stiffness compared with RAP(A) as indicated by the high temperature PGs. The continuous high temperature grades observed for the extracted binders from RAP(A) and RAP(B) were 101.9°C and 108.5°C, respectively. Therefore, the addition of RAP(B) is expected to cause greater stiffness for the binder blends compared with RAP(A).

The high temperature grades found for the PG64+R25(A) and PG64+R25(B) blends were 74.8°C and 77.3°C, respectively. Therefore, about 2.5°C greater high PG was observed when using RAP(B) instead of RAP(A) with the same control binder (PG 64) and the same amount of binder replacement (25%). Adding RAS had a greater effect on the continuous grade than adding RAP, as expected, considering the types of asphalt binders used in shingles (harder than paving binders) and the extended aging they typically experience on roofs. Adding 15% RAS binder with 19% RAP binder to PG 64 resulted in a high temperature grade (83.2°C) similar to the 50% RAP blend (83.0°C) with the same base binder. This finding is mainly attributed to the higher degree of aging of the RAS materials. An increased high temperature true grade indicates better rutting performance at high temperatures, which is the intent of the PG grading high temperature specification. Therefore, an increase in the RAP/RAS amount is expected to increase the rutting performance of asphalt mixes. Similar findings were also reported by other researchers *(6,7,12,13)*.

A reduction in binder high temperature grade was observed with an increase in recycling agent content. The recycling agent dosages were selected to maintain the high temperature PG of binder blends as close to that of the control base binder (PG64 Virgin) as possible. Also, an upper limit of 10% recycling agent by weight of the total binder was maintained to ensure workability, as mentioned previously. In this study, a 6% addition of aromatic-based RJ(a) was found to reduce the continuous high temperature grade to 66.8°C for the PG64+R19(A)+RJ6(a) blend. The high temperature grade for the PG64+R25(A) blend without recycling agent and with the same amount of binder replacement (25%) was 74.8°C. Therefore, an 8°C reduction in binder continuous high temperature was found for the binder blend after adding the RJ(a) recycling agent. A similar trend was also observed for other binder blends.

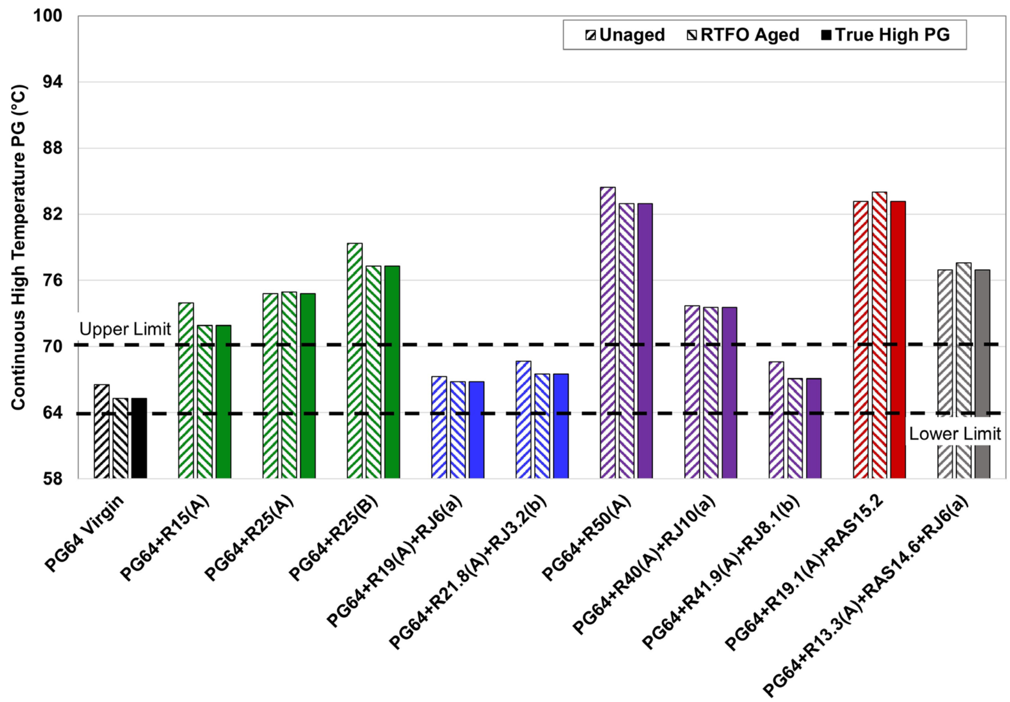
The efficiency of the tall oil-based recycling agent [RJ(b)] was found to be greater compared with the aromatic-based recycling agent [RJ(a)]. The true high temperature grades found for the PG64+R40(A)+RJ10(a) and PG64+R41.9(A)+RJ8.1(b) blends were 73.6°C and 67.1°C, respectively. Therefore, 10% use of RJ(a) was found to result in 6.5°C greater continuous high temperature compared with the use of 8.1% of RJ(b) for the same base binder (PG 64) at 50% binder replacement. Other researchers have also reported greater efficiency for tall oil-based recycling agents compared with aromatic-based recycling agents *(5)*. A high continuous temperature of 77.0°C was observed for the PG64+R13.3(A)+RAS14.6+RJ6(a) blend. For this blend, only 6% of aromatic-based recycling agent was used to lower the high temperature PG. Therefore, a greater dosage of tall oil-based recycling agent is required for the PG64+R13.3(A)+RAS14.6+RJ6(a) blend to match the high PG of the control binder (PG 64).

As expected, lower dosages of recycling agents are required for blends with PG 58 compared with PG 64. The high true grades found in the laboratory for PG 64 and PG 58 base binders were 65.3°C and 61.8°C, respectively. The amount of tall oil-based recycling agent required to get a high temperature grade similar to the control binder (PG 64) for the PG64+R21.8(A)+RJ3.2(b) and PG58+R22.5(A)+RJ2.5(b) blends with RAP(A) were 3.2% and 2.5%, respectively. About 0.7% less RJ(b) showed a similar high temperature true grade for the PG 58 blend compared with the PG 64 blend. Also, the unaged high temperatures were higher compared with RTFO-aged high temperatures for most of the PG 64 blends. For example, the unaged and RTFO-aged high temperatures found for the PG64+R25(B) blend were 79.4°C and 77.3°C, respectively. On the other hand, the unaged high temperatures were lower compared with the RTFO-aged high temperatures for most of the PG 58 blends. For example, the unaged and RTFO-aged high temperatures for the PG58+R25(B) blend were 76.9°C and 79.0°C, respectively. This is mainly attributed to the higher aging susceptibility of the PG58 Virgin binder used in this study compared with the PG64 Virgin binder, which were from different binder producers.

Table 4.1: True Binder Grading Results for All Binder Blends

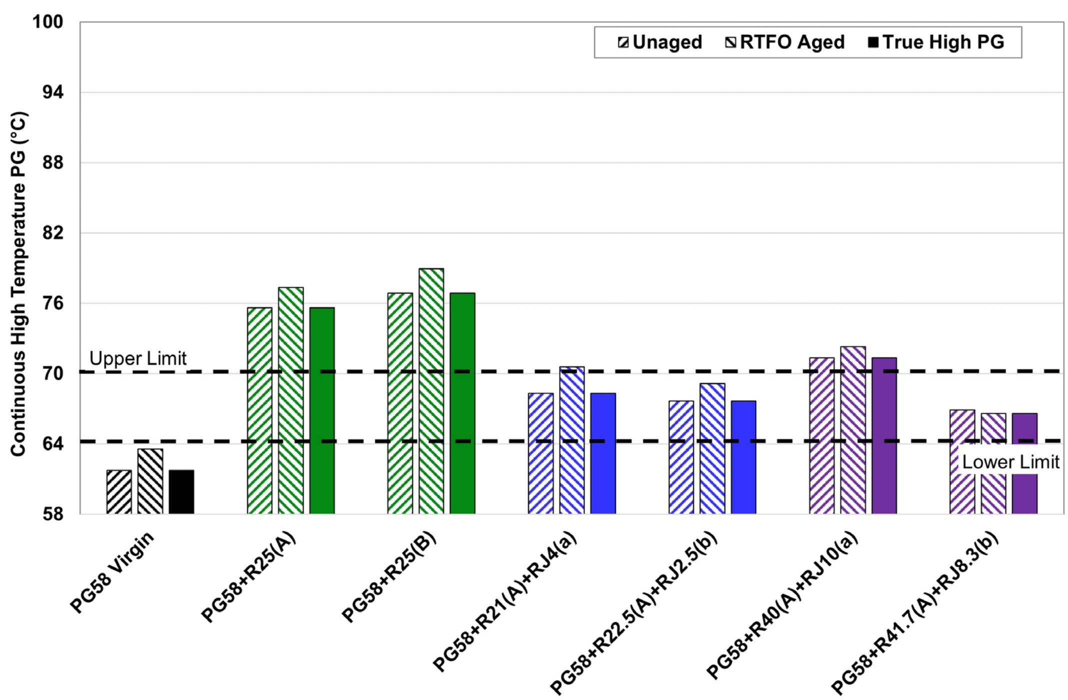
Blend ID	Correspondin g Mix Number	Unaged High PG (°C) (G*/sin δ = 1 kPa)	RTFO-Aged High PG (°C) (G*/sin δ = 2.2 kPa)	Continuous High Temp. PG (°C) (Minimum Between Unaged and RTFO Aged)	Inter. Temp. PG (°C)	Continuous Temp. from Stiffness (PAV 20) (°C)	Continuous Temp. from m-Value (PAV 20) (°C)	ΔTc (PAV 20) (°C)	Continuous Low Temp. PG (PAV 20) (°C)
RAP(A)	Not Tested	101.9	102.8	101.9	49.0	-7.9	-5.8	-2.1	-5.8
RAP(B)	Not Tested	108.8	108.5	108.5	51.1	-3.3	-1.9	-1.3	-1.9
PG64 Virgin	#1	66.6	65.3	65.3	28.7	-19.7	-21.4	1.7	-19.7
PG58 Virgin	#2	61.8	63.6	61.8	18.2	-31.5	-32.7	1.2	-31.5
PG64+R15(A)	Not Tested	74.0	71.9	71.9	31.2	-18.1	-18.2	0.1	-18.1
PG64+R25(A)	#3	74.8	75.0	74.8	32.9	-16.1	-16.8	0.7	-16.1
PG58+R25(A)	#4	75.6	77.4	75.6	24.9	-28.6	-24.0	-4.7	-24.0
PG64+R25(B)	#5	79.4	77.3	77.3	34.4	-16.6	-15.5	-1.1	-15.5
PG58+R25(B)	#6	76.9	79.0	76.9	26.2	-27.5	-22.9	-4.7	-22.9
PG64+R19(A)+RJ6(a)	#7	67.3	66.8	66.8	26.5	-19.0	-22.5	3.5	-19.0
PG58+R21(A)+RJ4(a)	#8	68.3	70.6	68.3	22.4	-29.1	-28.3	-0.7	-28.3
PG64+R21.8(A)+RJ3.2(b)	#9	68.7	67.5	67.5	27.7	-22.6	-22.4	-0.2	-22.4
PG58+R22.5(A)+RJ2.5(b)	#10	67.7	69.2	67.7	20.3	-31.8	-27.5	-4.3	-27.5
PG64+R50(A)	Not Tested	84.5	83.0	83.0	36.6	-14.6	-13.8	-0.8	-13.8
PG64+R40(A)+RJ10(a)	#15	73.7	73.6	73.6	30.7	-17.0	-19.3	2.3	-17.0
PG58+R40(A)+RJ10(a)	#16	71.4	72.3	71.4	25.9	-26.0	-25.4	-0.6	-25.4
PG64+R41.9(A)+RJ8.1(b)	#17	68.6	67.1	67.1	22.9	-27.5	-27.4	-0.1	-27.4
PG58+R41.7(A)+RJ8.3(b)	#18	66.9	66.6	66.6	16.9	-34.2	-34.2	0.0	-34.2
PG64+R19.1(A)+RAS15.2	#23	83.2	84.0	83.2	35.6	-15.6	-14.8	-0.8	-14.8
PG64+R13.3(A)+RAS14.6+RJ6(a)	#24	77.0	77.6	77.0	32.9	-19.5	-16.0	-3.5	-16.0

Notes: R(A): Southern California RAP(A) (PGH of 102°C); R(B): Inland Valley RAP(B) (PGH of 109°C); RAS: reclaimed asphalt shingles (RAS); RJ(a): aromatic-based recycling agent; RJ(b): tall oil-based recycling agent.



Notes: R(A): Southern California RAP(A) (high PG of 102°C); R(B): Inland Valley RAP(B) (high PG of 109°C); RAS: reclaimed asphalt shingles (RAS); RJ(a): aromatic-based recycling agent; RJ(b): tall oil-based recycling agent.

Figure 4.1: Continuous high temperature performance grades for blends with PG 64 base binder.



Notes: R(A): Southern California RAP(A) (high PG of 102°C); R(B): Inland Valley RAP(B) (high PG of 109°C); RAS: reclaimed asphalt shingles (RAS); RJ(a): aromatic-based recycling agent; RJ(b): tall oil-based recycling agent.

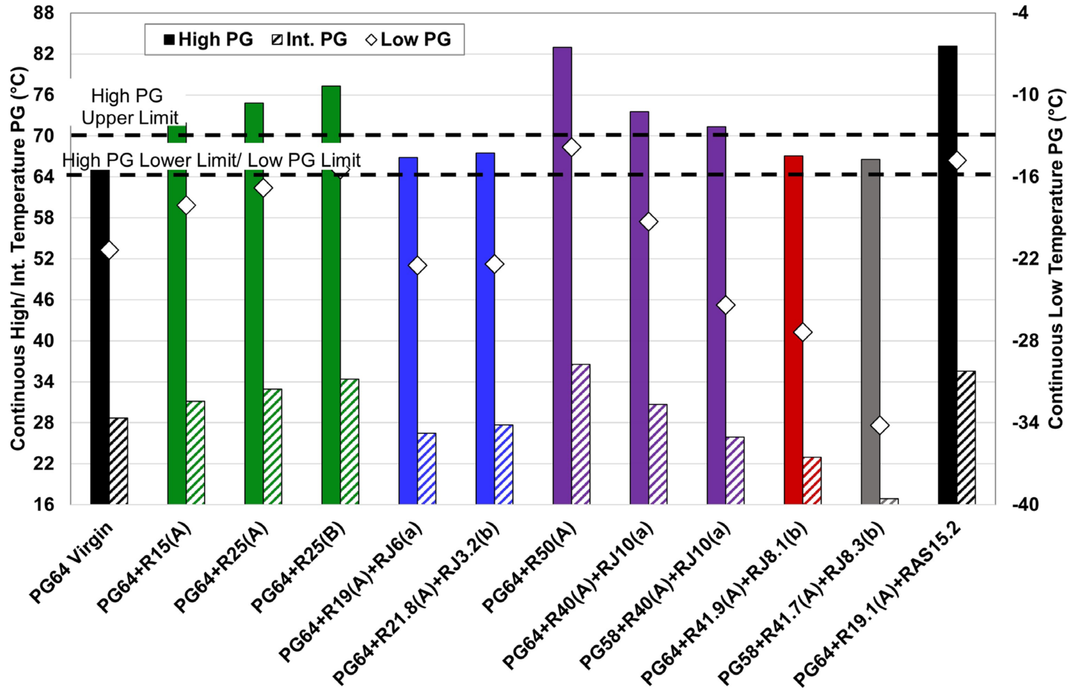
Figure 4.2: Continuous high temperature performance grades for blends with PG 58 base binder.

Figure 4.3 and Figure 4.4 show the high, intermediate, and low continuous grades for blends with PG 64 and PG 58 base binders, respectively. The intermediate temperatures were found to increase with an increase in RAP content. However, an increase in recycling agent dosages was found to counteract the effect of RAP content on intermediate temperature PGs. A higher intermediate binder true grade temperature indicates that the mix will be stiffer at intermediate temperatures, which for thin overlays will often produce lower fatigue and reflective cracking resistance. Therefore, the addition of RAP is expected to show lower fatigue resistance for thin overlays. Also, base binder 2 (PG 58) showed a much lower intermediate temperature compared with the control base binder (PG 64). The intermediate true grades found for the PG 64 and PG 58 base binders were 28.7°C and 18.2°C, respectively. Therefore, blends with PG 58 base binders are expected to show better fatigue resistance for thin structures.

The tall oil-based recycling agent [RJ(b)] showed a greater decrease in intermediate temperatures compared with the aromatic-based recycling agent [RJ(a)] for the dosage rates that had been set based on matching the high temperature grade of the control binder. The intermediate temperatures found for the PG58+R21(A)+RJ4(a) and PG58+R22.5(A)+RJ2.5(b) blends were 22.4°C and 20.3°C, respectively. Therefore, the tall oil-based recycling agent was found to show greater efficiency in improving the intermediate temperature. The addition of RAP(B) resulted in a slightly greater intermediate true grade compared with RAP(A). The intermediate temperatures obtained for the PG64+R25(A) and PG64+R25(B) blends were 32.9°C and 34.4°C, respectively. A similar effect was observed for both high and intermediate temperature grades with the addition of RAP and recycling agent.

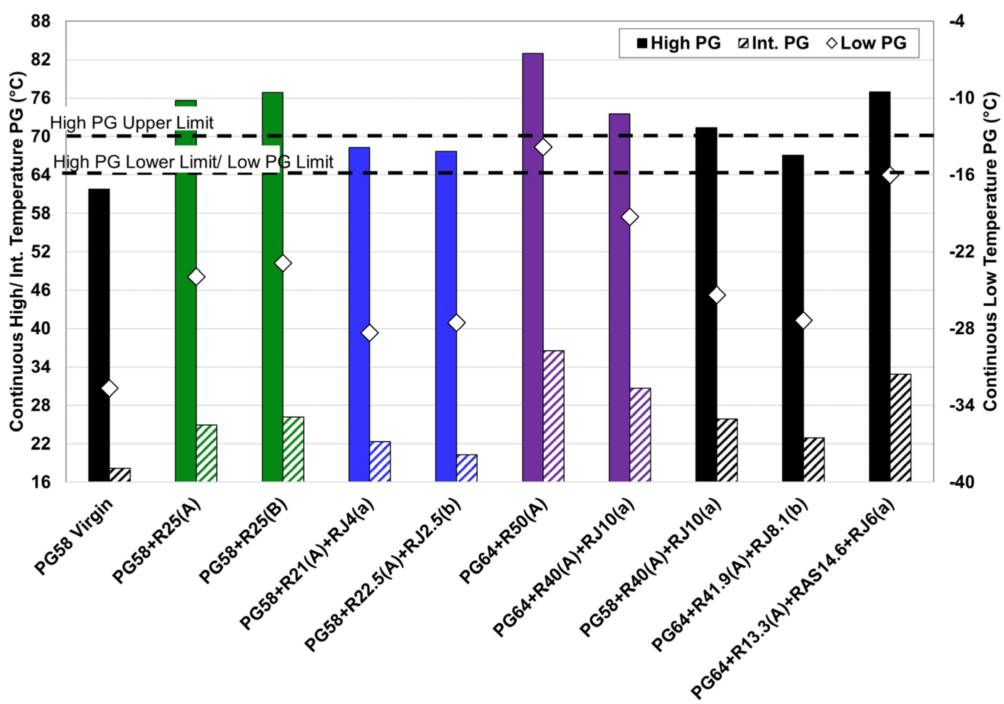
The continuous low temperature true grades observed for the control base binder 1 (PG 64) and base binder 2 (PG 58) were -19.7°C and -31.5°C, respectively. A binder with a more negative low temperature grade is expected to withstand more severe low temperatures in the field with regard to low temperature cracking. The binder blends with the PG 58 base binder satisfied the limit of -16°C for all cases. The blend with 25% of RAP(B) without any recycling agent for PG 58 [PG58+R25(B)] showed a better low temperature grade (-22.9°C) compared with the control binder (PG64). The addition of RAP/RAS was found to produce more low temperature cracking prone blends, while both recycling agents [RJ(a) and RJ(b)] were found to improve the low temperature cracking resistance. Other researchers have also reported similar findings due to the addition of RAP/RAS *(5,7,14)*.

The tall oil-based recycling agent [RJ(b)] showed greater efficiency in improving the low temperature grade compared with the aromatic-based recycling agent, shown in Figure 4.3 and Figure 4.4. For example, the continuous low temperature grades observed for the PG64+R19(A)+RJ6(a) and PG64+R21.8(A)+RJ3.2(b) blends were -19.0°C and -22.4°C, respectively. Therefore, about 3°C better continuous low temperature grade was observed for RJ(b) compared with RJ(a) with 2.8% less dosage, where the dosage had been determined based on matching the high temperature grade of the control binder. The binder blend with RAS and RJ(a) recycling agent [PG64+R13.3(A)+RAS14.6+RJ6(a)] marginally satisfied the low temperature requirement of -16°C.



Notes: R(A): Southern California RAP(A) (high PG of 102°C); R(B): Inland Valley RAP(B) (high PG of 109°C); RAS: reclaimed asphalt shingles (RAS); RJ(a): aromatic-based recycling agent; RJ(b): tall oil-based recycling agent.

Figure 4.3: Continuous performance grades for blends with PG 64 base binder.

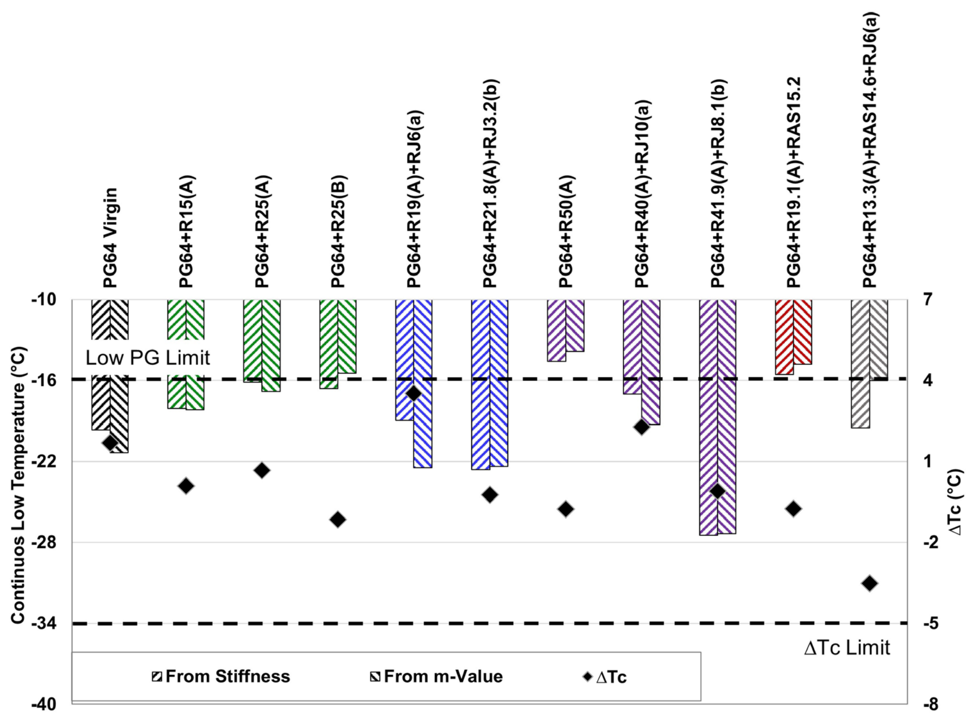


Notes: R(A): Southern California RAP(A) (high PG of 102°C); R(B): Inland Valley RAP(B) (high PG of 109°C); RAS: reclaimed asphalt shingles (RAS); RJ(a): aromatic-based recycling agent; RJ(b): tall oil-based recycling agent.

Figure 4.4: Continuous performance grades for blends with PG 58 base binder.

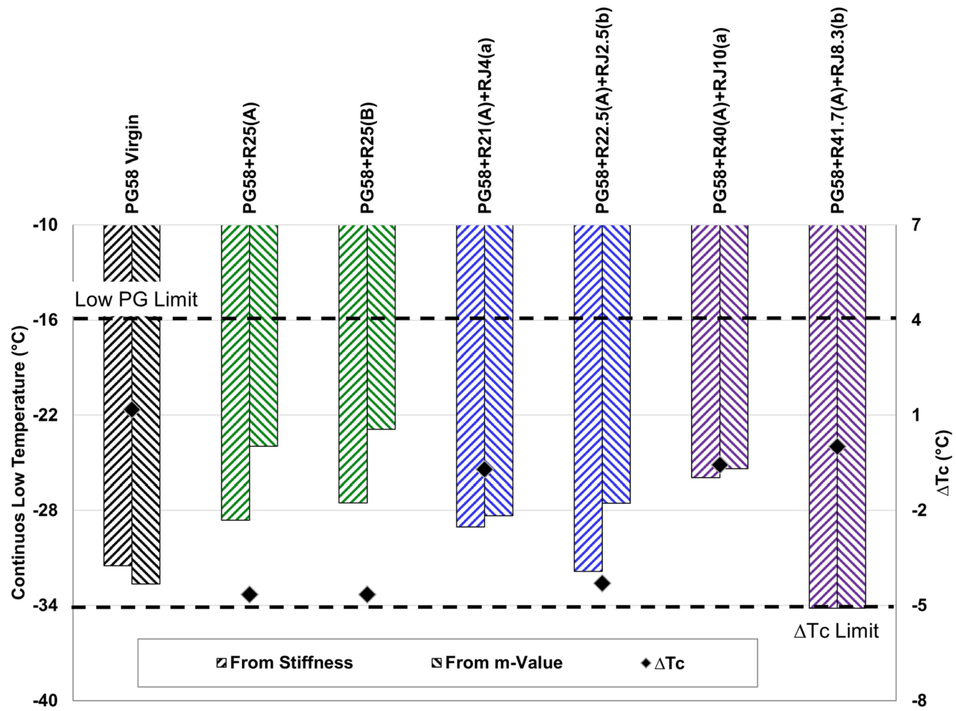
Figure 4.5 and Figure 4.6 show the delta T_c values for blends with PG 64 and PG 58, respectively. Both PG 64 and PG 58 virgin binders showed positive delta Tc values after 20 hours of pressurized aging vessel (PAV) aging, indicating that low temperature performance is controlled more by creep stiffness than slope, which is considered an indication of better performance with regard to block cracking (*15*). All the binder blends met the specification for a delta T_c value greater than -5.0. However, the tall oil-based recycling agent [RJ(b)] was found to show a slightly more negative delta T_c value compared with the aromatic-based recycling agent [RJ(a)]. For example, the delta T_c values for the PG58+R21(A)+RJ4(a) and PG58+R22.5(A)+RJ2.5(b) blends were -0.7 and -4.3°C, respectively. Therefore, RJ(b) is expected to produce more aging-prone asphalt mixes compared with RJ(a).

The use of the softer base binder (PG 58) with highly aged RAP resulted in more negative delta T_c values compared with the PG 64 base binder with the same RAP. The delta T_c values observed for the PG64+R25(B) and PG58+R25(B) blends were -1.1°C and -4.7°C, respectively. A similar trend was also observed for blends with RAP(A) [PG64+R25(A) and PG58+R25(A) blends]. In this study, PAV aging up to 20 hours was considered to evaluate the long-term aging effect. PAV aging at 40 hours is expected to show more negative delta T_c values, as suggested by other researchers *(5,7)*.



Notes: R(A): Southern California RAP(A) (high PG of 102°C); R(B): Inland Valley RAP(B) (high PG of 109°C); RAS: reclaimed asphalt shingles (RAS); RJ(a): aromatic-based recycling agent; RJ(b): tall oil-based recycling agent.

Figure 4.5: ΔTc values for blends with PG 64 base binder (PAV 20).



Notes: R(A): Southern California RAP(A) (high PG of 102°C); R(B): Inland Valley RAP(B) (high PG of 109°C); RAS: reclaimed asphalt shingles (RAS); RJ(a): aromatic-based recycling agent; RJ(b): tall oil-based recycling agent.

Figure 4.6: ΔTc values for blends with PG 58 base binder (PAV 20).

4.2 Frequency Sweep

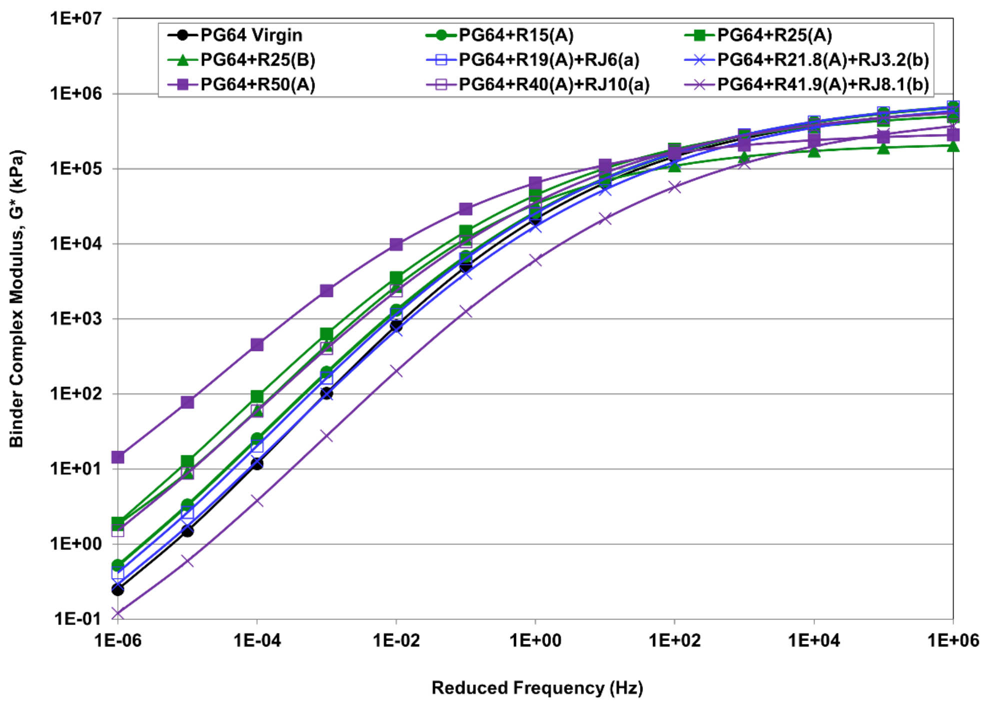
Figure 4.7 and Figure 4.9 show the master curves for the RTFO-aged PG 64 and PG 58 binder blends, respectively. Figure 4.8 and Figure 4.10 plot the curves normalized to the control binder (PG 64) to facilitate comparison of the PG 64 and PG 58 binder blends, respectively. The master curves for binder blends with RAS were plotted separately with RAP(A)and RAP(B) to compare RAP stiffness to the stiffness of the RAS binder blends. The master curves were developed at a reference temperature of 15°C using dynamic moduli and phase angles from frequency sweep tests (test temperatures of 4°C, 10°C, 25°C, and 40°C).

The addition of RAP was found to increase the stiffness of asphalt binder blends at low reduced frequencies (high temperatures) with a greater increase when more RAP was included. At 15°C and 1E-05 Hz, which nearly corresponds to 64°C and 10 Hz on a trafficked pavement based on the time-temperature superposition principle, the normalized moduli of the blends containing 25% RAP(A) and RAP(B) with PG 64 base binder were 8.4 and 6.0 times higher than the control binder, respectively. These results indicate greater rutting resistance at higher temperatures and slower speeds for mixes containing RAP.

However, the addition of a recycling agent was found to reduce the blend modulus values at low reduced frequencies. The blend with PG 64 base binder and tall oil-based recycling agent [PG64+R41.9(A)+RJ8.1(b)] at 50% binder replacement showed half of the stiffness at 1E-05 Hz reduced frequency compared with the control binder, shown in Figure 4.8. Also, a higher drop in the binder moduli was observed due to the addition of a tall oil-based recycling agent compared with the aromatic-based recycling agent. The binder moduli found at 1E-05 Hz reduced frequency for the PG64+R19(A)+RJ6(a) and PG64+R21.8(A)+RJ3.2(b) blends were 2.6 kPa and 1.7kPa, respectively. Therefore, lower stiffness was observed with RJ(b) compared with RJ(a) despite the dose of RJ(b) being smaller than the dose of RJ(a). The rutting resistance of asphalt mixes might be a point of concern when adding the tall oil-based recycling agent.

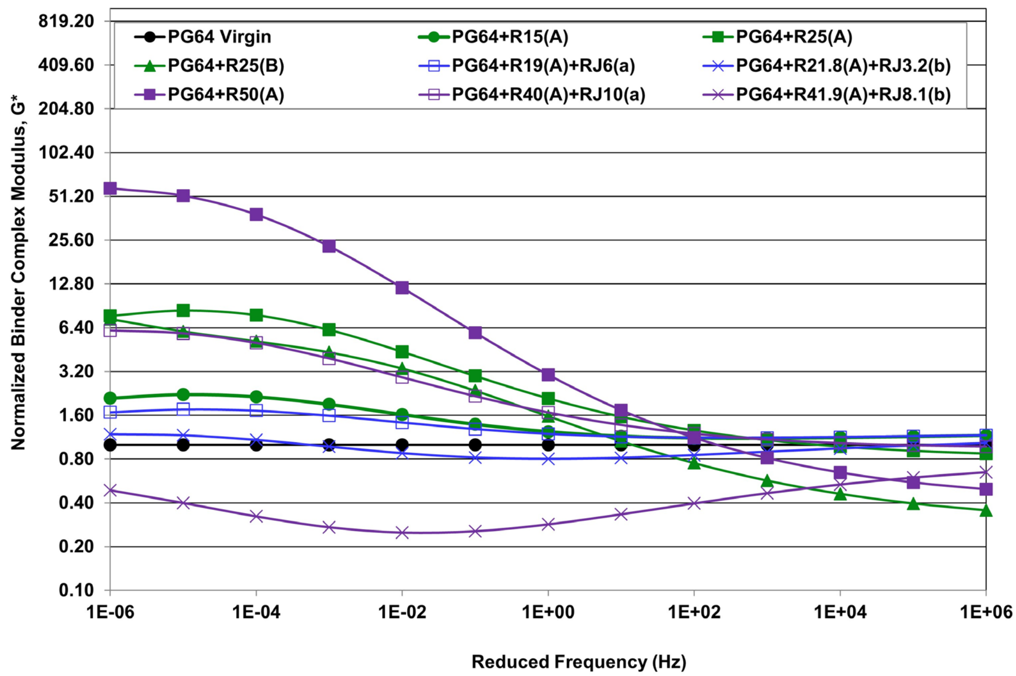
Figure 4.9 and Figure 4.10 show that the binder blends with PG 58 had lower binder modulus values compared with blends with PG 64, as expected. The complex modulus value observed at 15°C and 1E-05 Hz for the PG64+R25(B) blend was 1.5 times higher compared with the PG58+R25(B) blend. Therefore, early-stage rutting could be seen for asphalt mixes placed in hot climate regions with PG 58 base binder.

The complex modulus values at higher frequencies (>1E+04 Hz at 15°C) can be considered an indicator of low temperature performance *(15)*. However, it was found in the literature that the master curve regression model is often not precise at these higher frequencies *(17)*. Therefore, BBR tests are considered in this study to be more indicative of low temperature performance.



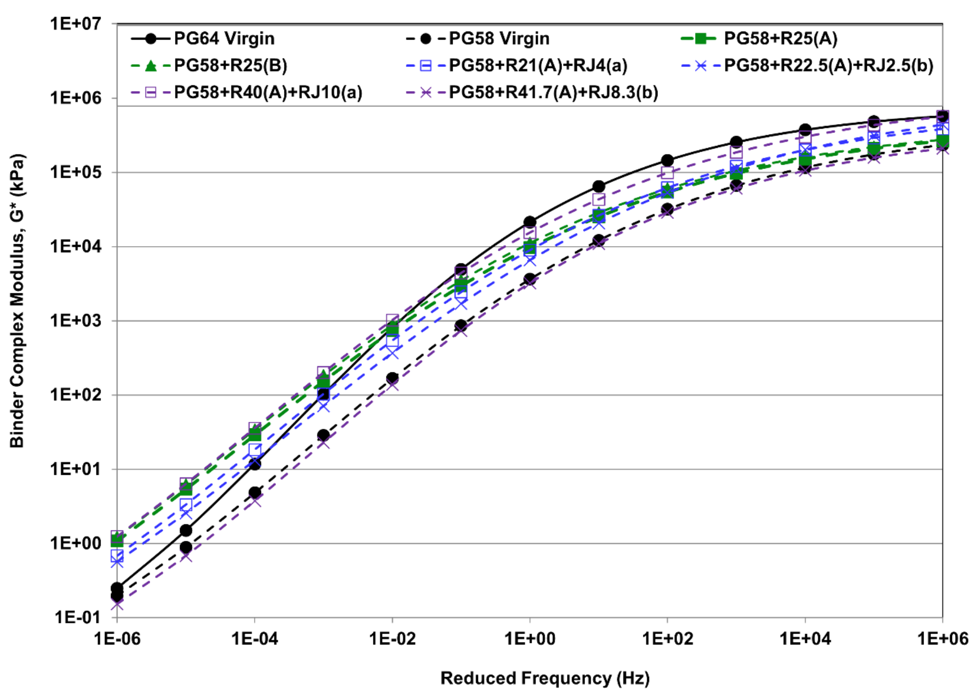
Notes: R(A): Southern California RAP(A) (high PG of 102°C); R(B): Inland Valley RAP(B) (high PG of 109°C); RAS: reclaimed asphalt shingles (RAS); RJ(a): aromatic-based recycling agent; RJ(b): tall oil-based recycling agent.

Figure 4.7: Frequency sweep master curves for RAP blends with PG 64 base binder at 15°C (RTFO aged).



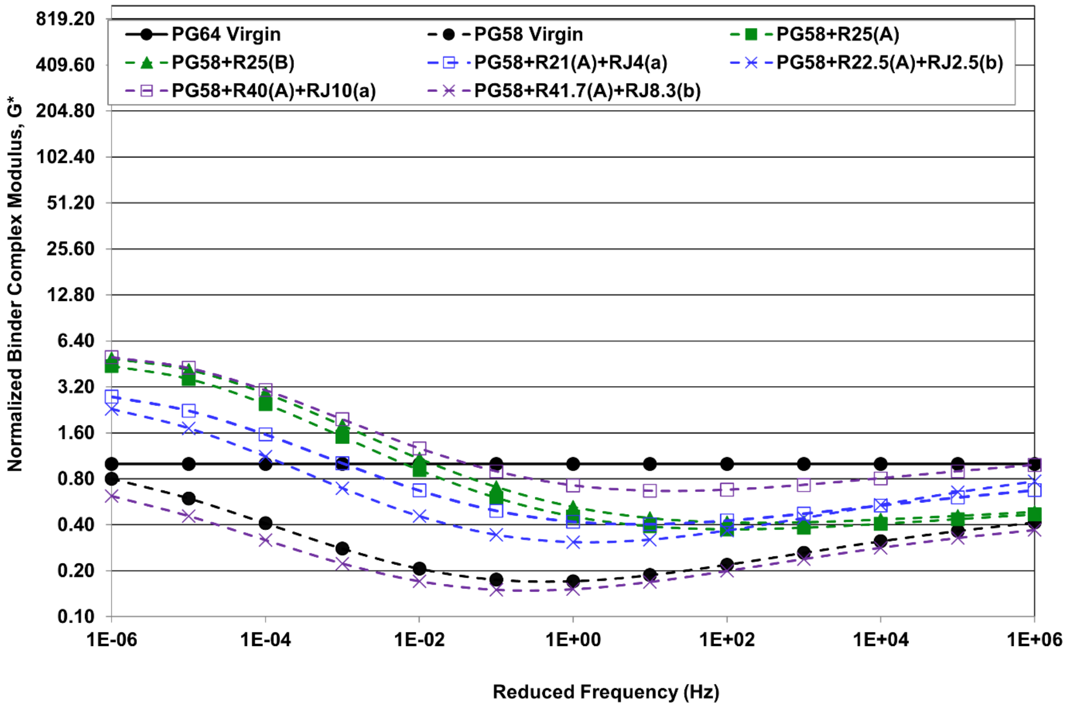
Notes: R(A): Southern California RAP(A) (high PG of 102°C); R(B): Inland Valley RAP(B) (high PG of 109°C); RAS: reclaimed asphalt shingles (RAS); RJ(a): aromatic-based recycling agent; RJ(b): tall oil-based recycling agent.

Figure 4.8: Frequency sweep master curves for RAP blends with PG 64 base binder normalized to PG 64 virgin binder at 15°C (RTFO aged).



Notes: R(A): Southern California RAP(A) (high PG of 102°C); R(B): Inland Valley RAP(B) (high PG of 109°C); RAS: reclaimed asphalt shingles (RAS); RJ(a): aromatic-based recycling agent; RJ(b): tall oil-based recycling agent.

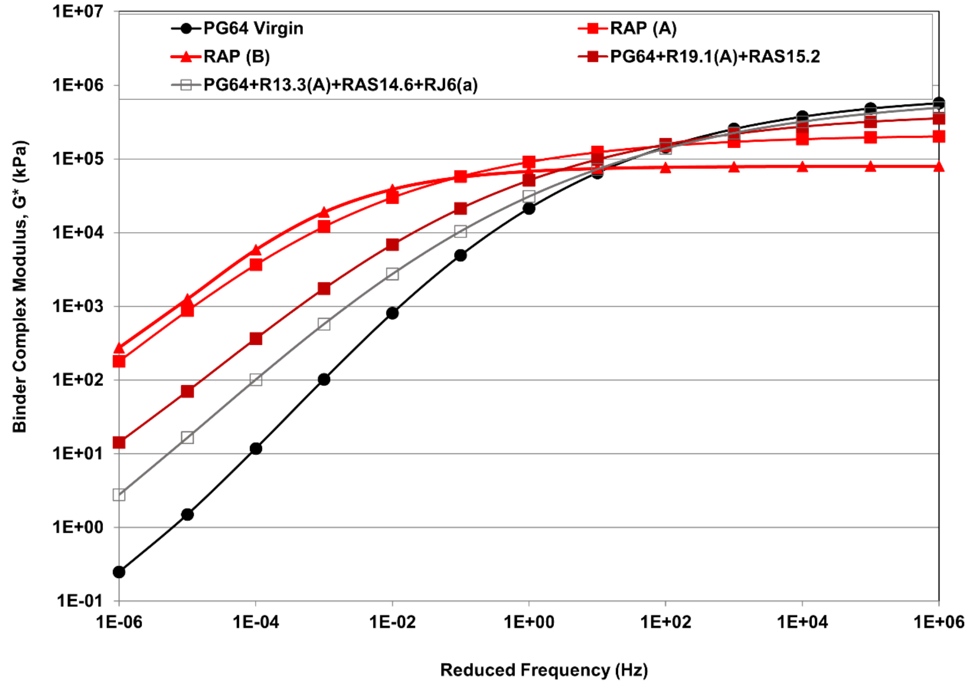
Figure 4.9: Frequency sweep master curves for RAP blends with PG 58 base binder at 15°C (RTFO aged).



Notes: R(A): Southern California RAP(A) (high PG of 102°C); R(B): Inland Valley RAP(B) (high PG of 109°C); RAS: reclaimed asphalt shingles (RAS); RJ(a): aromatic-based recycling agent; RJ(b): tall oil-based recycling agent.

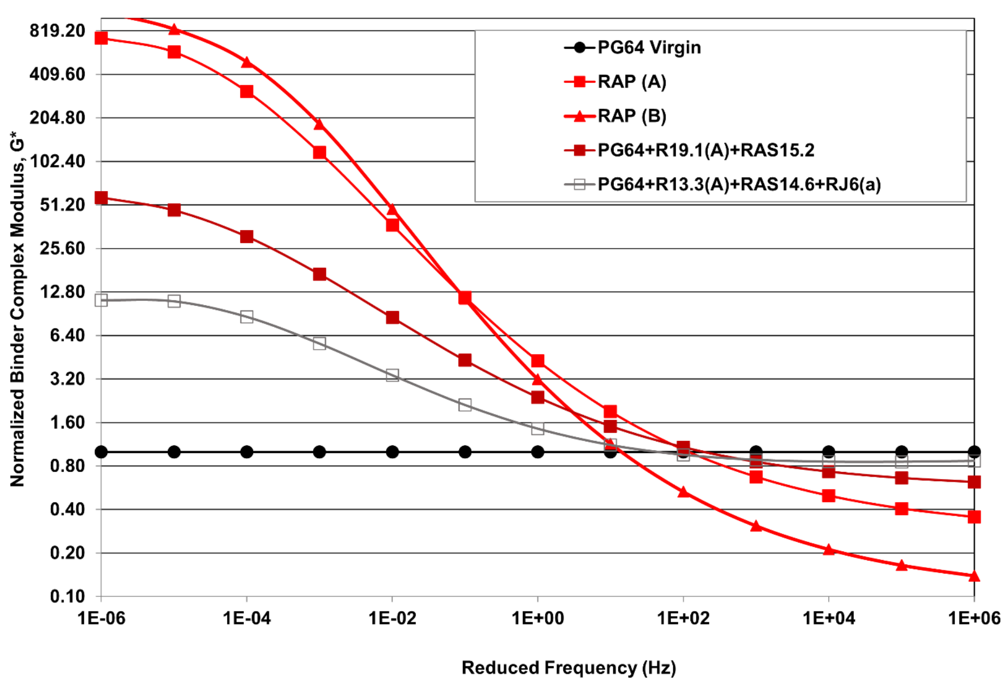
Figure 4.10: Frequency sweep master curves for RAP blends with PG 58 base binder normalized to PG 64 virgin binder at 15°C (RTFO aged).

Figure 4.11 shows the master curves for the RTFO-aged binders and Figure 4.12 plots the curves normalized to the control binder (PG64 Virgin) for RAP binders and RAS binder blends. As expected, much higher complex modulus values were observed for these blends at low reduced frequencies, indicating better rutting resistance. Complex modulus values about 800 times higher were found for extracted RAP binders compared with the control base binder at the 1E-05 Hz reduced frequency. The RAS binder blend without recycling agent [PG64+R19.1(A)+RAS15.2] showed complex modulus values 50 times higher compared with the control binder. The 6% addition of RJ(a) to the RAS blend lowered the complex modulus values, shown in Figure 4.12. However, the PG64+R13.3(A)+RAS14.6+RJ6(a) blend still showed complex modulus values about 10 times higher compared with the control binder at the 1E-05 Hz reduced frequency. The blends with RAP(A) and RAP(B) had flatter master curves above the 10 Hz frequency compared with the control binder. As discussed earlier, the master curve regression model is often not precise at these higher frequencies for highly aged RAP binders.



Notes: R(A): Southern California RAP(A) (high PG of 102°C); R(B): Inland Valley RAP(B) (high PG of 109°C); RAS: reclaimed asphalt shingles (RAS); RJ(a): aromatic-based recycling agent; RJ(b): tall oil-based recycling agent.

Figure 4.11: Frequency sweep master curves for extracted RAP binders and blends with RAS at 15°C (RTFO aged).



Notes: R(A): Southern California RAP(A) (high PG of 102°C); R(B): Inland Valley RAP(B) (high PG of 109°C); RAS: reclaimed asphalt shingles (RAS); RJ(a): aromatic-based recycling agent; RJ(b): tall oil-based recycling agent.

Figure 4.12: Frequency sweep master curves for extracted RAP binders and blends with RAS normalized to PG 64 virgin binder at 15°C (RTFO aged).

4.3 Glover-Rowe Analysis Results

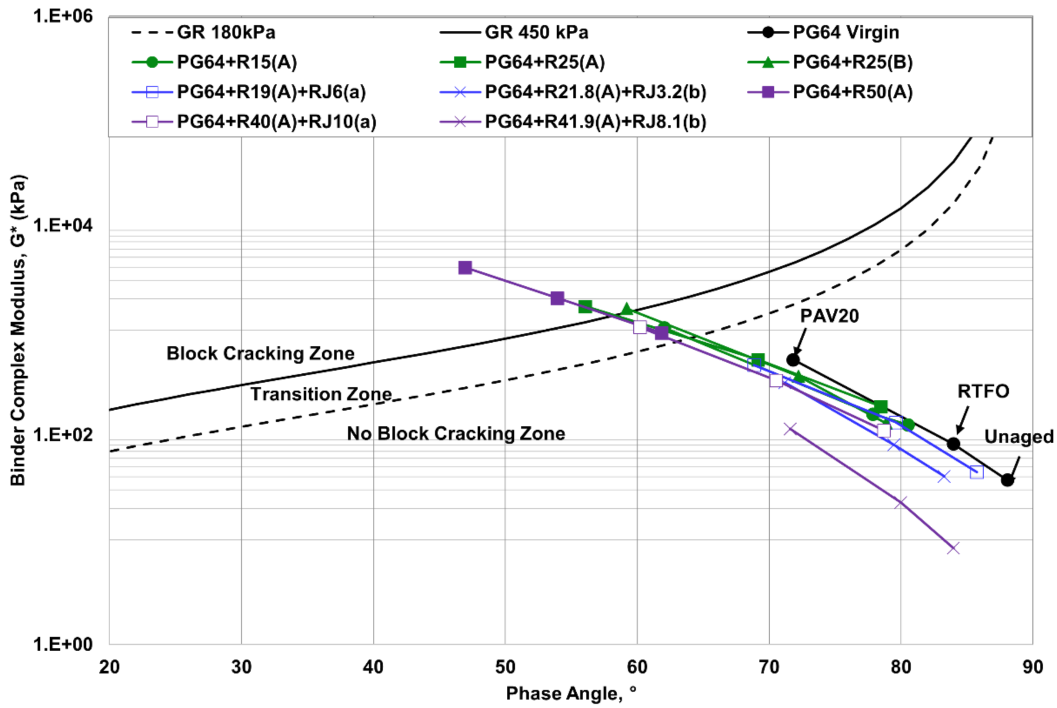
Figure 4.13 and Figure 4.15 present the black space diagram (stiffness versus phase angle) with stiffness at a temperature of 15°C and frequency of 8 (10^{-4}) Hz for blends with PG 64 and PG 58 base binders, respectively. Three aging conditions are considered in this study: (1) unaged, (2) RTFO aged, and (3) 20-hour PAV aged. Imposed on the plot are the Glover-Rowe (GR) thresholds that have been identified to correlate with an increased risk of low temperature and age-related cracking. The GR value is $G \times \cos(\delta)^2/\sin(\delta)$, where G is dynamic shear modulus and δ is phase angle. GR values less than 180 kPa generally indicate a low risk of cracking, 180 to 450 kPa indicate a transition zone, and greater than 450 kPa indicate that the binder is prone to cracking *(18)*. Figure 4.14 and Figure 4.16 show the GR values for blends with PG 64 and PG 58 base binders, respectively.

Figure 4.13 and Figure 4.15 show that different base binders follow different paths in the black space diagram. The path for the binder blends in the black space diagram is also governed by the base binder types. The blends with PG 58 were found to have much lower phase angle values compared with the blends with PG 64, shown in Figure 4.13 and Figure 4.15. The RTFO and PAV aging in the laboratory were found to increase the GR values for all binder blends. The GR values observed for the PG virgin binder at unaged, RTFO-aged, and 20-hours of PAV-aged conditions were 0.04, 0.92, and 53.87 kPa, respectively. An increase in RAP binder content in the PG64+R25(A) blend increased the cracking potential, shown in Figure 4.14. The GR value for this blend after PAV aging was 638 kPa, which was higher than the 450 kPa limit value. However, the addition of 6% recycling agent with 19% RAP [PG64+R19(A)+RJ6(a)] reduced the GR parameter to 65.21 kPa after 20 hours of PAV aging, which was close to the GR parameter of the base binder (53.87 kPa) at the same aging condition.

The tall oil-based recycling agent was found to show better efficiency in improving the GR values compared with the aromatic-based recycling agent. The GR values observed after 20 hours of PAV aging for the PG64+R19(A)+RJ6(a) and PG64+R21.8(A)+RJ3.2(b) blends were 65.2 and 34.7 kPa, respectively. Both GR values were found to be below the lower limit of 180 kPa. However, a lower dosage (3.2% by total weight of binder) of tall oil-based recycling agent is required compared with the aromatic-based recycling agent (6% by total weight of binder) to result in the same or better GR values. RJ(a) was found to perform better in terms of delta T_c values compared with RJ(b) after 20 hours of PAV aging for most cases. Comparing the delta T_c values, which were worse for RJ(b) than RJ(a), and the GR parameters for the two recycling agents, the results are contradictory. This finding may indicate that delta T_c values may not be a reliable tool in evaluating the efficiency of recycling agents in terms of temperature and age-related cracking.

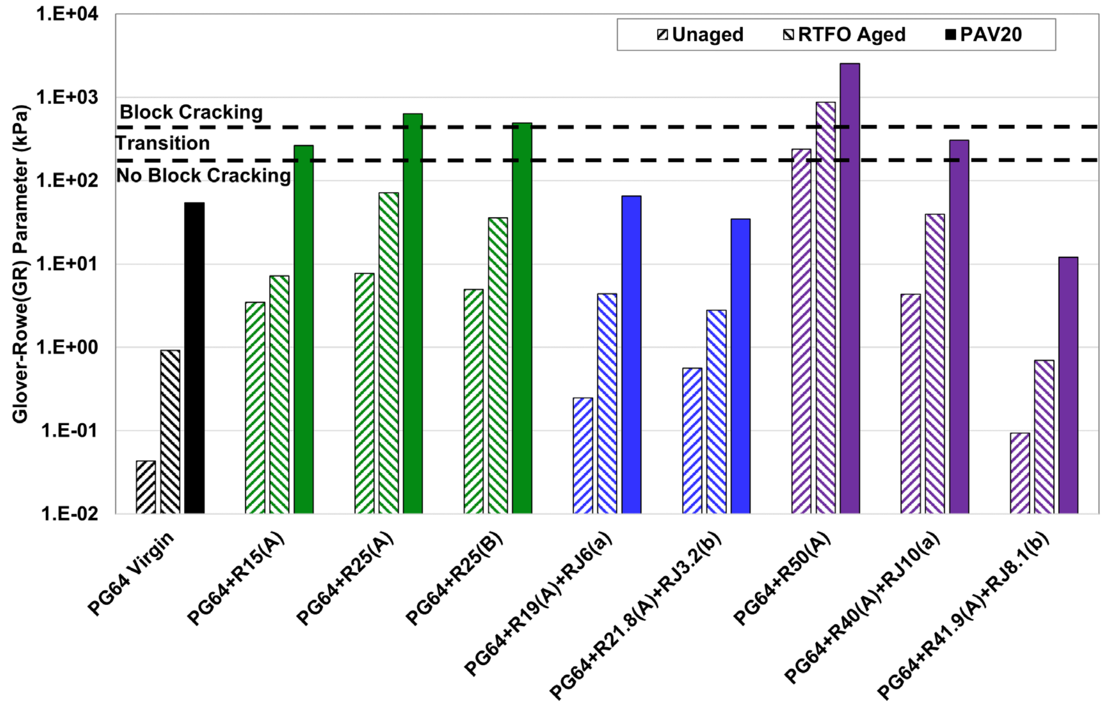
Figure 4.17 presents the black space diagram and Figure 4.18 shows the GR values for extracted RAP binders and blends with RAS. The RAS blend with recycling agent [PG64+R13.3(A)+RAS14.6+RJ6(a)] after PAV aging had a GR value of 753 kPa (in the cracking zone shown in Figure 4.17), indicating that higher doses of recycling agent would be required for the PG64+R13.3(A)+RAS14.6+RJ6(a) binder blend to eliminate the cracking potential. Hence, this GR diagram can be potentially used in combination with rutting parameters to optimize recycling agent dosage rates in asphalt mixes. Care must be taken to ensure that optimal recycling agent rates are not exceeded as this may lead to over-softening of the binder, which can lead to rutting or to a tendency to replace virgin binder contents with recycling agent beyond what is needed to prevent cracking risk, in addition to increasing the cost of the mix.

The results for the two extracted RAP binders shown in Figure 4.17 show that the more aged RAP(B) shows little change in stiffness or phase angle with increased aging from RTFO and PAV conditioning, indicating that most molecules in it that can age already have aged prior to conditioning.



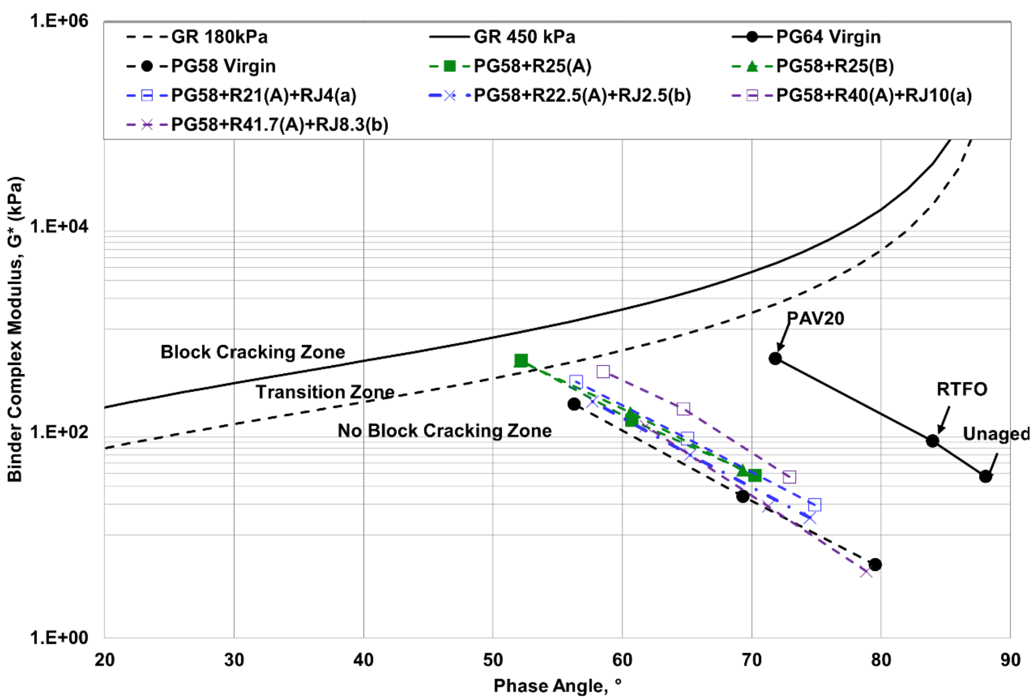
Notes: R(A): Southern California RAP(A) (high PG of 102°C); R(B): Inland Valley RAP(B) (high PG of 109°C); RAS: reclaimed asphalt shingles (RAS); RJ(a): aromatic-based recycling agent; RJ(b): tall oil-based recycling agent.

Figure 4.13: Black space plot for RAP blends with PG64 base binder.



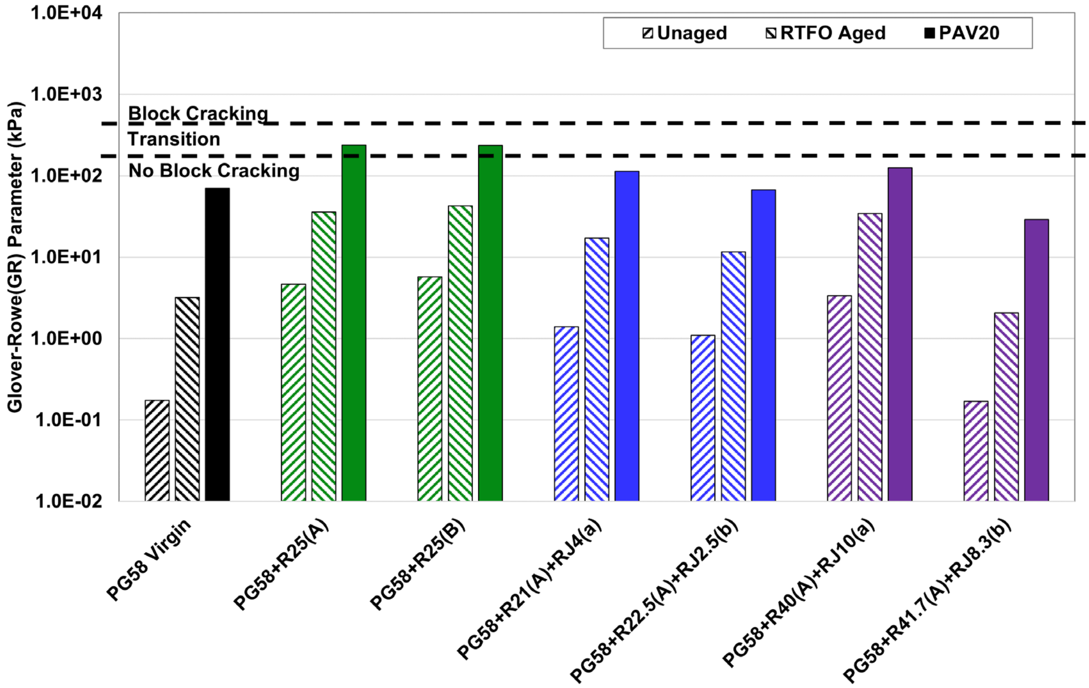
Notes: R(A): Southern California RAP(A) (high PG of 102°C); R(B): Inland Valley RAP(B) (high PG of 109°C); RAS: reclaimed asphalt shingles (RAS); RJ(a): aromatic-based recycling agent; RJ(b): tall oil-based recycling agent.

Figure 4.14:Glover-Rowe (GR) parameters for RAP blends with PG 64 base binder.



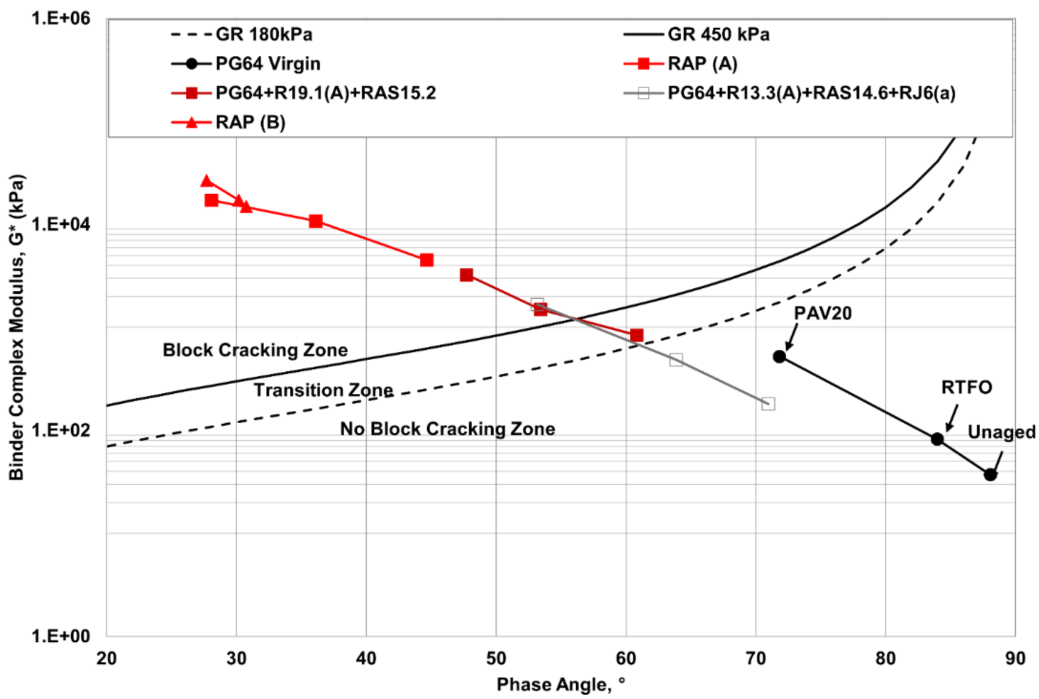
Notes: R(A): Southern California RAP(A) (high PG of 102°C); R(B): Inland Valley RAP(B) (high PG of 109°C); RAS: reclaimed asphalt shingles (RAS); RJ(a): aromatic-based recycling agent; RJ(b): tall oil-based recycling agent.

Figure 4.15: Black space plot for RAP blends with PG 58 base binder.



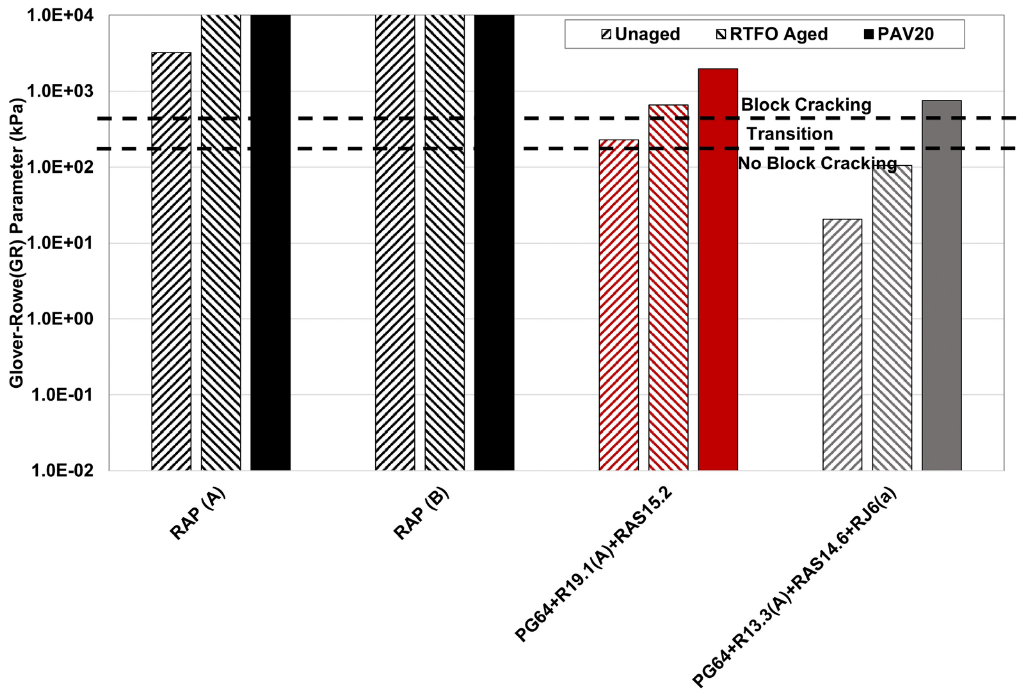
Notes: R(A): Southern California RAP(A) (high PG of 102°C); R(B): Inland Valley RAP(B) (high PG of 109°C); RAS: reclaimed asphalt shingles (RAS); RJ(a): aromatic-based recycling agent; RJ(b): tall oil-based recycling agent.

Figure 4.16:Glover-Rowe (GR) parameters for RAP blends with PG 58 base binder.



Notes: R(A): Southern California RAP(A) (high PG of 102°C); R(B): Inland Valley RAP(B) (high PG of 109°C); RAS: reclaimed asphalt shingles (RAS); RJ(a): aromatic-based recycling agent; RJ(b): tall oil-based recycling agent.

Figure 4.17:Black space plot for extracted RAP binders and blends with RAS.



Notes: R(A): Southern California RAP(A) (high PG of 102°C); R(B): Inland Valley RAP(B) (high PG of 109°C); RAS: reclaimed asphalt shingles (RAS); RJ(a): aromatic-based recycling agent; RJ(b): tall oil-based recycling agent.

Figure 4.18: Glover-Rowe (GR) parameters for extracted RAP binders and blends with RAS.

4.4 Fourier Transform Infrared Spectroscopy

Binder blends were tested in unaged, RTFO-aged, and PAV-aged conditions for the carbonyl (CA) and sulfoxide (SUL) area indices, which are indicators of aging-related chemical products in the binder. Figure 4.19 and Figure 4.20 show the plots for the CA indices for blends with PG 64 and PG 58 base binders, respectively. Figure 4.21 and Figure 4.22 show the SUL indices for blends with PG 64 and PG 58 base binders, respectively. The increasing CA and SUL indices indicate greater aging *(6,7)*. Table A.2 shows the summary of the FTIR test results.

Figure 4.19 and Figure 4.20 show that the CA indices were found to increase with laboratory aging for all binder blends. The control base binder 1 (PG 64) had larger initial but lower final CA values compared with base binder 2 (PG 58), indicating that the control base binder is less aging susceptible. The CA indices found for the PG64 Virgin binder under the unaged, RTFO-aged, and PAV-aged conditions were 0.18, 0.47, and 1.14, respectively (Table A.2). The CA indices observed for the PG58 Virgin binder under the unaged, RTFO-aged, and PAV-aged conditions were 0.12, 0.40, and 1.24, respectively. The addition of RAP was found to increase the CA indices for all aging conditions. The CA indices found for the PG64+R25(A) blend under the unaged, RTFO-aged, and PAV-aged conditions were 0.84, 1.05, and 1.70, respectively (Table A.2). Therefore, the CA index can be used for tracking the use of aged binder from RAP/RAS in asphalt mixes. Similar findings have been found in previous UCPRC studies *(6,7)*. However, the binder blend with 25% RAP(A) and no recycling agent [PG64+R25(A)] had a CA index for all aging conditions similar to the blend with 19% RAP(A) and

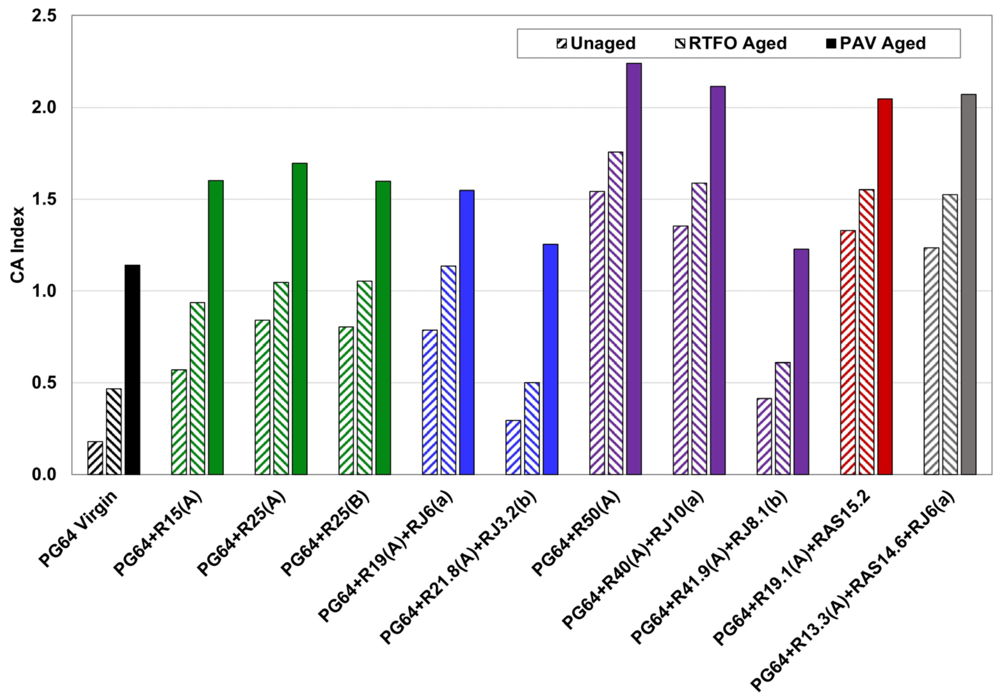
6% RJ(a) [PG64+R19(A)+RJ6(a)], shown in Table A.2. This finding was unexpected given that the addition of a recycling agent is expected to reduce the degree of aging of asphalt binders and was attributed to the presence of CA in the recycling agent.

The CA indices for the aromatic-based recycling agent [RJ(a)] under the unaged, RTFO-aged, and PAV-aged conditions were 1.89, 1.95, and 2.52, respectively. The CA index was zero for the tall oil-based recycling agent [RJ(b)]. Based on these results, a modified CA parameter (cAmod) was proposed to track the aging of binder blends containing RJ(a), shown in Equation 4.1 *(6)*. In this equation, the CA values of recycling agent were selected based on the aging conditions (unaged, RTFO-aged, or PAV-aged) of the rejuvenated binder blends. The cAmod values are shown in Appendix Table A.3 and are further considered to evaluate the correlation between binder chemical and rheological parameters.

$$cAmod = Measured\ CA - [(\%\ Recycling\ agent\ used) * CA\ of\ Recycling\ agent] \quad \textbf{(4.1)}$$

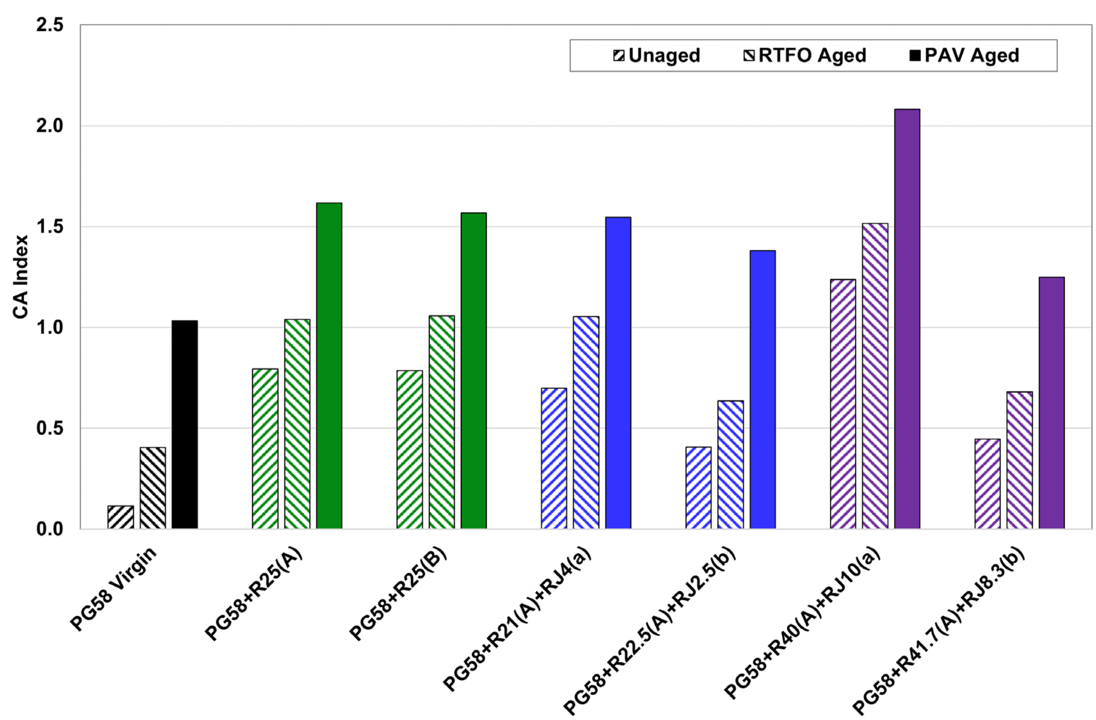
Figure 4.21 and Figure 4.22 show that the SUL indices were not increasing consistently with the increase in degree of aging. The SUL indices observed for the PG64+R25(B) blend under the unaged, RTFO-aged, and PAV-aged conditions were 3.05, 2.94, and 5.25, respectively. Therefore, a lower SUL index was observed after RTFO aging compared with the unaged condition for the PG64+R25(B) blend. Inconsistent SUL index results with aging were also observed for other blends, shown in Figure 4.21 and Figure 4.22. An earlier study also reported similar findings for blends containing RAP/RAS and recycling agent *(7)*.

Previous literature indicates that the CA index is a good indicator of the changes in binder rheological properties with different amounts of aging for rutting at high temperatures and for stiffness related to different types of cracking at lower temperatures (*6,7,19*). The findings of one study suggested that the correlation between binder chemical and rheological properties depends on the base binder grades and sources *(6)*. For mixes with RAP, the blended binder properties also play an important role in defining the relation between chemical and rheological parameters *(5)*. The results obtained in this research, shown below, indicate a strong correlation between the modified CA index (cAmod) and the stiffness at 64°C and 10 Hz (Figure 4.23), Glover-Rowe criteria (Figure 4.24), and the crossover modulus (Figure 4.25) for both base binder types. The crossover modulus is the stiffness at which the phase angle is 45 degrees, with a decreasing crossover modulus indicating less ability to relax stresses under thermal contraction. The results show how the risk of temperature-related cracking increases with aging while the risk of rutting decreases.



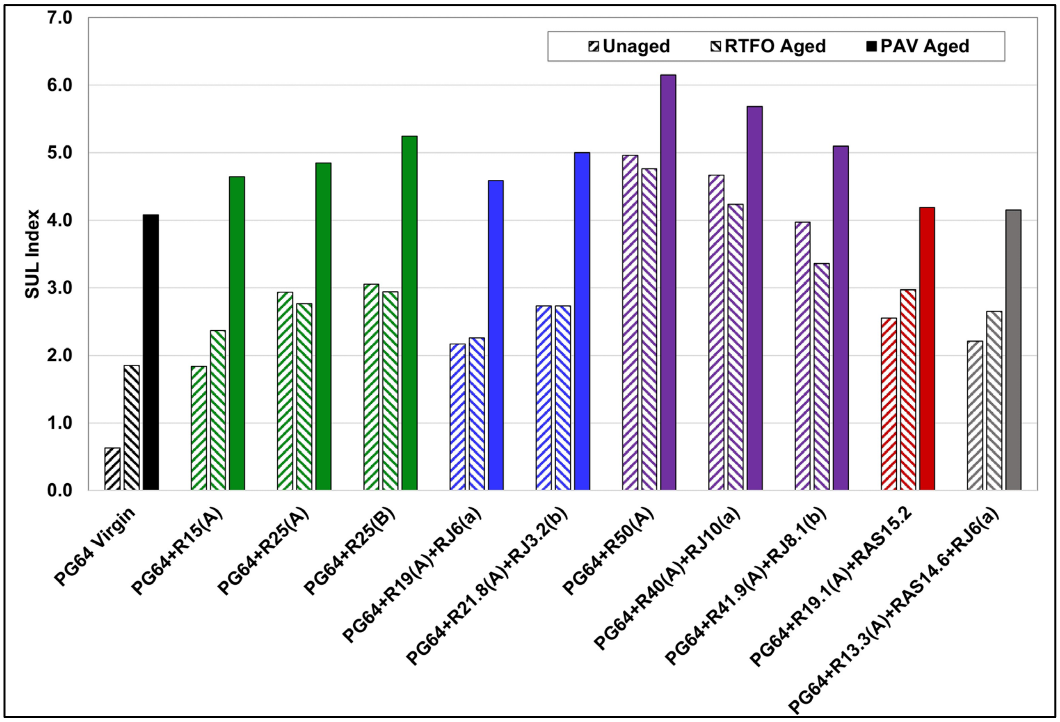
Notes: R(A): Southern California RAP(A) (high PG of 102°C); R(B): Inland Valley RAP(B) (high PG of 109°C); RAS: reclaimed asphalt shingles (RAS); RJ(a): aromatic-based recycling agent; RJ(b): tall oil-based recycling agent.

Figure 4.19: Carbonyl area (CA) index changes after aging for RAP and RAS blends with PG 64 base binder.



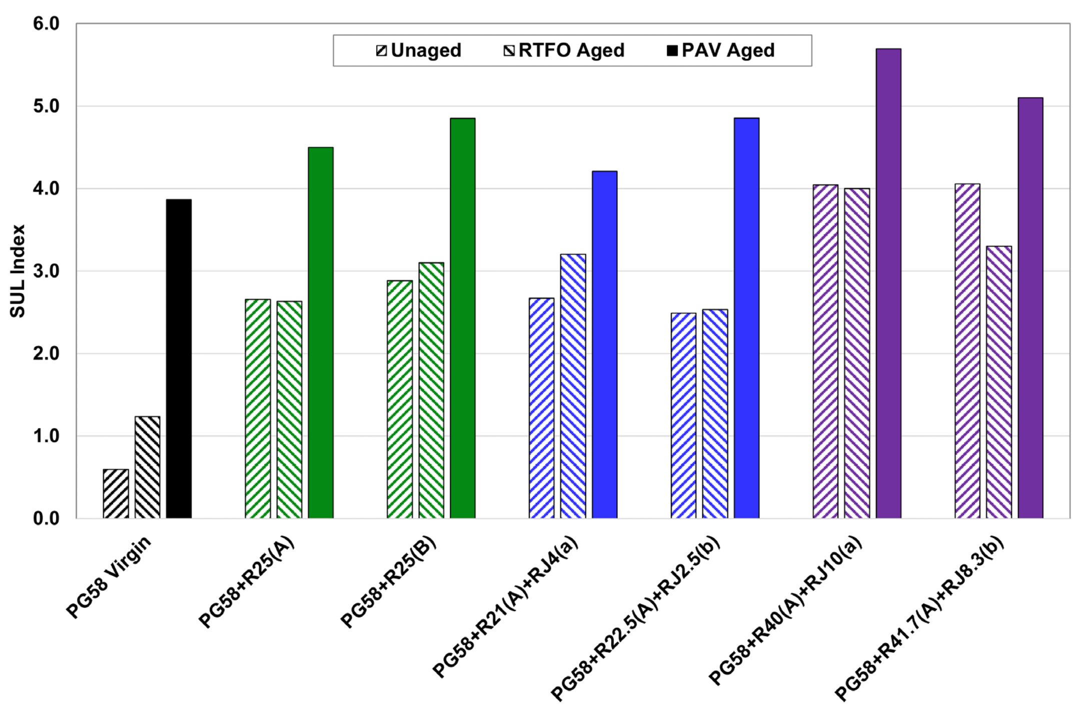
Notes: R(A): Southern California RAP(A) (high PG of 102°C); R(B): Inland Valley RAP(B) (high PG of 109°C); RAS: reclaimed asphalt shingles (RAS); RJ(a): aromatic-based recycling agent; RJ(b): tall oil-based recycling agent.

Figure 4.20: Carbonyl area (CA) index changes after aging for RAP and RAS blends with PG 58 base binder.



Notes: R(A): Southern California RAP(A) (high PG of 102°C); R(B): Inland Valley RAP(B) (high PG of 109°C); RAS: reclaimed asphalt shingles (RAS); RJ(a): aromatic-based recycling agent; RJ(b): tall oil-based recycling agent.

Figure 4.21: Sulfoxide area index changes after aging for RAP and RAS blends with PG 64 base binder.



Notes: R(A): Southern California RAP(A) (high PG of 102°C); R(B): Inland Valley RAP(B) (high PG of 109°C); RAS: reclaimed asphalt shingles (RAS); RJ(a): aromatic-based recycling agent; RJ(b): tall oil-based recycling agent.

Figure 4.22: Sulfoxide area index changes after aging for RAP and RAS blends with PG 58 base binder.

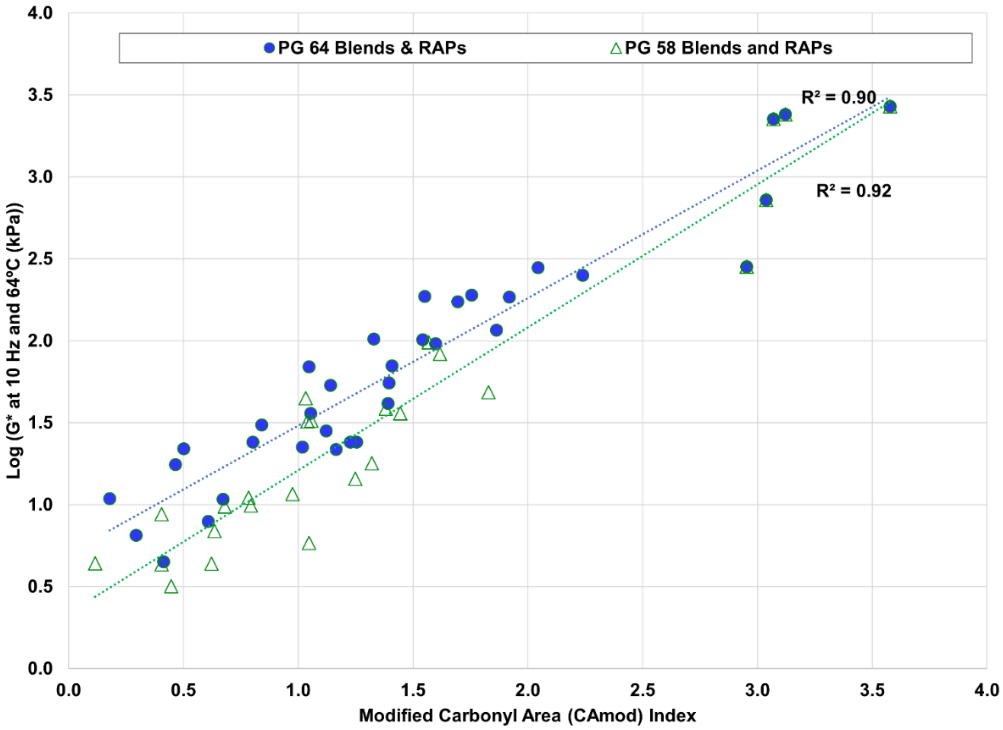


Figure 4.23: Modified carbonyl area (CA) versus G* at 10 Hz and 64°C for all binders.

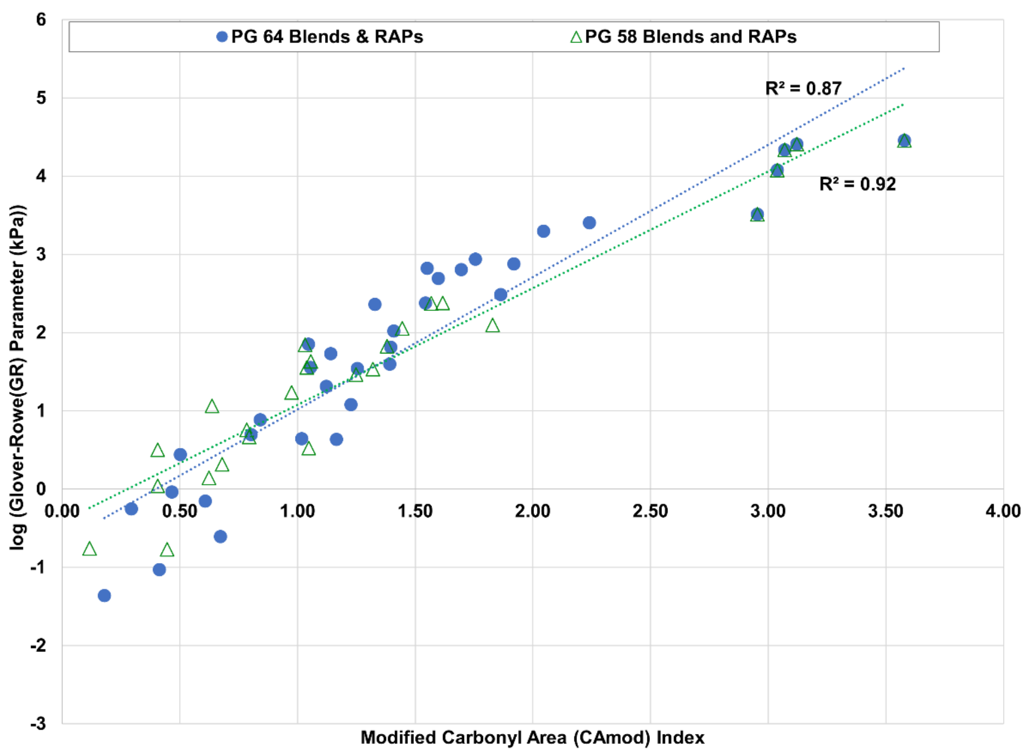


Figure 4.24: Modified carbonyl area (CA) index versus Glover-Rowe (GR) parameter for all binders.

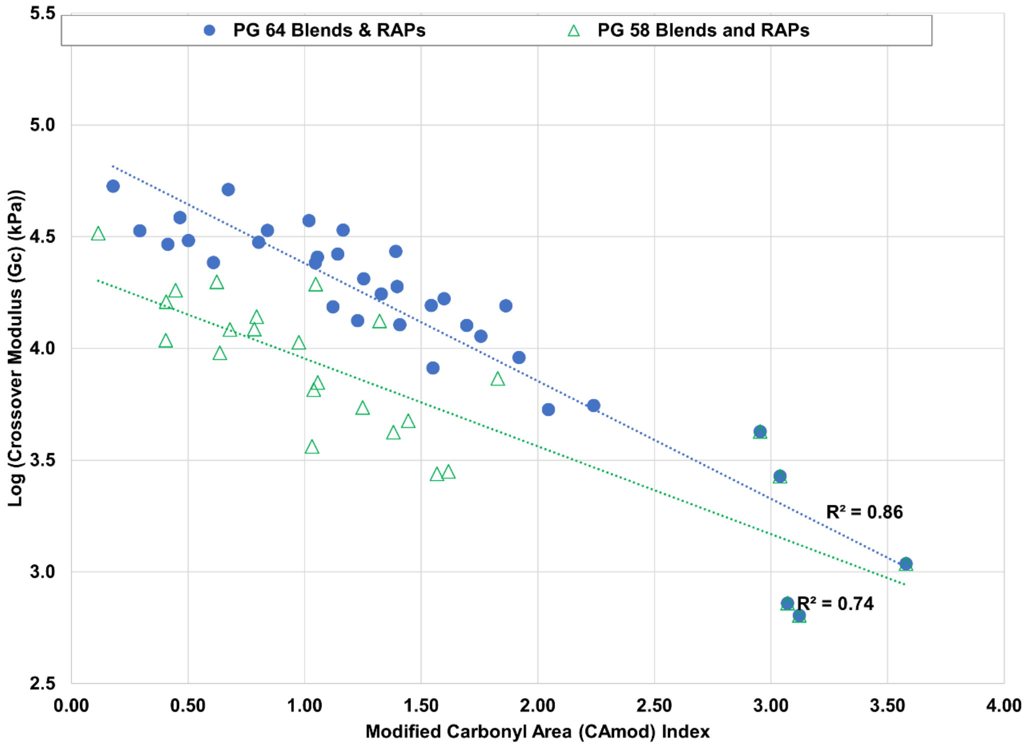


Figure 4.25: Modified carbonyl area (CA) index versus crossover modulus for all binders.

5 MIX TESTING RESULTS

The results of the laboratory testing of the mixes are presented in this chapter. In Chapter 6, the same results are regrouped for presentation within the context of each of the questions posed in Section 1.3 and discussed to answer the questions.

5.1 Axial Dynamic Modulus Test

The results of the axial dynamic modulus testing are shown in Figure 5.1 and Figure 5.2 for the mixes with PGH 64 and in Figure 5.3 for the mixes with PGH 58. The reduced frequency range in the figures (10^{-5} to 10^{+5} Hz) corresponds to the range of temperature and frequency applied in the AMPT dynamic modulus testing (39°F-129°F [4°C-54°C] and 0.1-25 Hz).

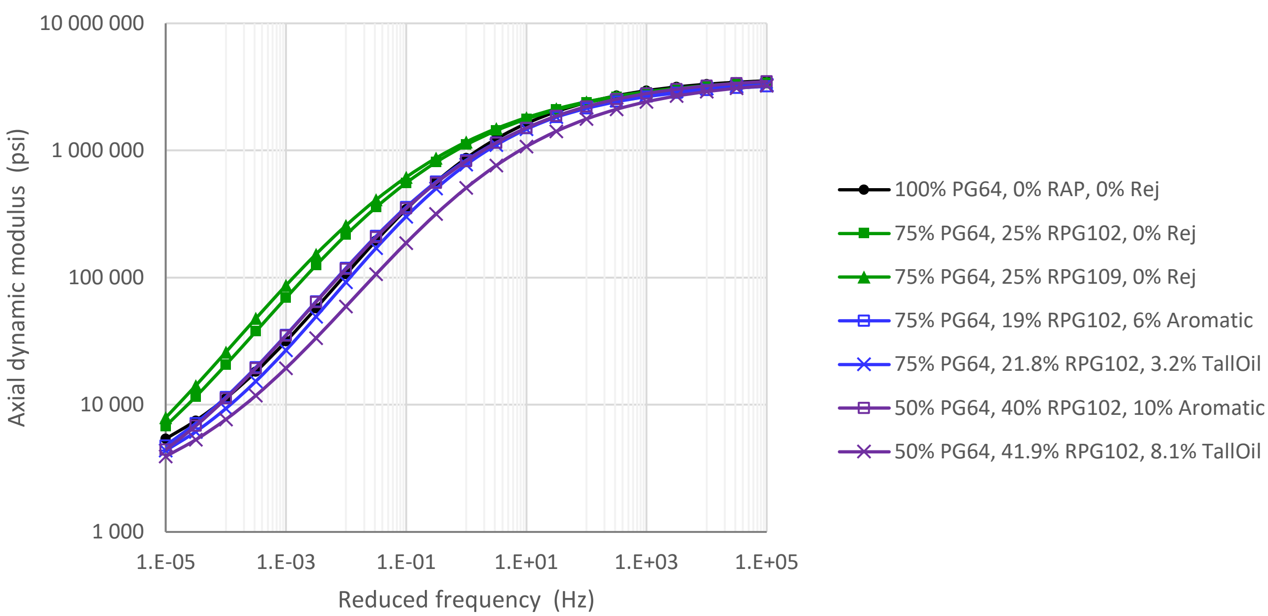


Figure 5.1: Axial dynamic modulus test results at 68°F (20°C)—mixes with PGH 64 and RAP.

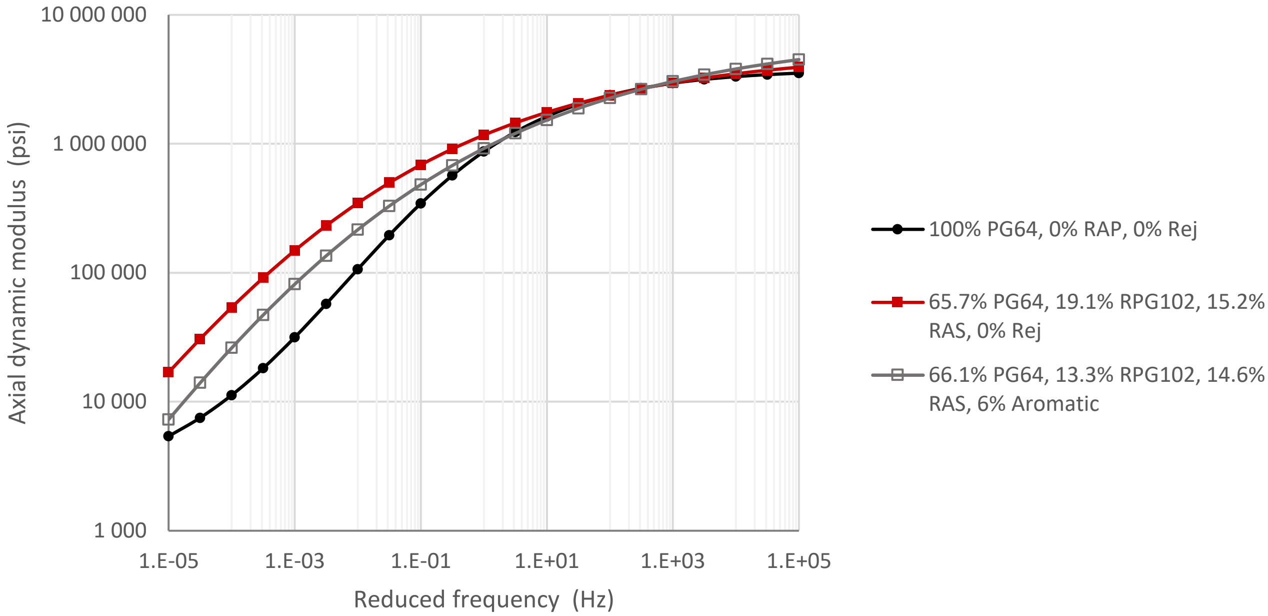


Figure 5.2: Axial dynamic modulus test results at 68°F (20°C)—mixes with PGH 64 and RAS.

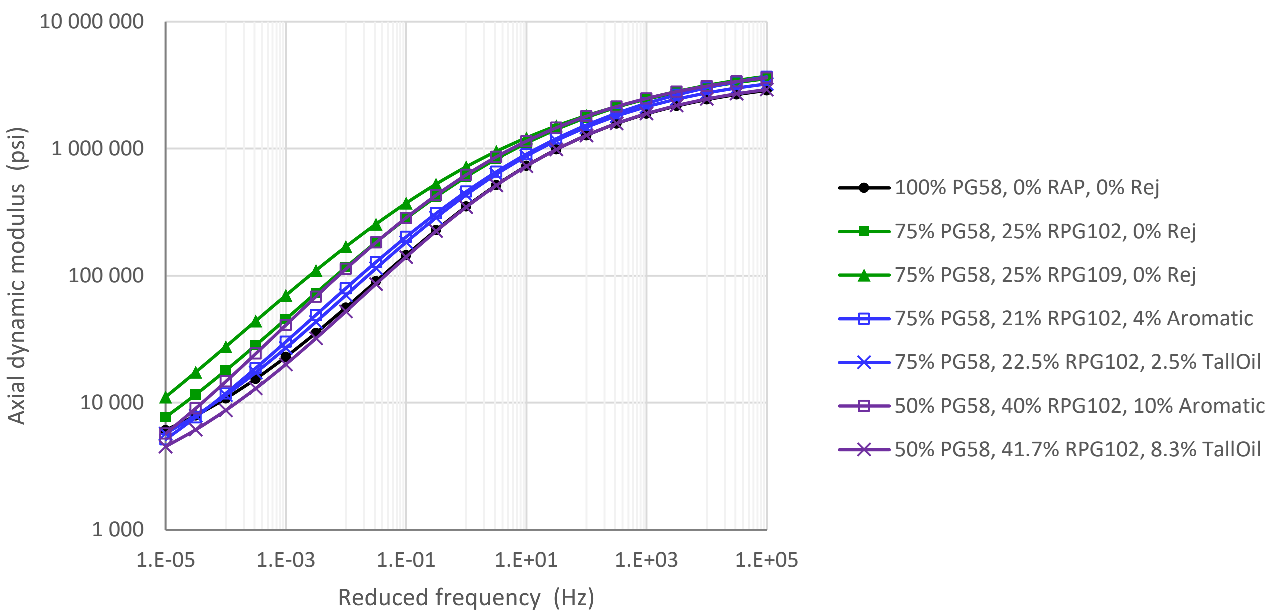


Figure 5.3: Axial dynamic modulus test results at 68°F (20°C)—mixes with PGH 58 and RAP.

5.2 Flexural Dynamic Modulus Test

The results of the flexural dynamic modulus testing are shown in Figure 5.4 and Figure 5.5 for the mixes with PGH 64 and in Figure 5.6 for the mixes with PGH 58. The reduced frequency range in the figures (10^{-4} to 10^{+4} Hz) correspond to the range of temperature and frequency applied in the four-point bending (4PB) dynamic modulus testing (50°F-86°F [10°C-30°C] and 0.01-15 Hz). There is a strong correlation between the flexural dynamic modulus and axial dynamic modulus (measured in the

AMPT), as expected, shown in Figure 5.7. Overall, the flexural dynamic modulus is around 35% less than the axial dynamic modulus, most likely due to the anisotropy associated to the compaction (mix stiffer in vertical than in horizontal direction) and the AMPT loading (compression and shear) mobilizing the aggregate skeleton more than the 4PB flexural loading (tension and compression).

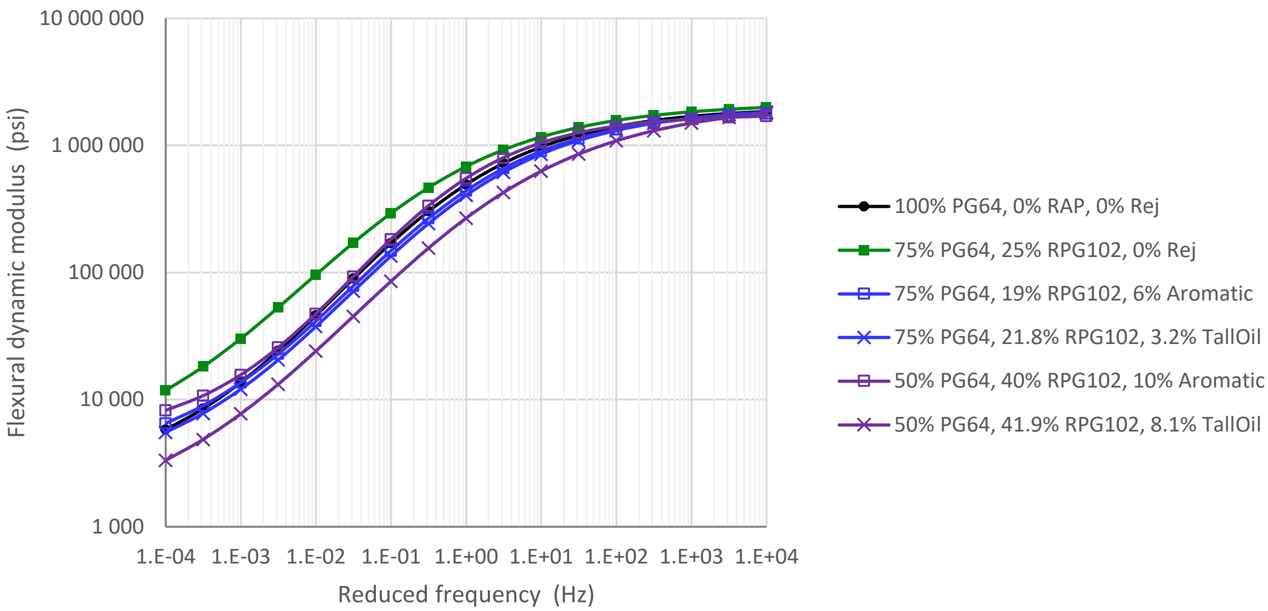


Figure 5.4: Flexural dynamic modulus test results—mixes with PGH 64 and RAP.

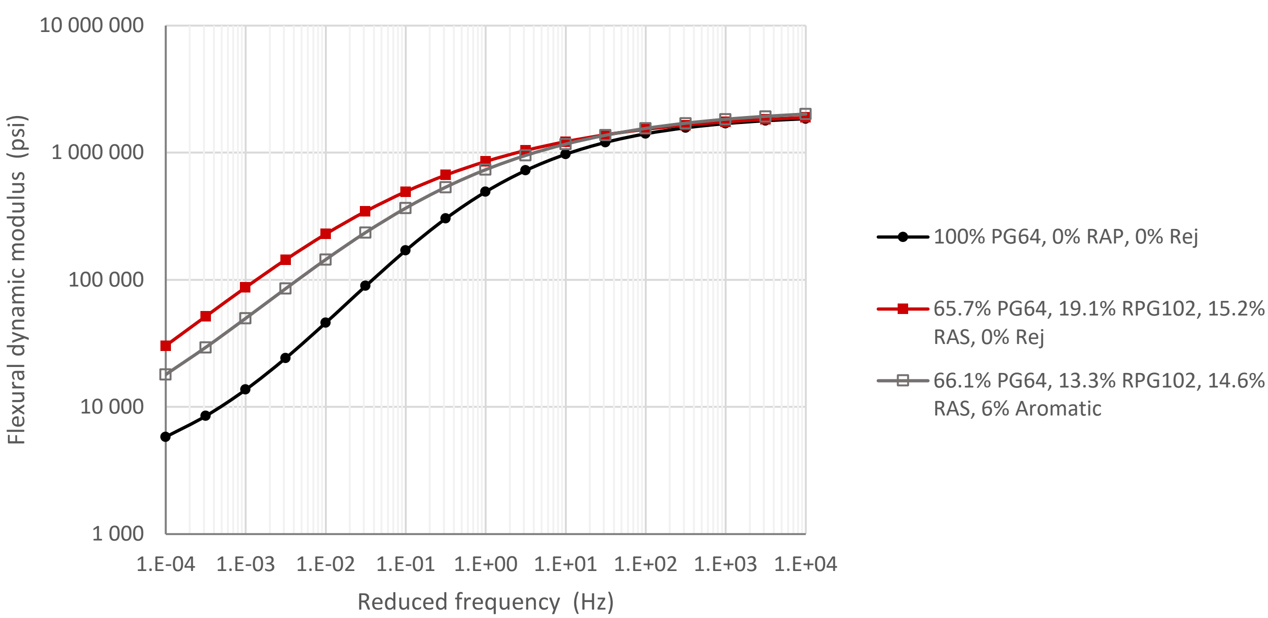


Figure 5.5: Flexural dynamic modulus test results—mixes with PGH 64 and RAS.

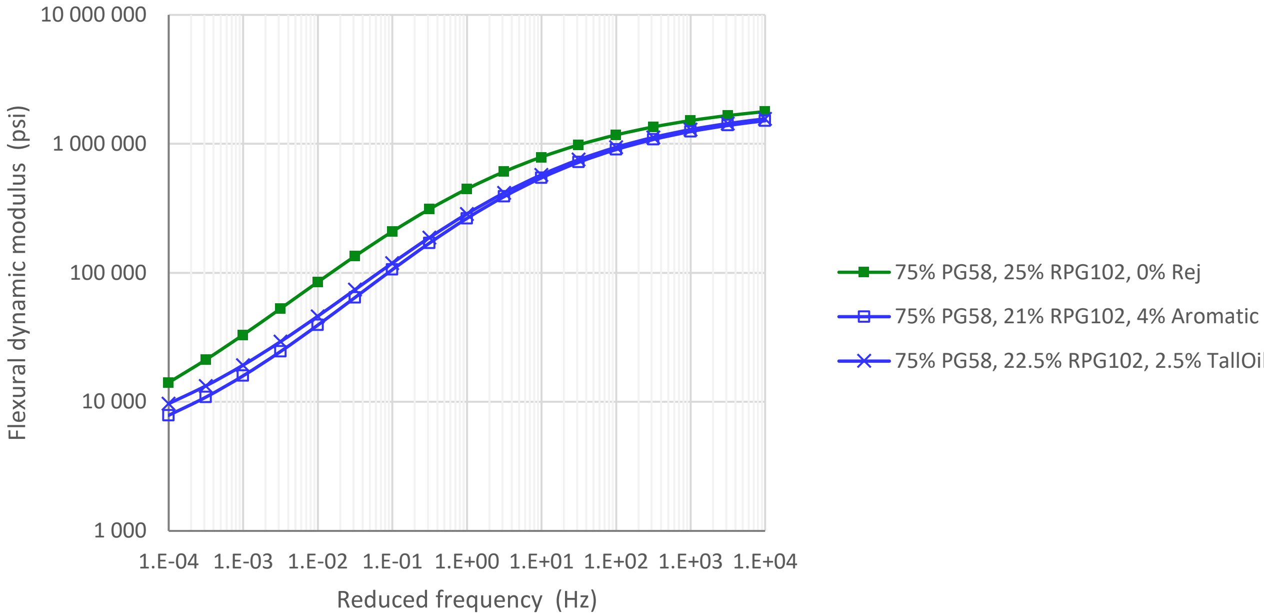


Figure 5.6: Flexural dynamic modulus test results—mixes with PGH 58 and RAP.

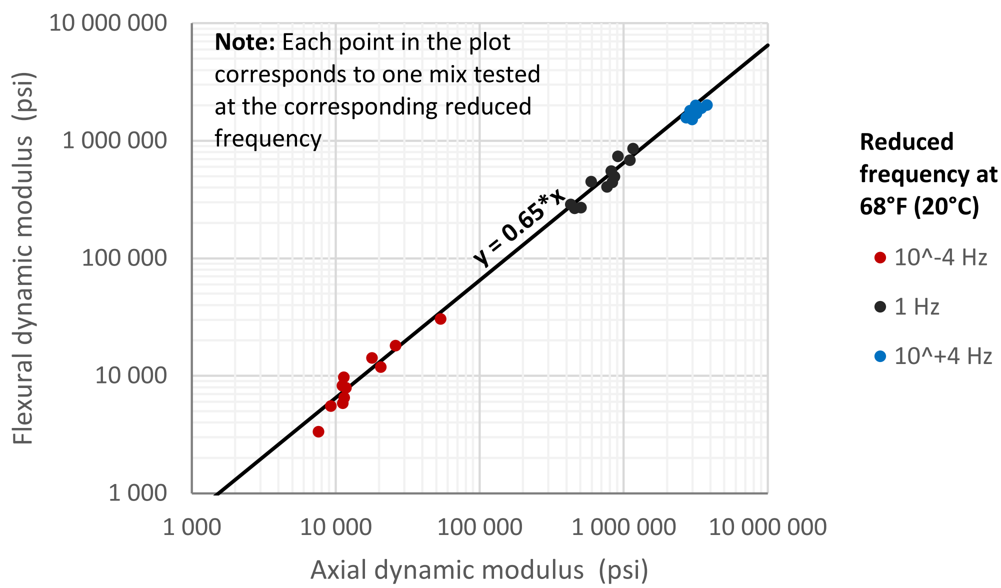


Figure 5.7: Relationship between axial dynamic modulus (AMPT) and flexural dynamic modulus—all mixes.

5.3 Flexural Fatigue Cracking Test

The results of the flexural fatigue testing are shown in Figure 5.8 and Figure 5.9 for the mixes with the PG 64 control binder and in Figure 5.10 for the mixes with the PG 58 binder. Surprisingly, the addition of the RAP did not have a negative effect on the fatigue life of the mixes at a given strain. In fact, the fatigue life of the mixes with RAP improves compared with the control mix with no RAP (Figure 5.8), including the mix with 25% RAP and no recycling agent, despite a significant increase in stiffness. The same applies to the addition of both RAP and RAS to the PG 64 mixes (Figure 5.9). The PG 58 mixes with RAP also have better fatigue performance than the PG 64 control mix with no RAP (Figure 5.10), regardless of whether they include recycling agent or not.

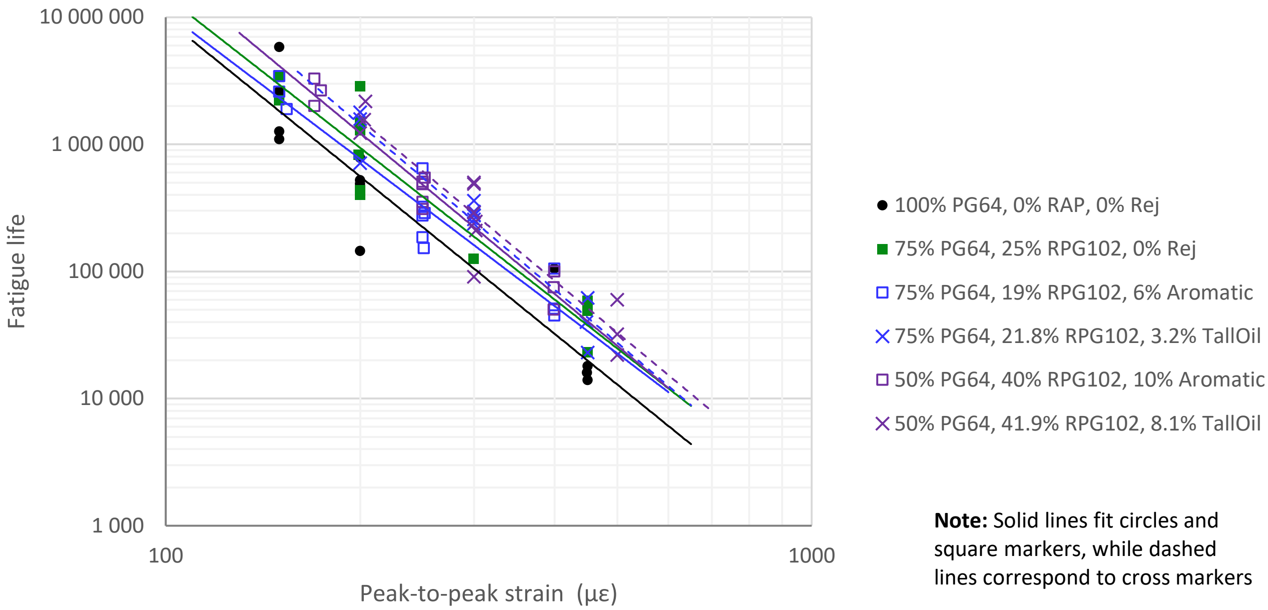


Figure 5.8: Flexural fatigue test results—mixes with PGH 64 and RAP.

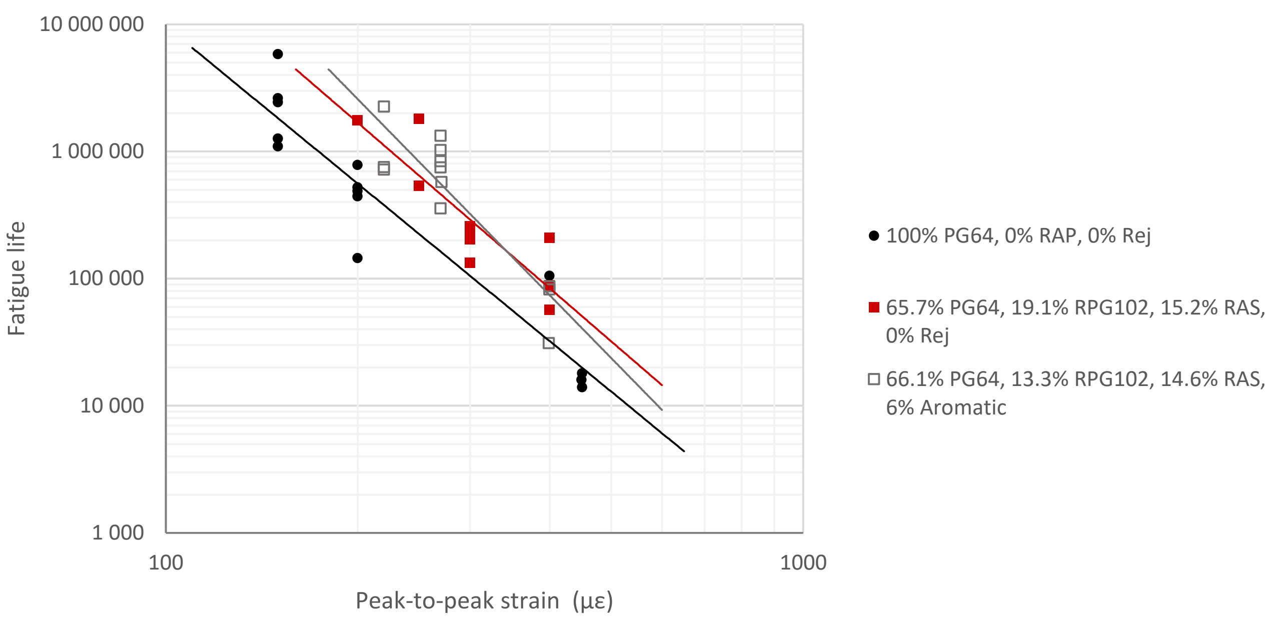


Figure 5.9: Flexural fatigue test results—mixes with PGH 64 and RAS.

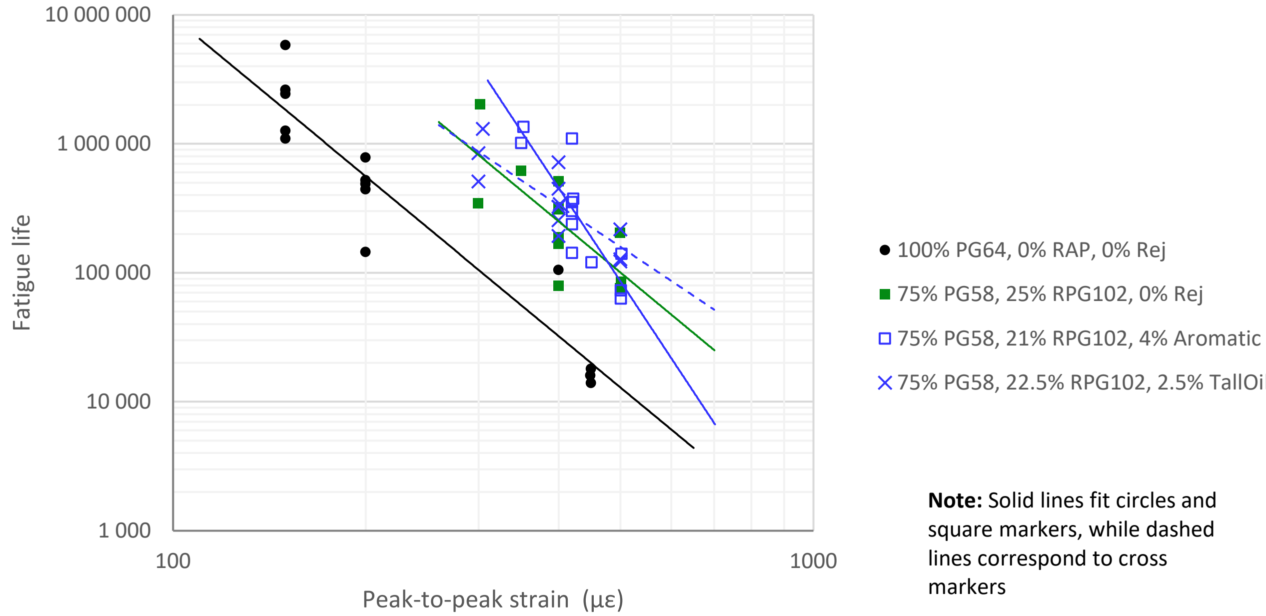


Figure 5.10: Flexural fatigue test results—mixes with PGH 58 and RAP.

5.4 IDEAL-CT Test

The results of the IDEAL-CT test are shown in Figure 5.11 and Figure 5.12 for the mixes with the PG 64 base binder and in Figure 5.13 for the mixes with PG 58 base binder. As explained above, two measures that result from the IDEAL-CT test are the *Cracking Tolerance Index* (CT_{Index}) and the *Strength*. There is poor correlation between CT_{Index} and 4PB fatigue life, shown in Figure 5.14 (ε_6 is the strain at which the 4PB fatigue life is 10^6 cycles). The same poor correlation was reported in a previous UCPRC study *(20)*. The CT_{Index} is correlated to the *Strength*, though the correlation is binder and most likely mix dependent. As shown in Figure 5.15, the relationship between CT_{Index} and *Strength* differs between the mixes with PG 64 base binder and the mixes with PG 58 base binder. In contrast, the relationship between axial dynamic stiffness at intermediate temperatures (and therefore also with flexural stiffness) and *Strength* is the same for the two groups of mixes (Figure 5.16). Similar outcomes were shown in the previously mentioned UCPRC study *(20)*.

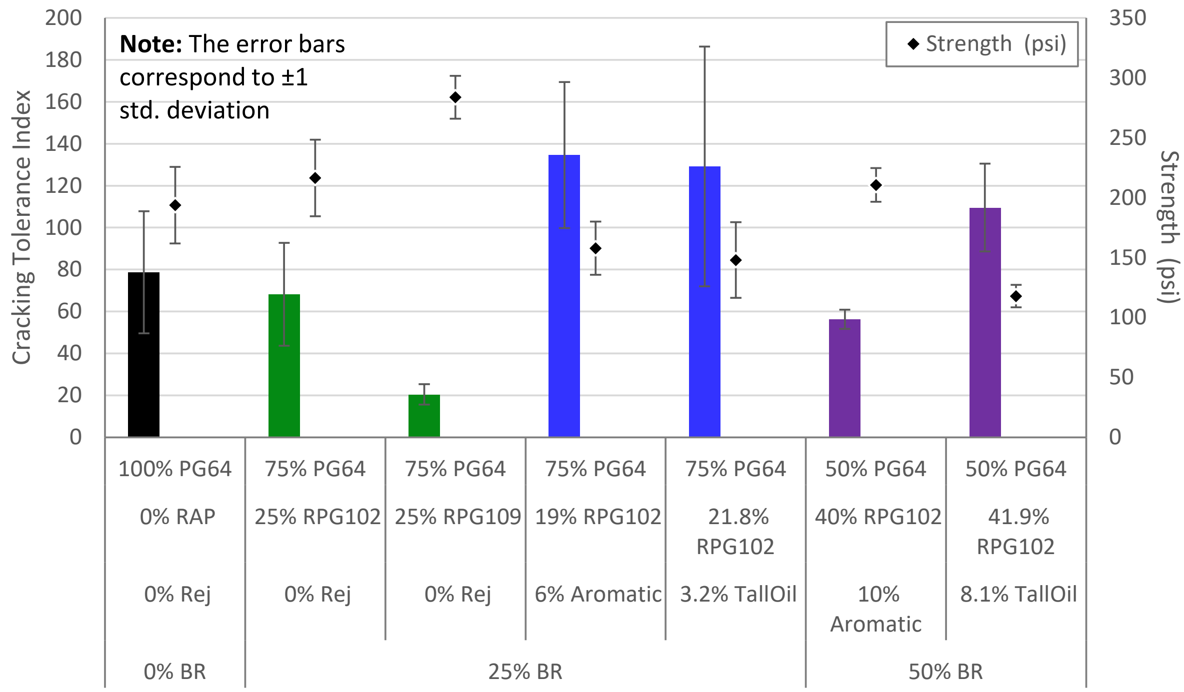


Figure 5.11: IDEAL-CT test results—mixes with PGH 64 and no RAS.

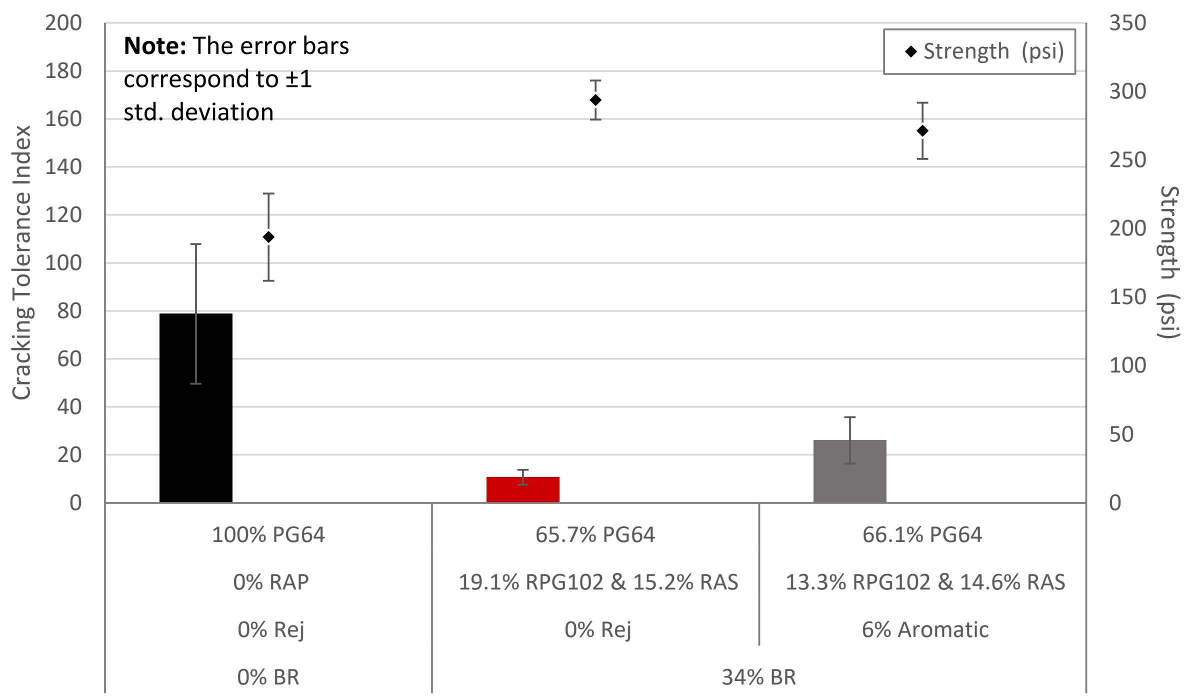


Figure 5.12: IDEAL-CT test results—mixes with PGH 64 and RAS.

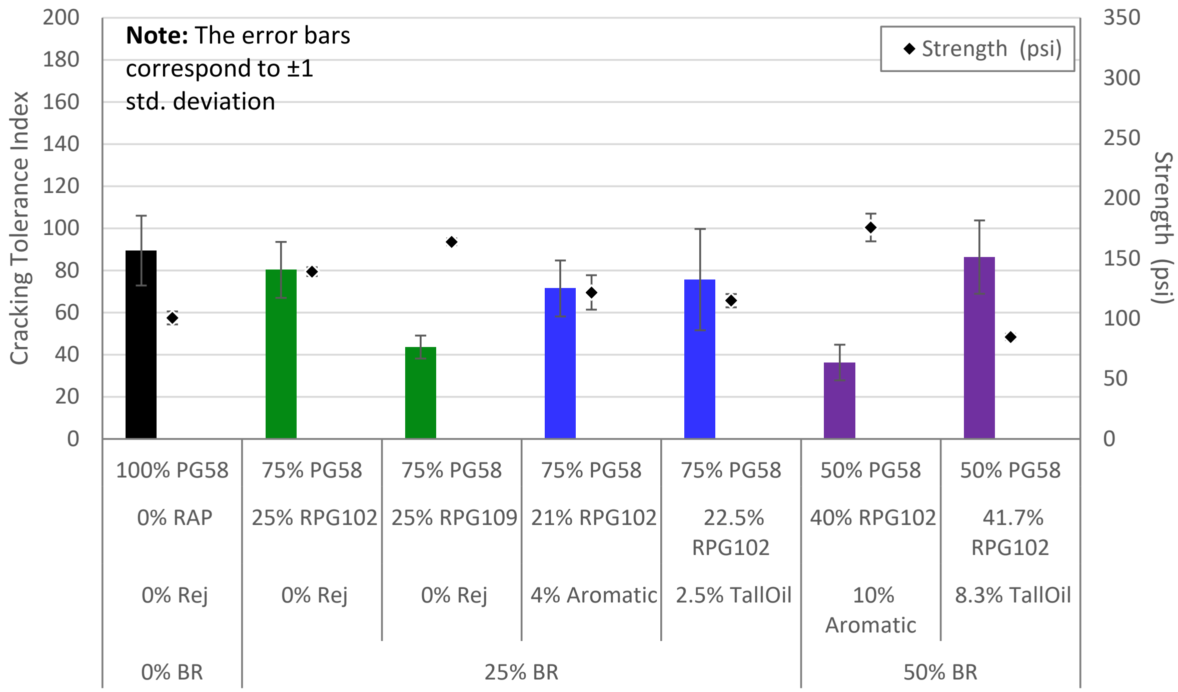


Figure 5.13: IDEAL-CT test results—mixes with PGH 58.

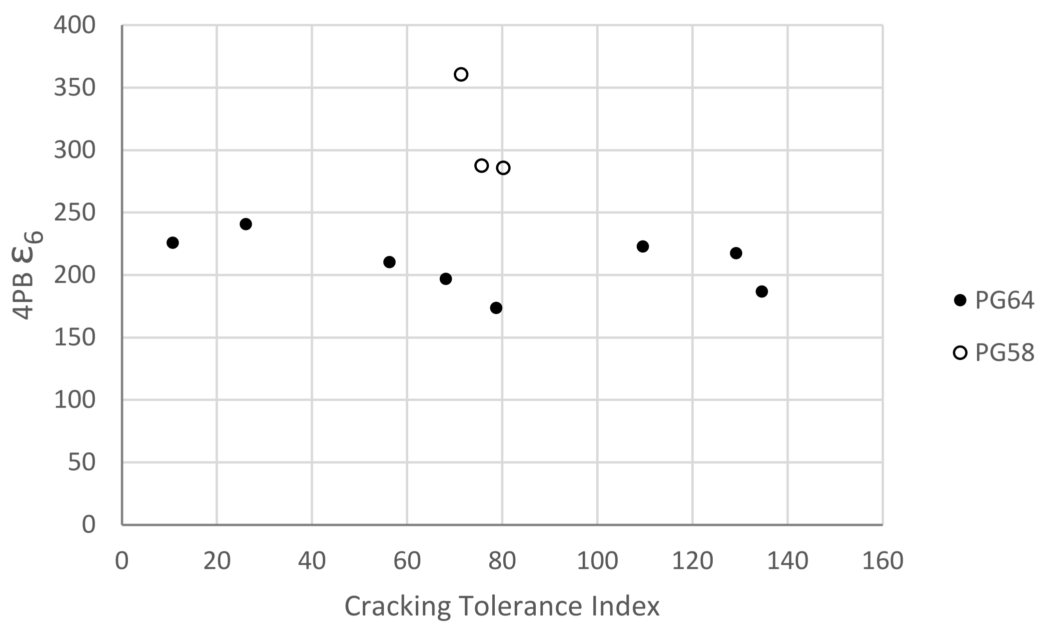


Figure 5.14: Relationship between ε_6 (4PB fatigue) and IDEAL CT_{Index}.

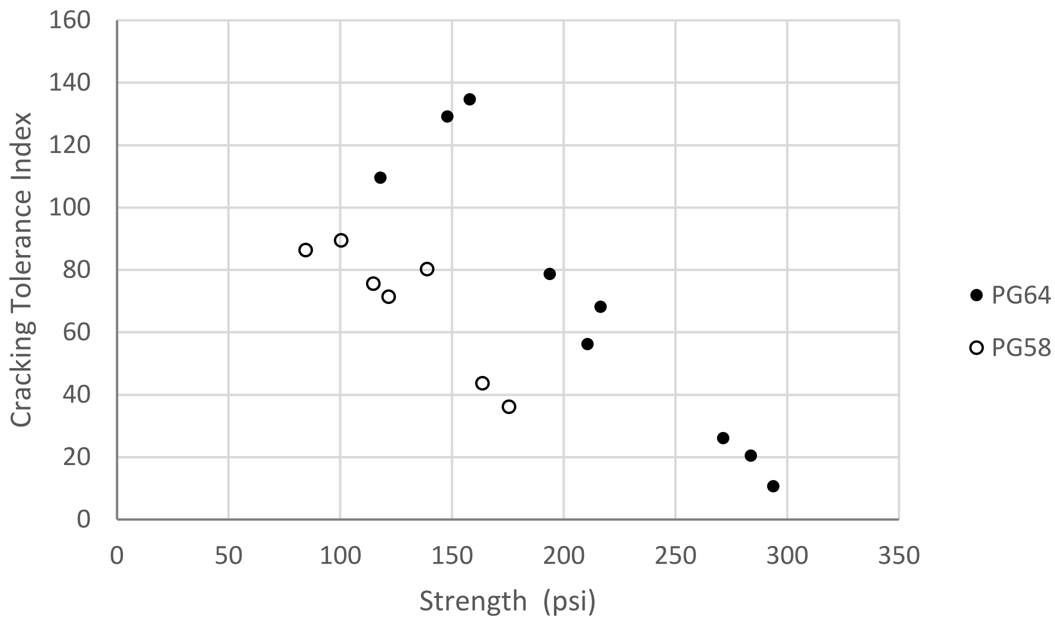


Figure 5.15: Relationship between IDEAL CT_{Index} and *Strength*.

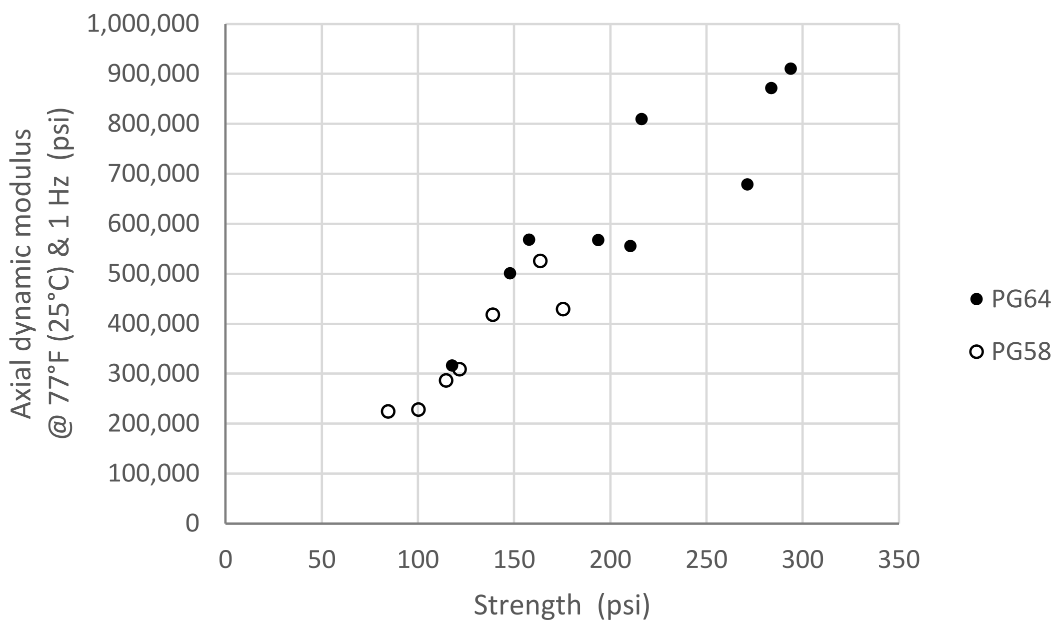


Figure 5.16: Relationship between axial dynamic stiffness at 77°F (25°C) and 1 Hz and IDEAL *Strength*.

5.5 Repeated Load Test

The results of the AMPT repeated load testing are shown in Figure 5.17 to Figure 5.20 for the mixes with PG 64 base binder and in Figure 5.21 and Figure 5.22 for the mixes with PG 58 base binder. The figures include the unconfined and confined (5 psi [35 kPa]) flow number at 122°F (50°C), with a repeated axial loading deviator stress of 483 psi (70 kPa). While there is a good correlation between the confined and unconfined flow number, there are also some outliers versus the overall trend (Figure 5.23).

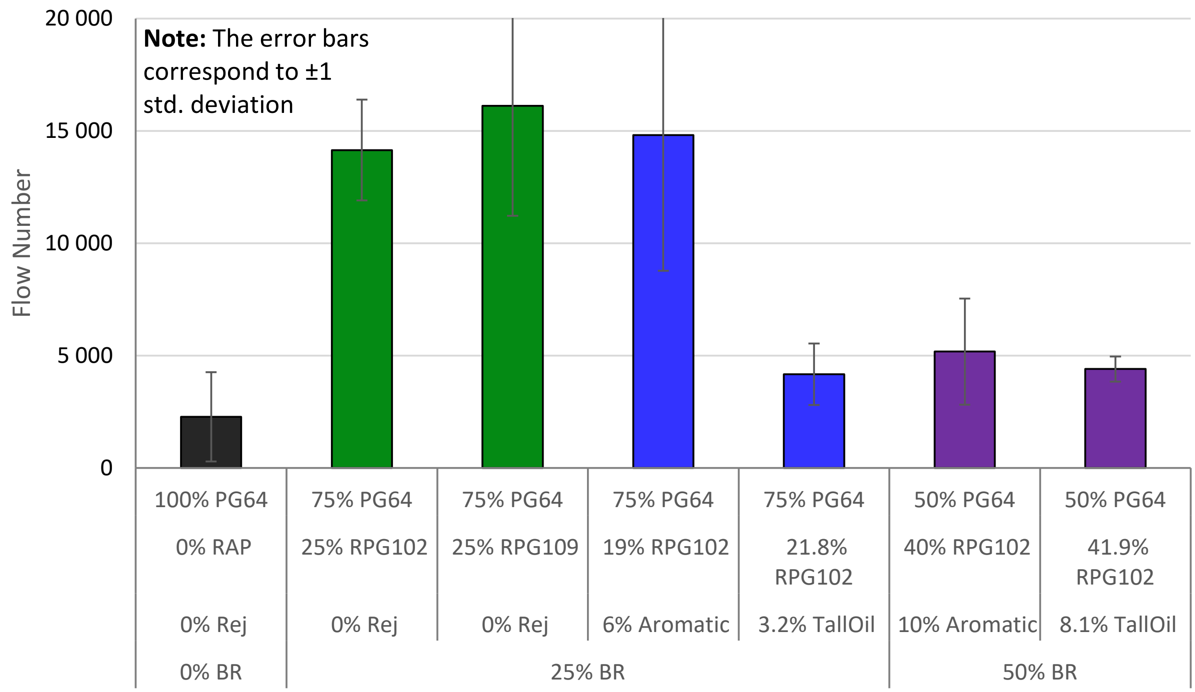


Figure 5.17: Repeated load test results at 122°F (50°C) and 5 psi (35 kPa) confinement—mixes with PG 64 and RAP.

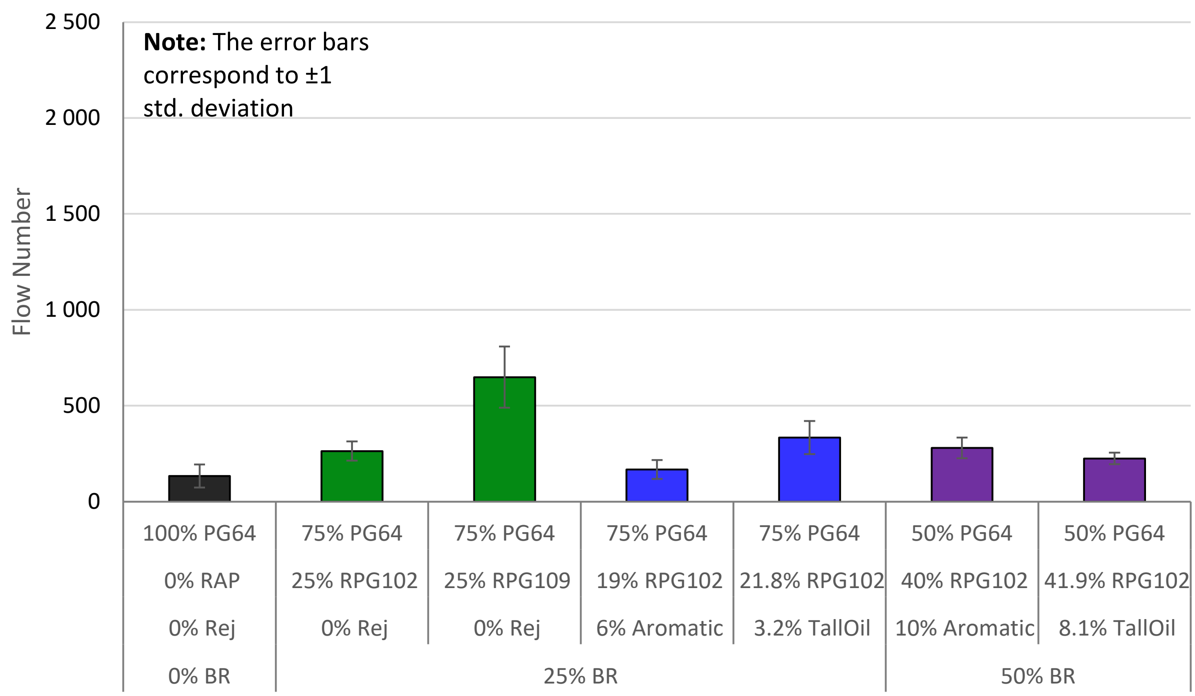


Figure 5.18: Repeated load test at 122°F (50°C) and no confinement—mixes with PG 64 and RAP.

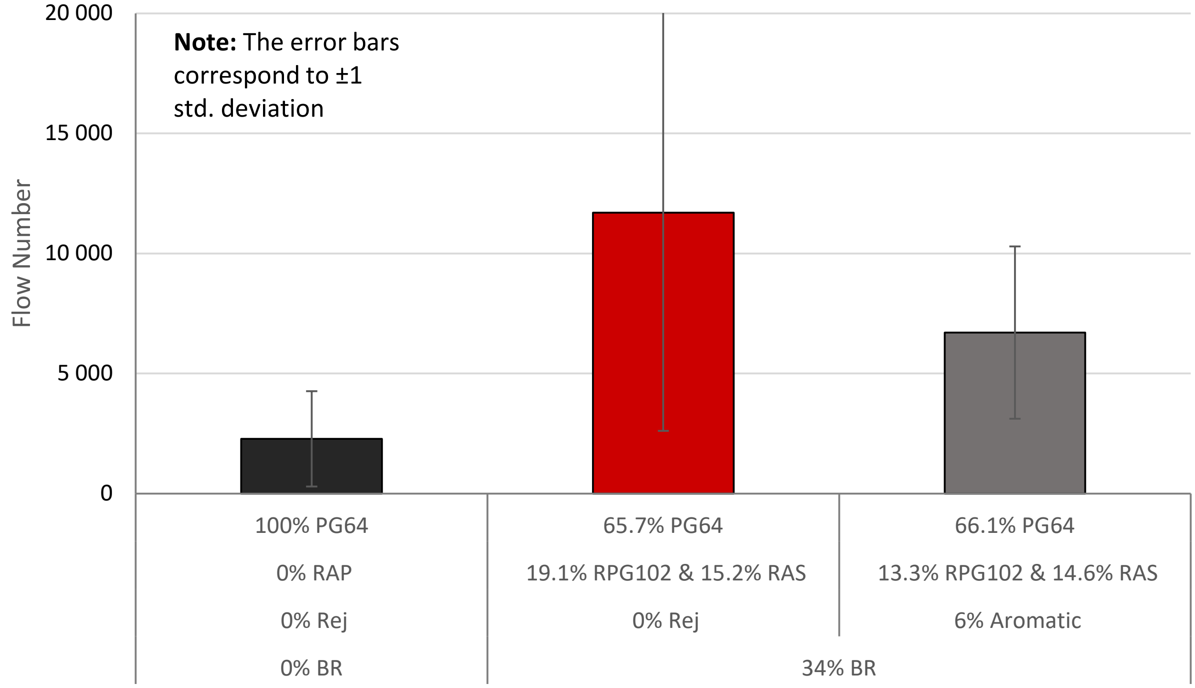


Figure 5.19: Repeated load test results at 122°F (50°C) and 5 psi (35 kPa) confinement—mixes with PG 64 and RAP.

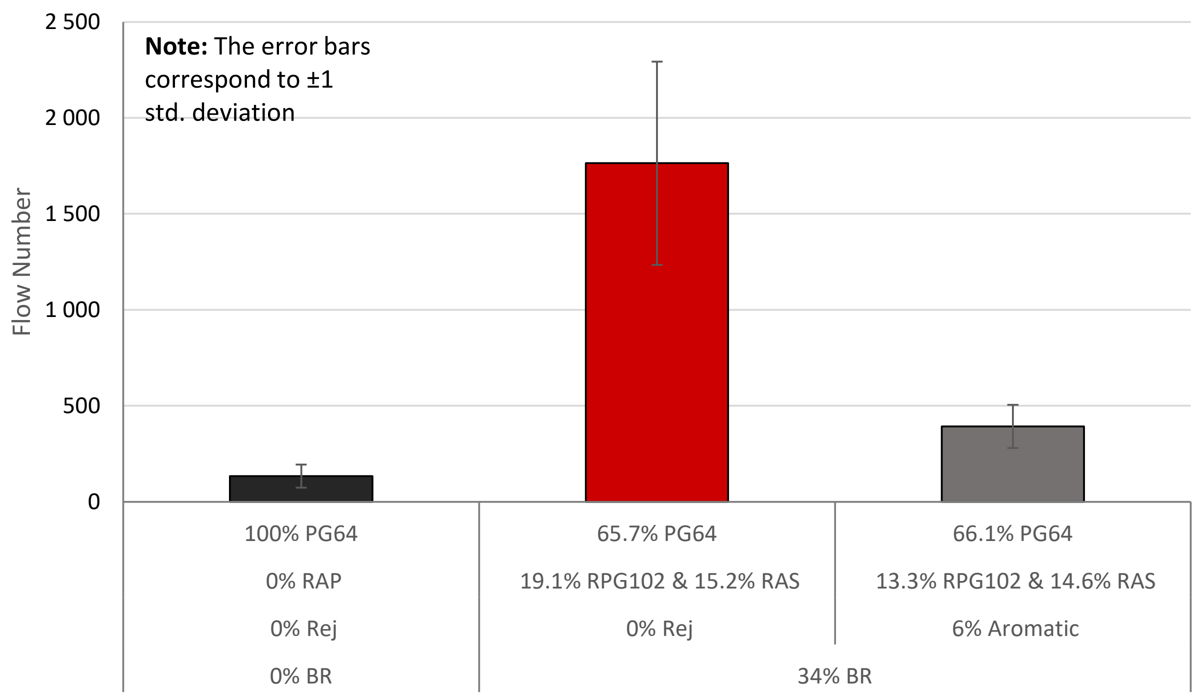


Figure 5.20: Repeated load test results at 122°F (50°C) and no confinement—mixes with PG 64 and RAS.

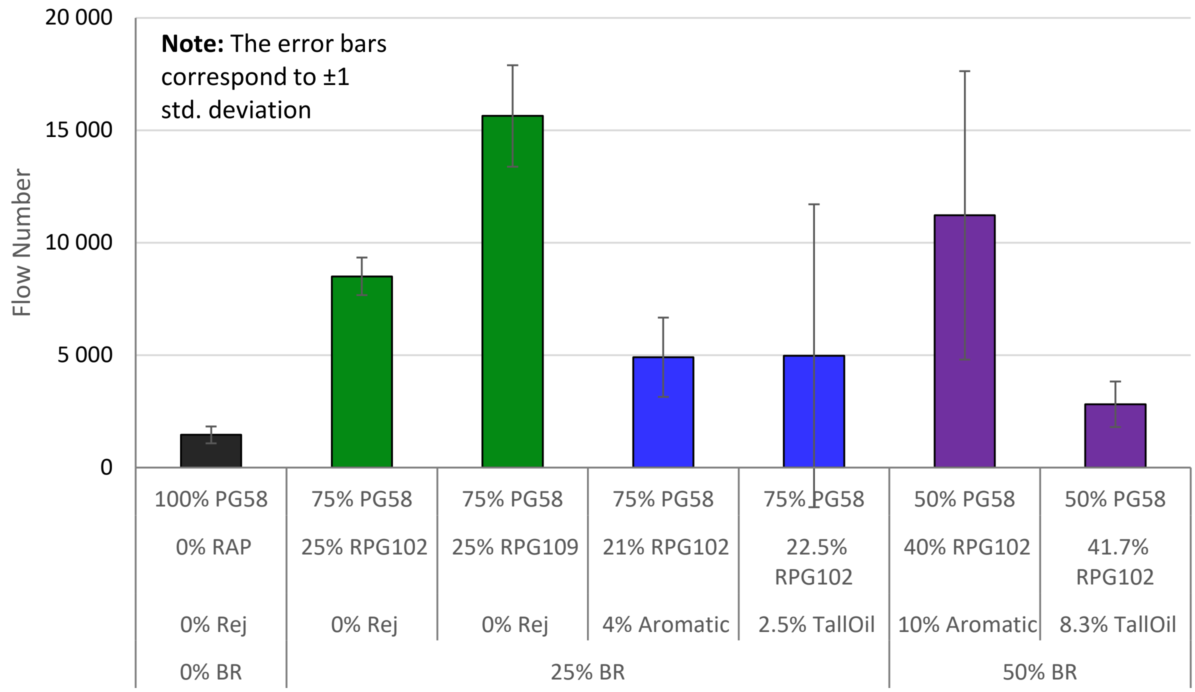


Figure 5.21: Repeated load test results at 122°F (50°C) and 5 psi (35 kPa) confinement—mixes with PG 58 and RAP.

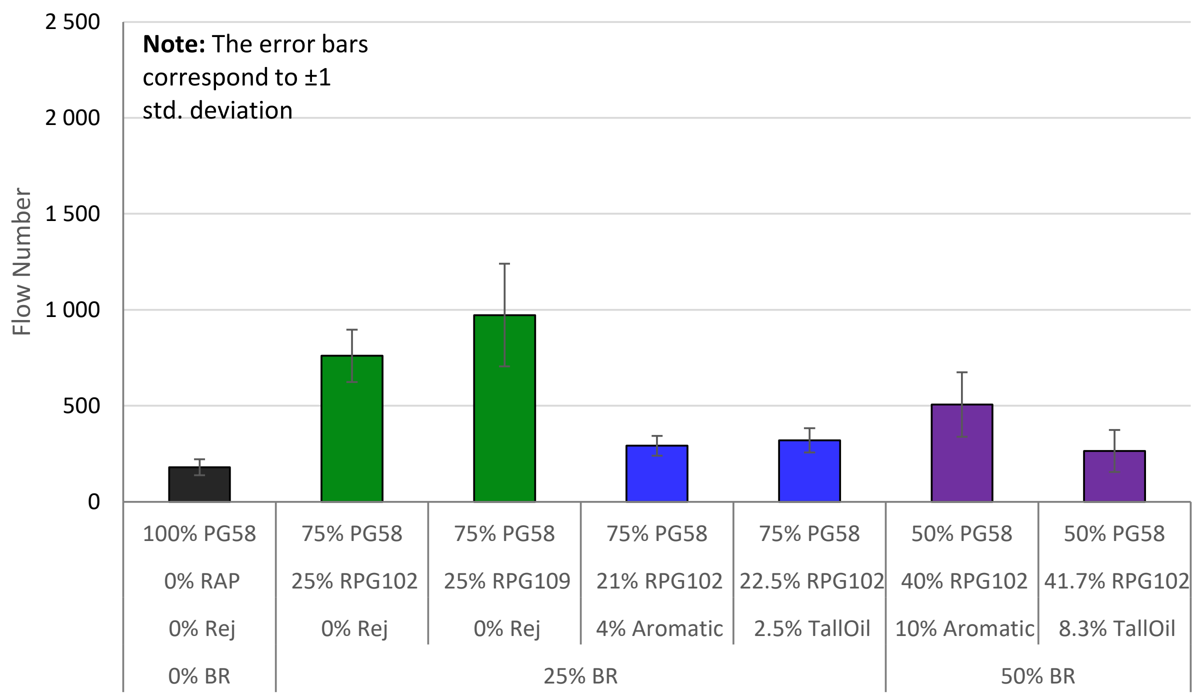


Figure 5.22: Repeated load test results at 122°F (50°C) and no confinement—mixes with PGH 58 and RAP.

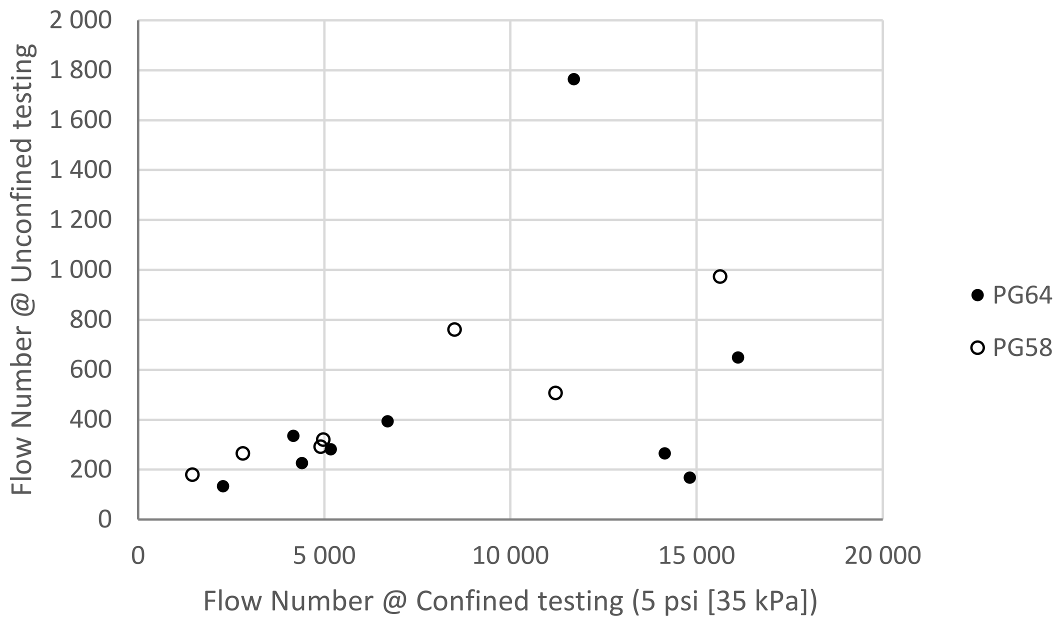
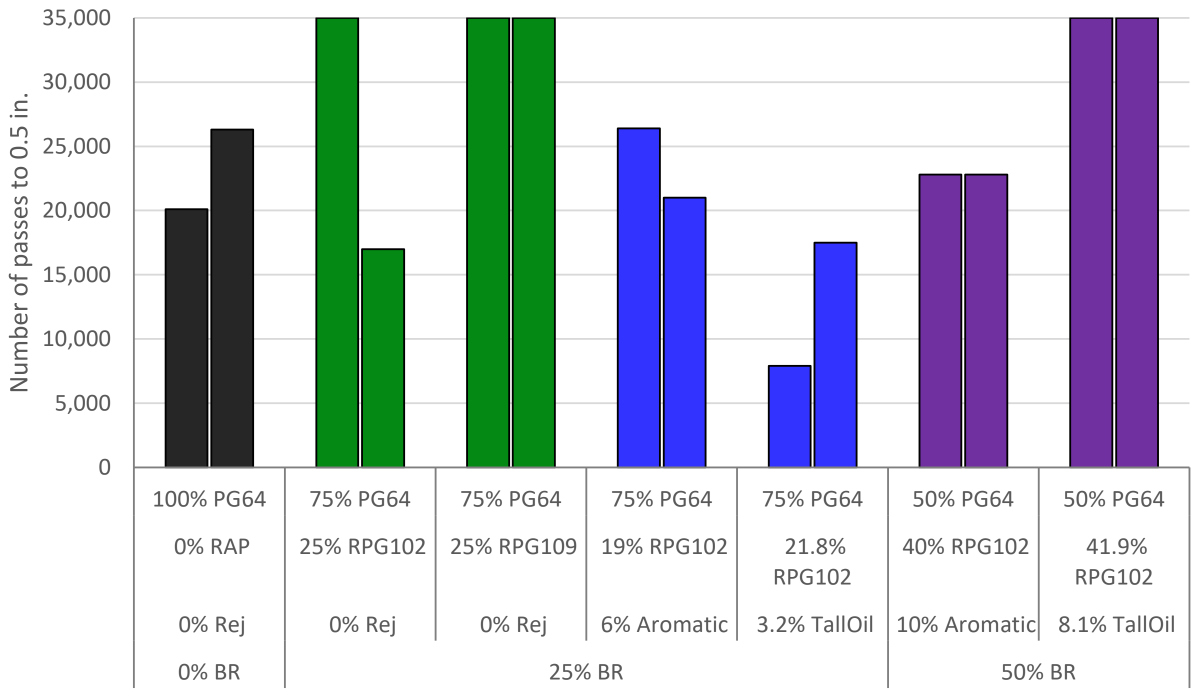


Figure 5.23: Relationship between unconfined and confined (5 psi [35 kPa]) flow number.

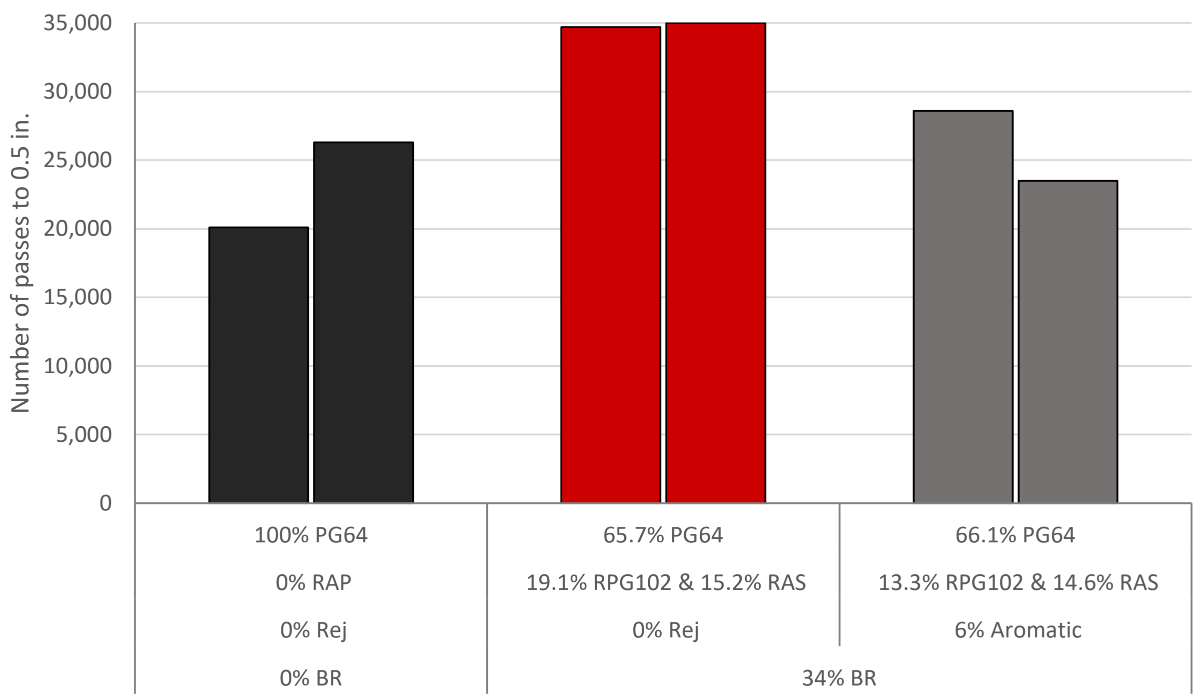
5.6 Hamburg Wheel-Tracking Test

The results of the Hamburg Wheel-Tracking (HWT) test are shown in Figure 5.24 and Figure 5.25 for the mixes with PG 64 base binder and in Figure 5.26 for the mixes with PG 58 base binder. The maximum number of passes applied in the HWT test was 35,000. There is poor correlation between the HWT test results (number of passes to 0.5 in. [12.5 mm]) and the AMPT flow number, both confined and unconfined, shown in Figure 5.27 and Figure 5.28, respectively.



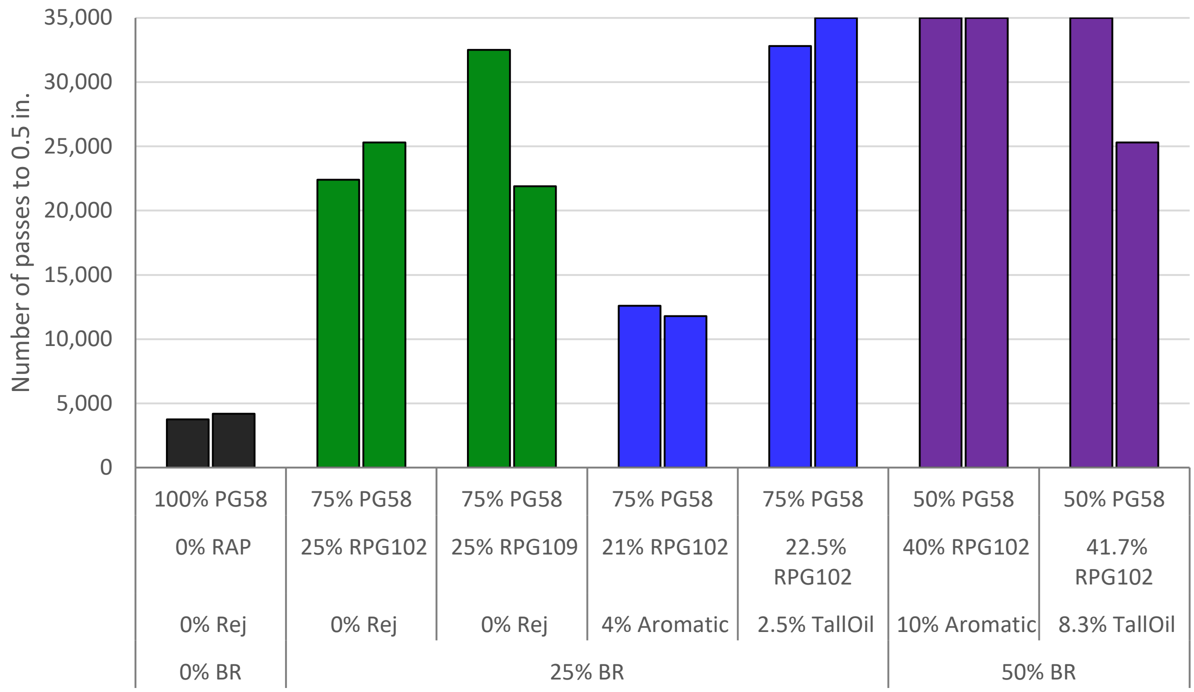
Note: For each mix, the two columns correspond to left and right wheels of the HWT, respectively.

Figure 5.24: Hamburg Wheel-Tracking test results—mixes with PGH 64 and no RAS.



Note: For each mix, the two columns correspond to left and right wheels of the HWT, respectively.

Figure 5.25: Hamburg Wheel-Tracking test results—mixes with PGH 64 and RAS.



Note: For each mix, the two columns correspond to left and right wheels of the HWT, respectively.

Figure 5.26: Hamburg Wheel-Tracking test results—mixes with PGH 58.

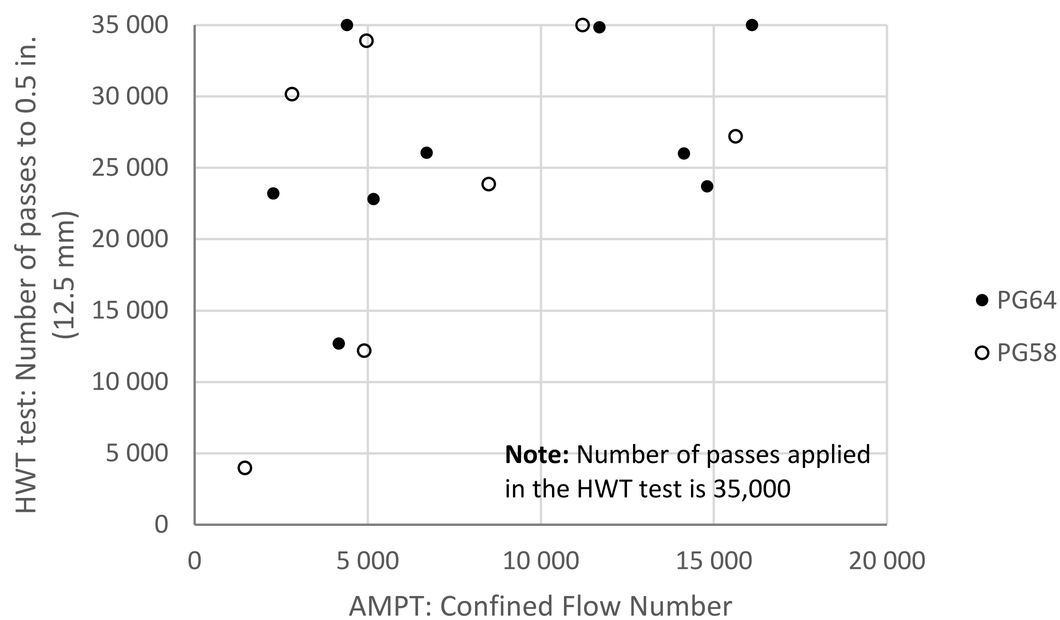


Figure 5.27: Relationship between confined (5 psi [35 kPa]) AMPT flow number and HWT test number of passes to 0.5 in. (12.5 mm); both tests conducted at 122°F (50°C).

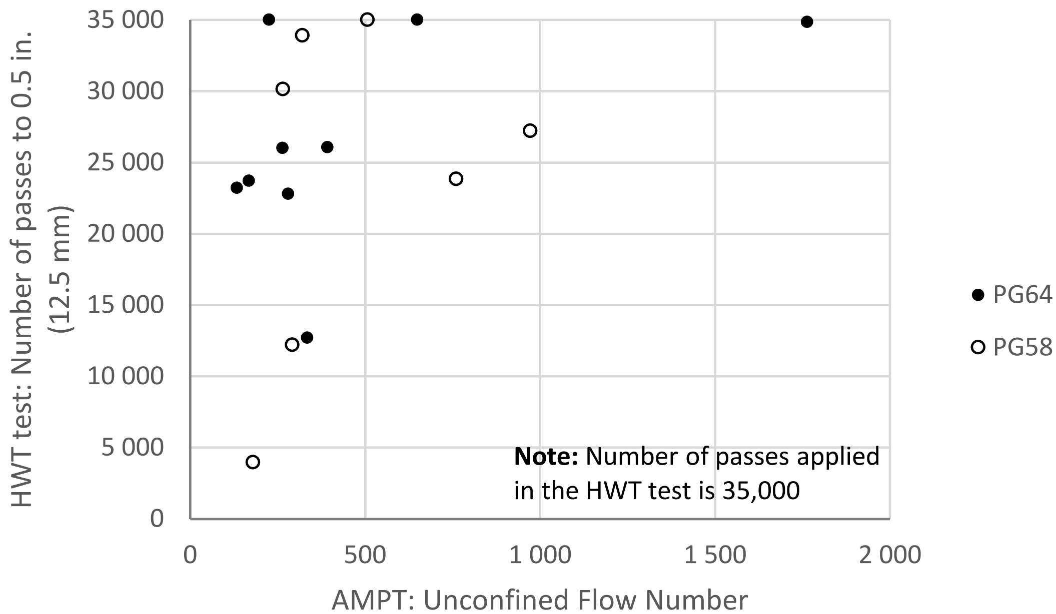


Figure 5.28: Relationship between unconfined AMPT flow number and HWT test number of passes to 0.5 in. (12.5 mm); both tests conducted at 122°F (50°C).

6 DISCUSSION OF RESULTS

The results of the testing of mixes and binders are discussed in this chapter. The discussion is organized around the different questions that this research study was expected to answer (Section 1.3).

6.1 What Are the Effects of the Addition of High RAP content on the Mechanical Properties of the HMA?

The effects of the RAP addition can be evaluated by comparing the mechanical properties of the mixes with 25% RAP and no recycling agent versus the mechanical properties of the two mixes without RAP (with a PGH of either 64°C or 58°C). The 50% binder replacement mixes were only evaluated with recycling agent. The addition of RAP to HMA produced the following effects:

- **HMA stiffness:** The HMA stiffness increased (Figure 6.1). The same conclusion has been reported by other studies *(2,3,4)*. As shown in Figure 6.1, the RAP addition shifts the dynamic modulus master curve of the HMAs with no RAP ("100% PG64, 0% RAP, 0% Rej" and "100% PG58, 0% RAP, 0% Rej") to the left (decreasing reduced frequency), which results in increasing stiffness for the same reduced frequency, or equivalently increasing stiffness for the same temperature.
- **HMA IDEAL-CT test results:** The IDEAL-CT test load-displacement curves showed increased strength and a steeper post-peak curve of load versus displacement (Figure 6.2). As shown in Figure 6.2, the curves expand in the y-axis direction (higher load) while contracting in the x-axis direction (lower displacement). Increased strength in this test has been highly correlated with axial and flexural stiffness at intermediate temperatures and frequencies of loading (Figure 5.16). The CT_{Index} is a function of the strength and other parameters describing the shape of the load-displacement curve (see Section 2.3.2.5) and decreased with the inclusion of 25% RAP (Figure 6.3).
- **HMA fatigue resistance:** The 4PB flexural fatigue life slightly increased (Figure 6.4) with the inclusion of 25% RAP. This outcome was not expected, and it is believed to be related to the virgin binder used in the control mix ("100% PG64, 0% RAP, 0% Rej"). To test the hypothesis, the 4PB fatigue life of the control mix with no RAP was compared with the fatigue life of other HMAs with a similar binder PG grade but from different sources and RAP contents from 0% to 25%. The comparison in Figure 6.5 shows that the fatigue life of the control mix is much lower than the fatigue life of HMAs produced with binders with same or similar PG grade from other sources for mixes with 0% to 25% RAP. Further, Figure 6.6 shows that increased binder replacement for the PG 64 control mix results in a greater ε_6, with an increased ε_6 meaning longer fatigue life at a given tensile strain, which indicates that the RAP binder alone and the combination of RAP binder and recycling agent provide better fatigue resistance than the base binder (PG 64) used in this study.
- **HMA rutting resistance:** The rutting resistance increased (Figure 6.7 and Figure 6.8) with the addition of RAP. The same conclusion has been reported by other studies *(2,3,4)*. Figure 6.7 shows the improvement in rutting resistance based on AMPT repeated load testing. Figure 6.8

shows the same result based on HWT test with one exception: the 25% RAP(A), which had less aging, did not improve the HWT rutting performance. In the two figures, the mixes with PG 64 and 25% RAP must be compared with the mix with PG 64 and 0% RAP while the mixes with PG 58 and 25% RAP must be compared with the mix with PG 58 and 0% RAP.

- **Others:** For all variables (stiffness, IDEAL CT_{Index} and *Strength*, and rutting resistance), the effect of the Inland Valley RAP(B) was greater than the effect of the Southern California RAP(A). This outcome agrees with the higher degree of aging of the Inland Valley RAP(B), whose PGH is 109°C, compared with the Southern California RAP(A), whose PGH is 102°C.

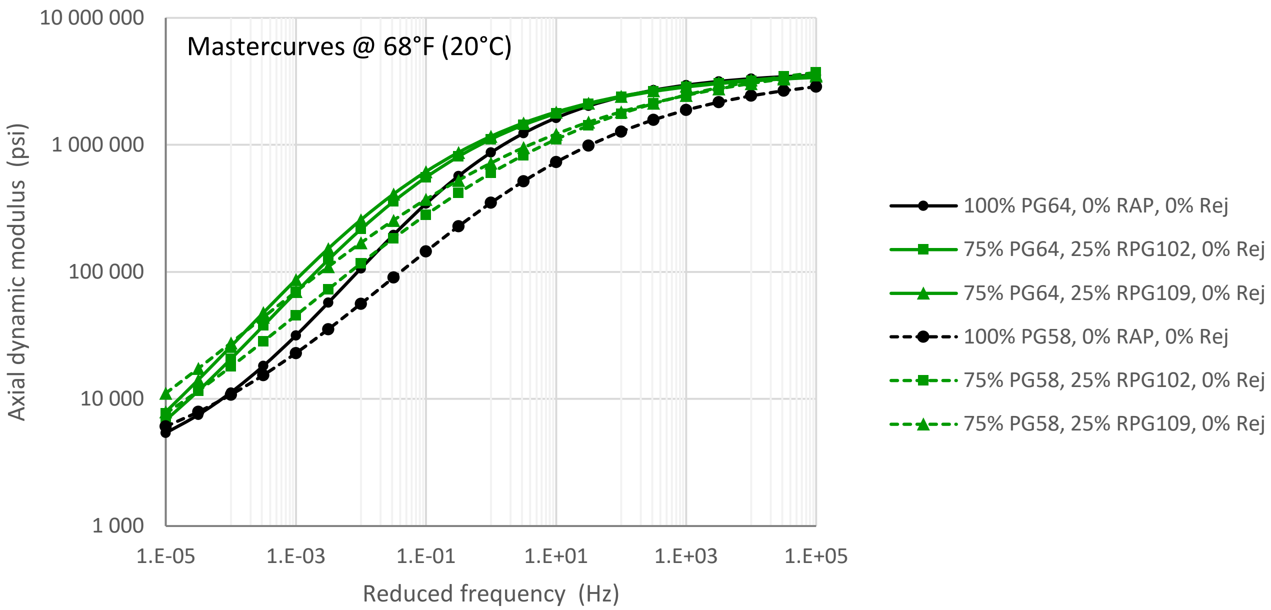


Figure 6.1: Effect of RAP on HMA stiffness.

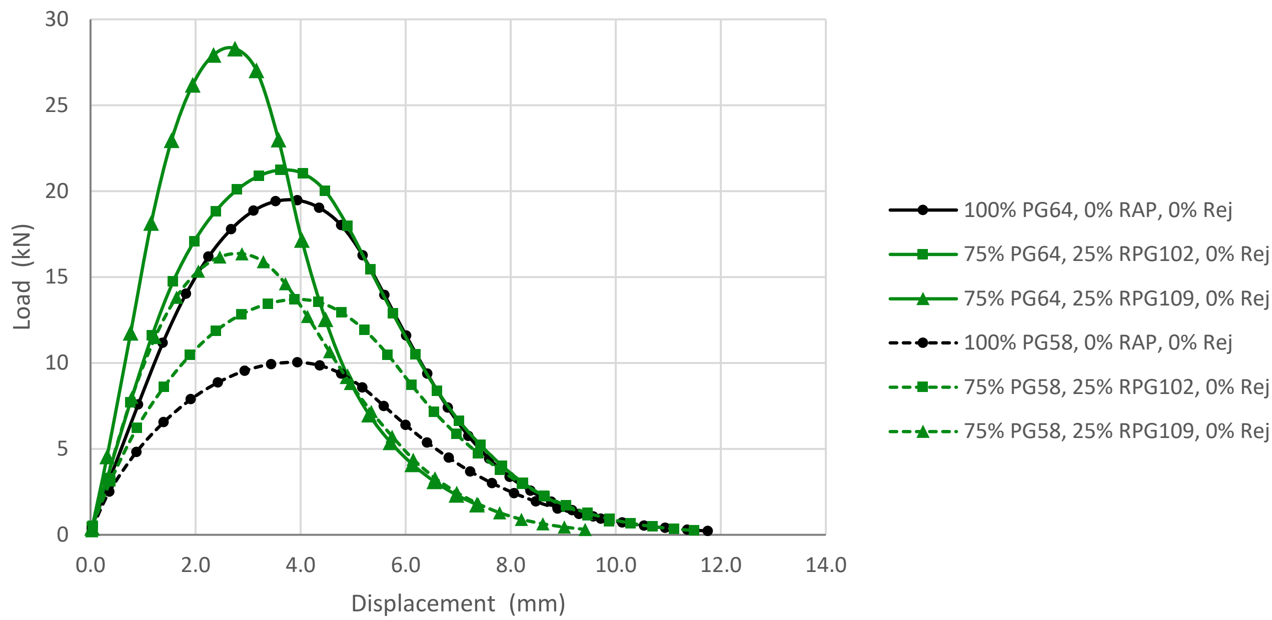


Figure 6.2: Effect of RAP on HMA IDEAL-CT test (load versus displacement curves).

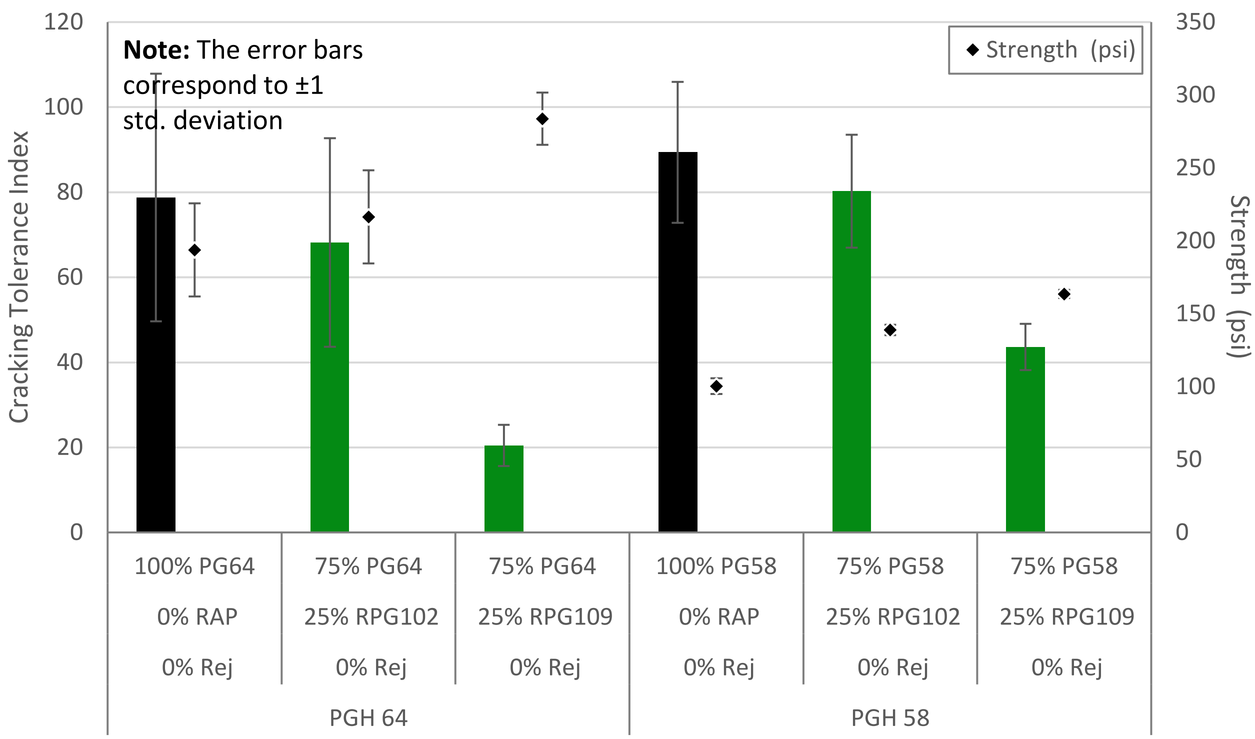


Figure 6.3: Effect of RAP on HMA IDEAL-CT test results.

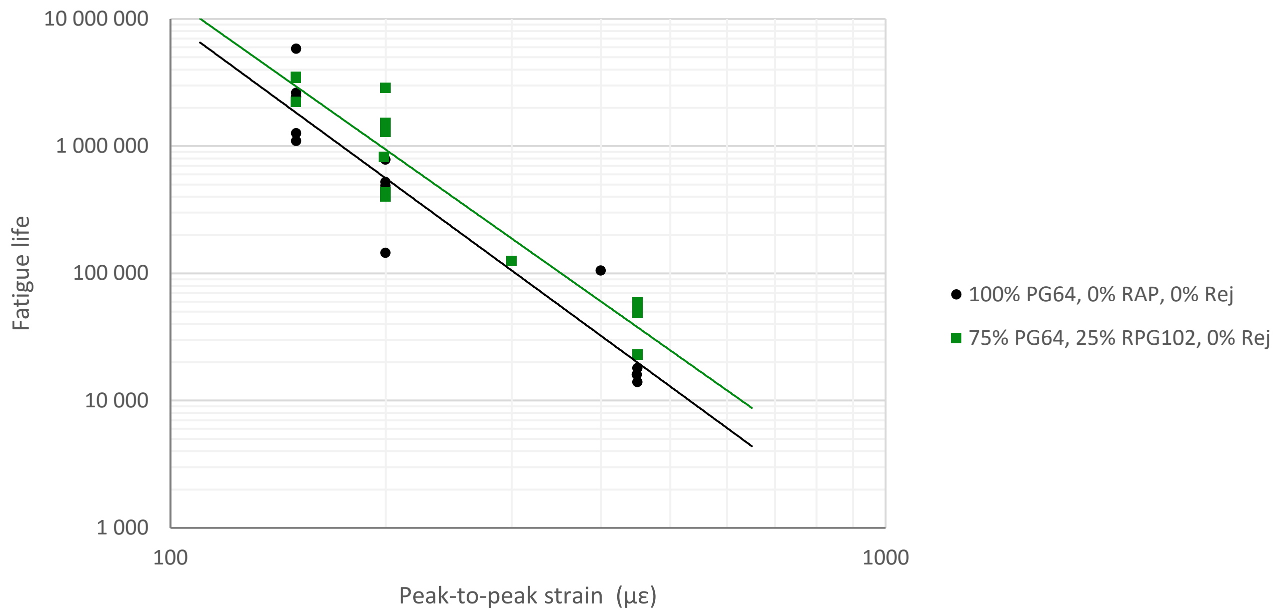


Figure 6.4: Effect of RAP on HMA 4PB fatigue life.

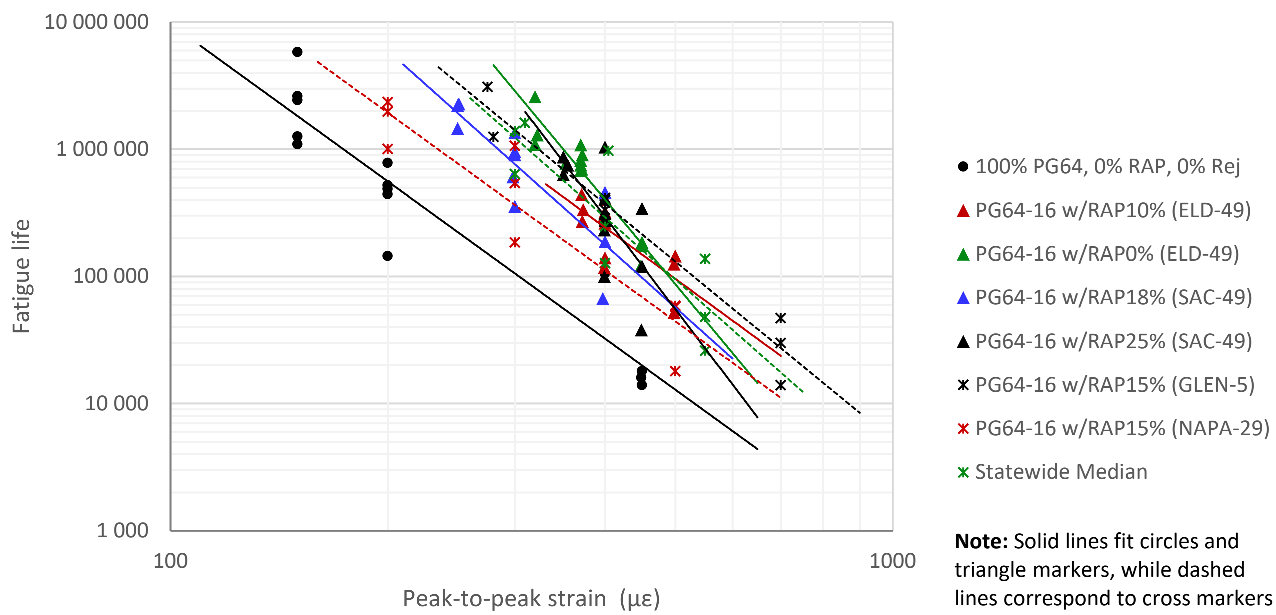


Figure 6.5: Comparison of fatigue life of the control mix (100% PG64, 0% RAP, 0% Rej) versus other HMAs with similar PG grade (either PG 64-16 or PG 64-10) and different binder sources with 0% to 25% RAP.

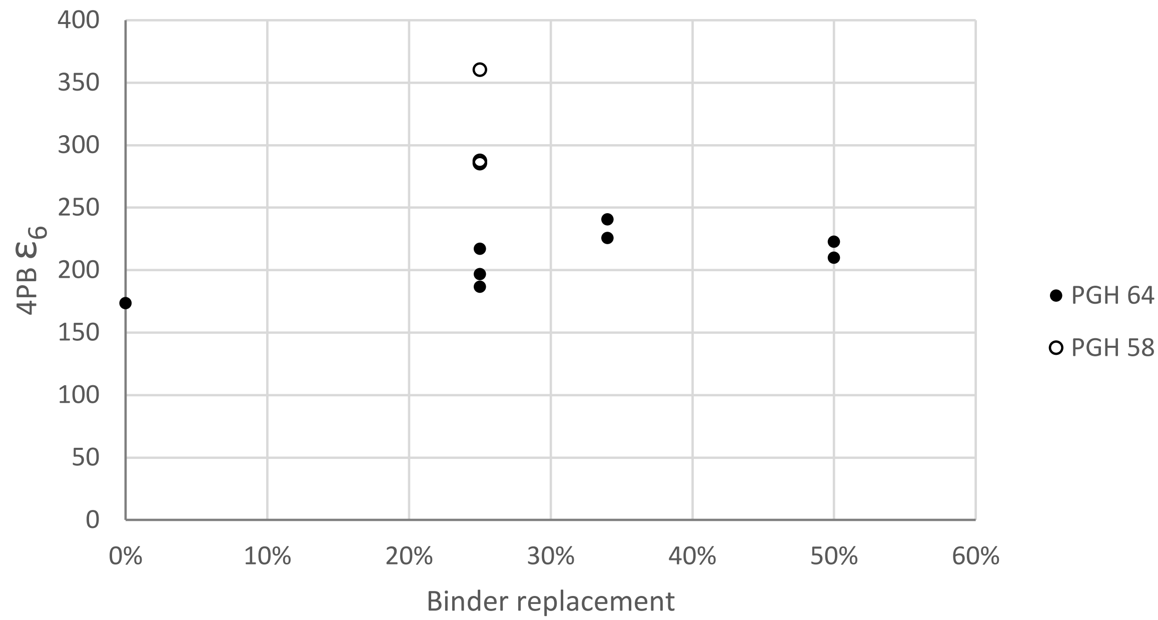


Figure 6.6: Binder replacement effect on flexural fatigue life of mix of PG64 and PG58 mixes.

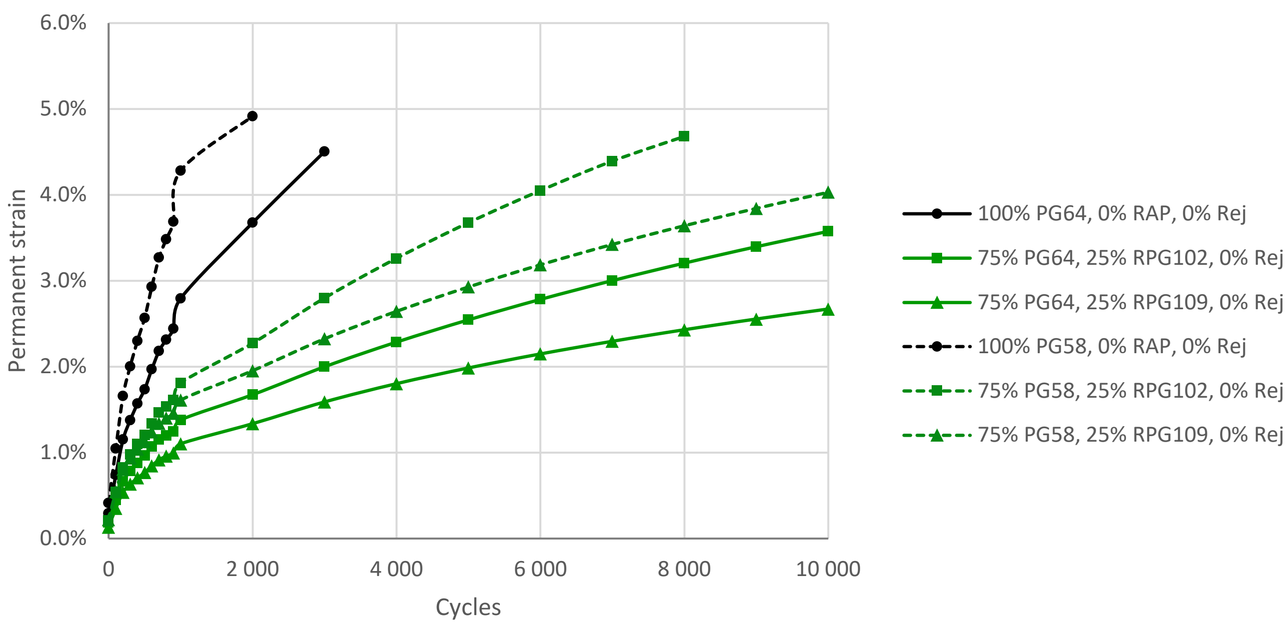


Figure 6.7: Effect of RAP on HMA rutting resistance (AMPT confined repeated load testing).

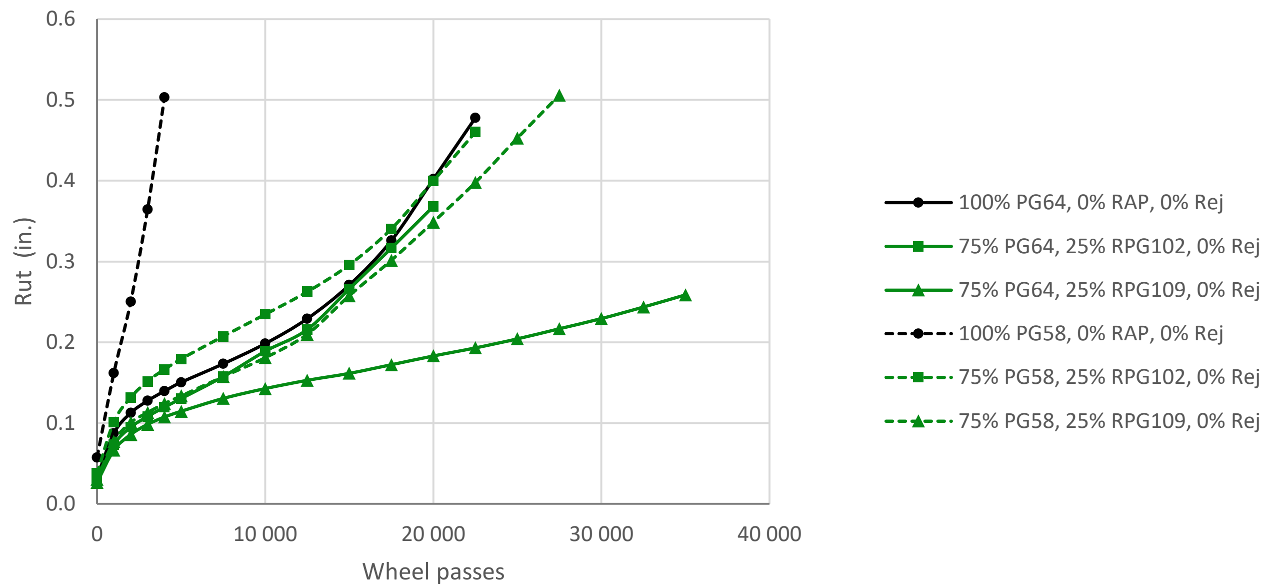


Figure 6.8: Effect of RAP on HMA rutting resistance (HWT testing).

6.2 Can the RAP Addition Effects Be Predicted Based on Testing of the Blended Binder?

The answer to the research question is addressed below for each of the HMA mechanical properties that were evaluated in this study:

- **HMA stiffness:** There is a strong correlation between HMA stiffness at high, intermediate, and low temperatures and the respective high, intermediate, and low PGs of the binder blend (Figure 6.9, Figure 6.10, and Figure 6.11, respectively). The increase in HMA stiffness at the high temperature (Figure 6.9) is also consistent with the high temperature PG of the RAP binder: higher for RAP(B) (PGH 109) than for RAP(A) (PGH 102), as expected. The relationships presented in Figure 6.9 to Figure 6.11 cannot be directly applied to other HMAs. Nonetheless, a similar pattern is expected for other HMAs: an increase in the PG high, intermediate, and low of the binder blend will be an indication of the HMA stiffening at high, intermediate, and low temperatures due to the RAP addition.
- **HMA IDEAL-CT test results:** There is a good correlation between the strength of the HMA, measured in the IDEAL-CT test, and the intermediate PG of the binder blend (Figure 6.12). This outcome is consistent with the good correlation found between HMA stiffness at the intermediate temperature and binder blend intermediate temperature PG (Figure 6.10), on the one hand, and between HMA stiffness at the intermediate temperature and IDEAL *Strength* (Figure 5.16), on the other hand. Unfortunately, the performance grade intermediate (PGI) of the binder blend was not a good indicator of the RAP effect on HMA IDEAL CT_{Index} (Figure 6.13). The same conclusion applies to the high and low temperature PGs (figures not shown in the report).

- **HMA fatigue resistance:** Only one of the HMAs with RAP was tested for 4PB flexural fatigue together with the corresponding mix with no RAP: the HMA with a PGH of 64°C and 25% RAP(A) (PGH of 102°C). While the PGI of the binder blend increased due to the RAP addition (from 28.7°C to 32.9°C), the fatigue resistance did not drop, which was the expected outcome. The PGI of the binder blend was not a good indicator of RAP effect on HMA fatigue resistance. The same conclusion applies to the PGHs and performance grade lows (PGLs) (figures not shown in the report).
- **HMA rutting resistance:** The increase in rutting resistance, measured with AMPT repeated load testing and HWT testing, is consistent with the increase in the PGH of the binder blend. There is a good correlation between rutting resistance and PGH, shown in Figure 6.15 (AMPT, unconfined flow number), Figure 6.16 (AMPT, confined flow number), and Figure 6.17 (HWT test, number of passes to 0.5 in. [12.5 mm]). The relationship between rutting resistance and PGH is somewhat less consistent for the unconfined flow number (Figure 6.15) than for the other two variables. Again, while the relationships presented in Figure 6.15 to Figure 6.17 cannot be directly applied to other HMAs, similar pattern is expected: an increase in the PGH of the binder blend will be an indication of the HMA improved rutting resistance due to the RAP addition.

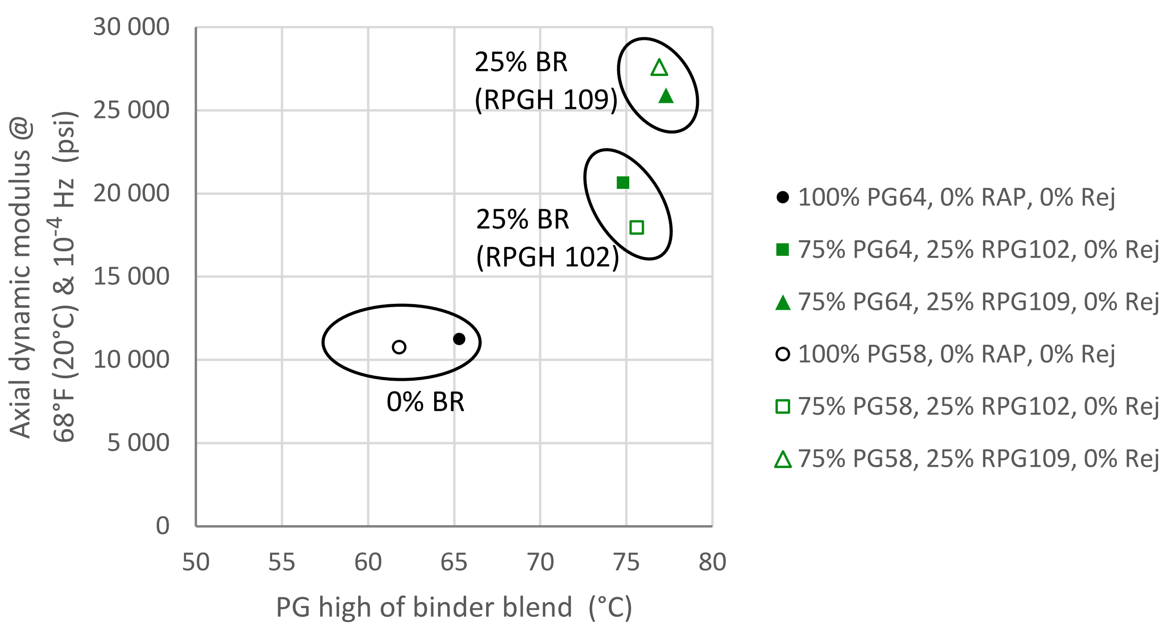


Figure 6.9: Relationship between HMA stiffness at high temperature (low reduced frequency) and binder blend PGH.

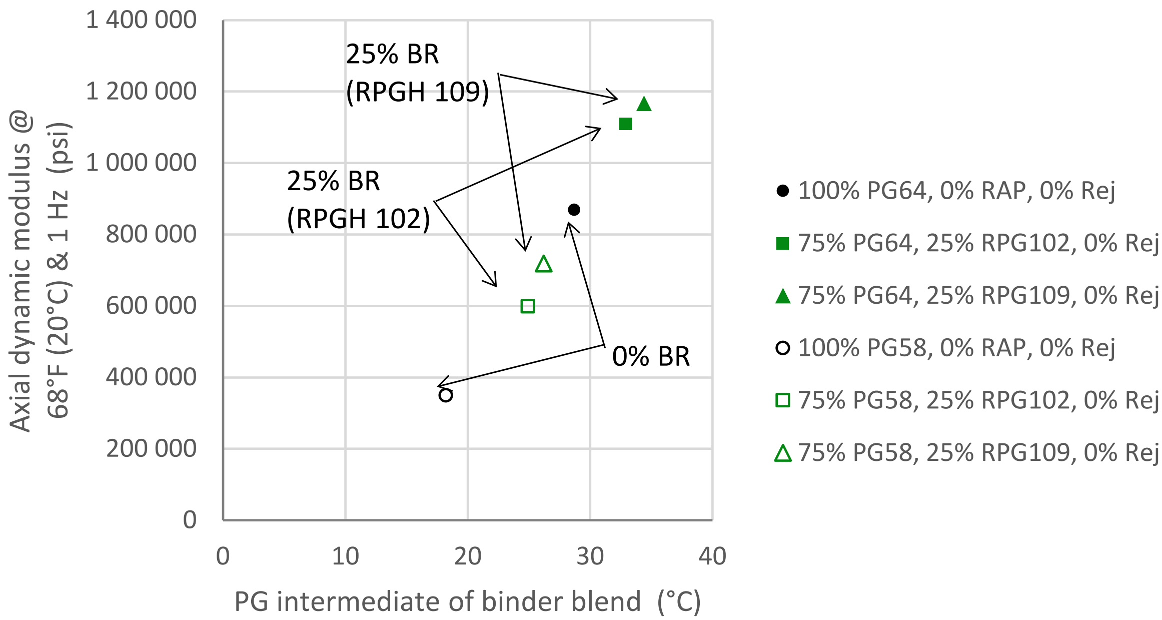


Figure 6.10: Relationship between HMA stiffness at intermediate temperature (intermediate reduced frequency) and binder blend PGI.

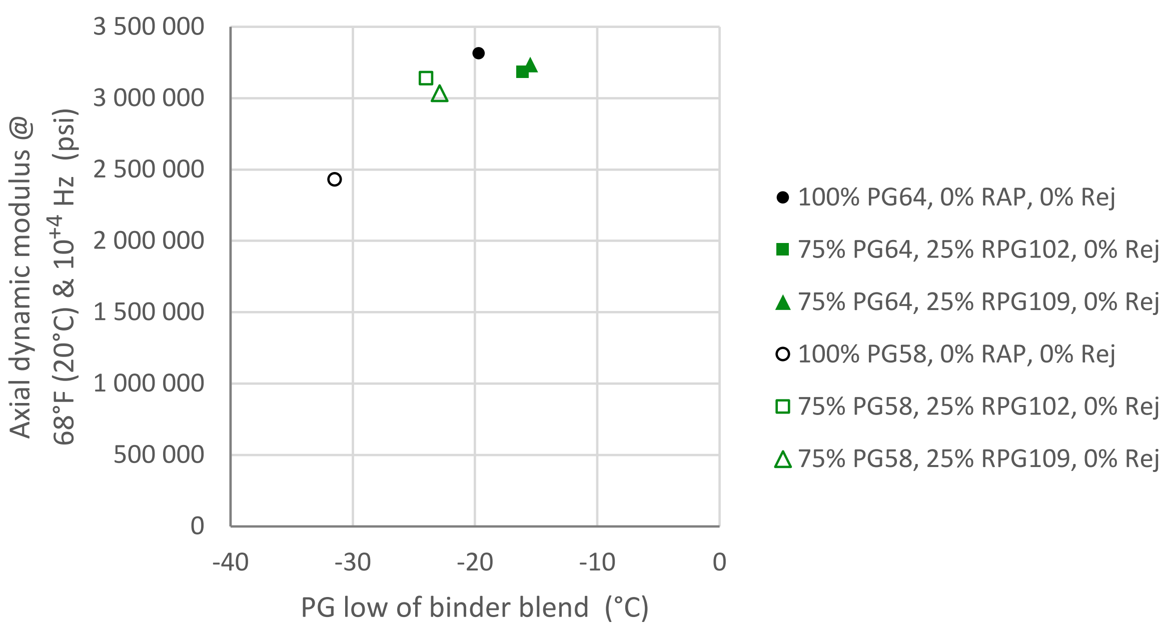


Figure 6.11: Relationship between HMA stiffness at low temperature (high reduced frequency) and binder blend PGL.

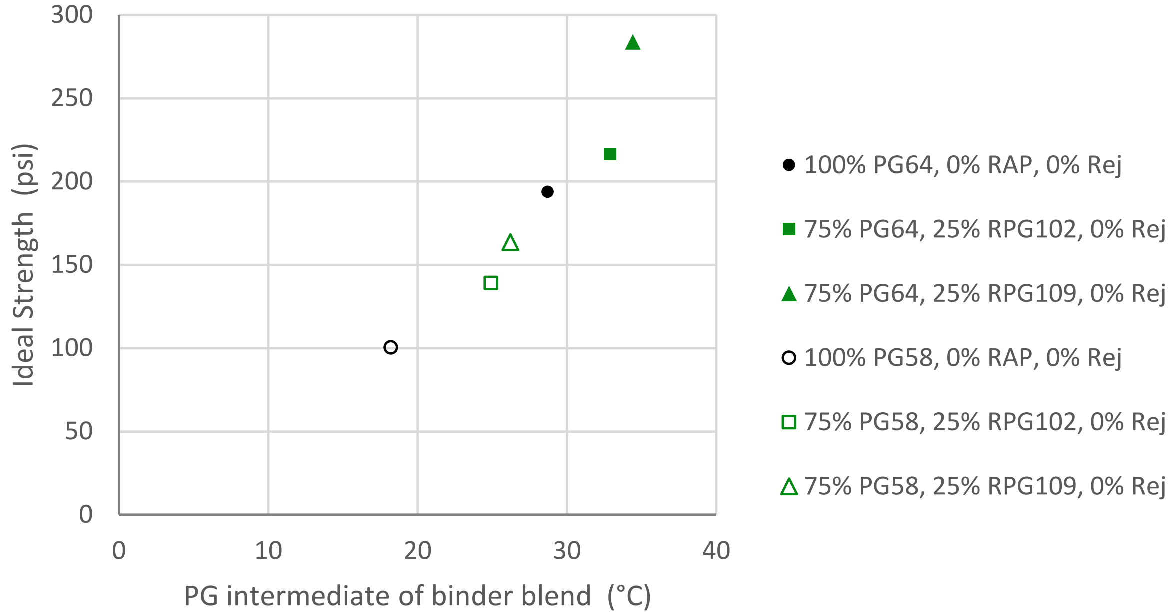


Figure 6.12: Relationship between IDEAL *Strength* and binder blend PGI.

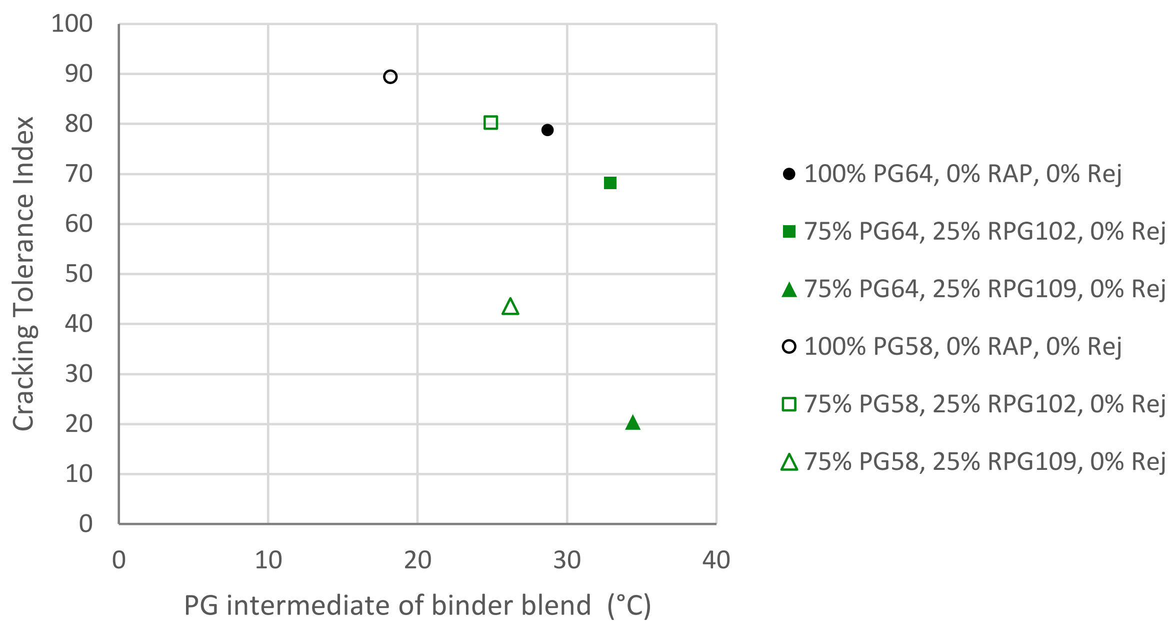


Figure 6.13: Relationship between IDEAL CT_{Index} and binder blend PGI.

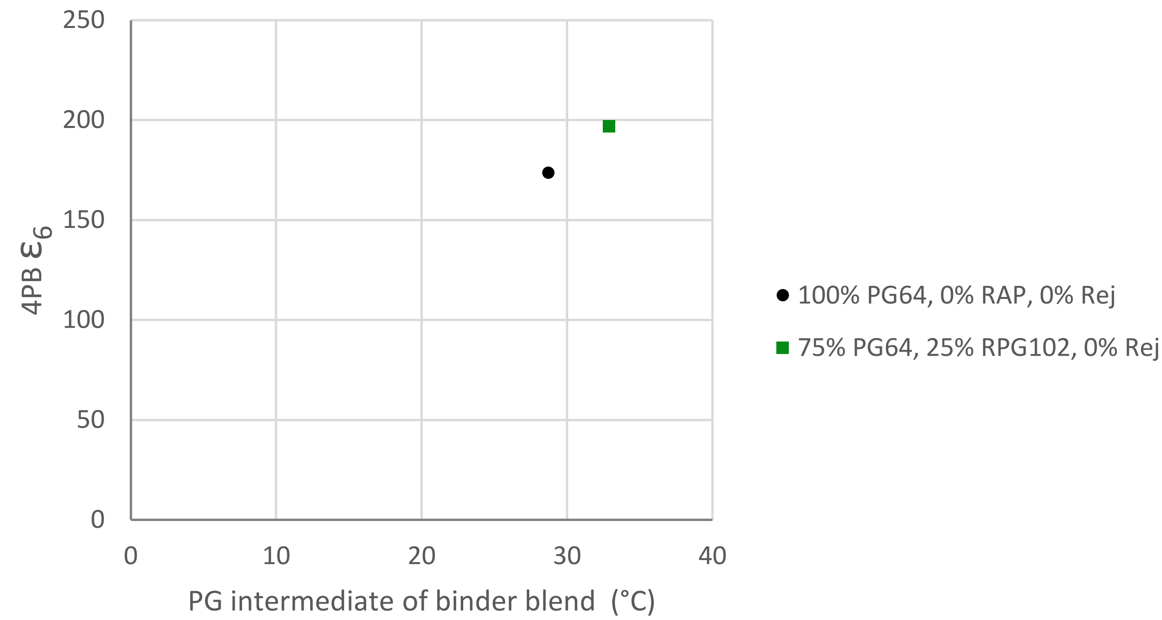


Figure 6.14: Relationship between ε_6 (strain for which fatigue life is 1 million load repetitions in the 4PB flexural fatigue test) and binder blend PGI.

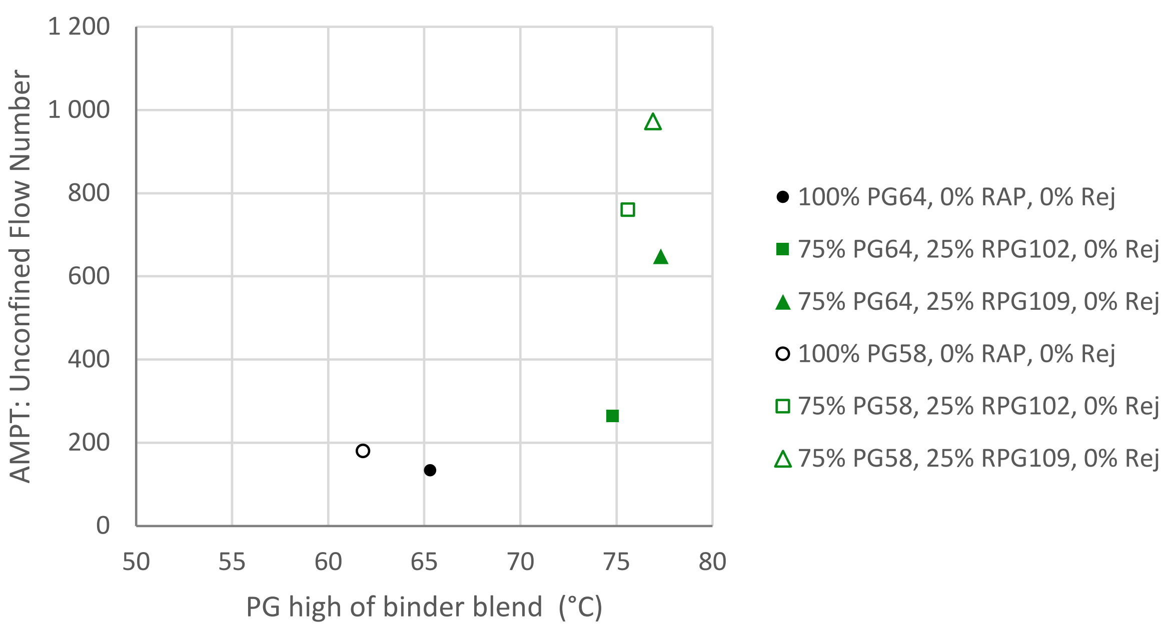


Figure 6.15: Relationship between HMA rutting resistance (AMPT, unconfined flow number) and binder blend PGH.

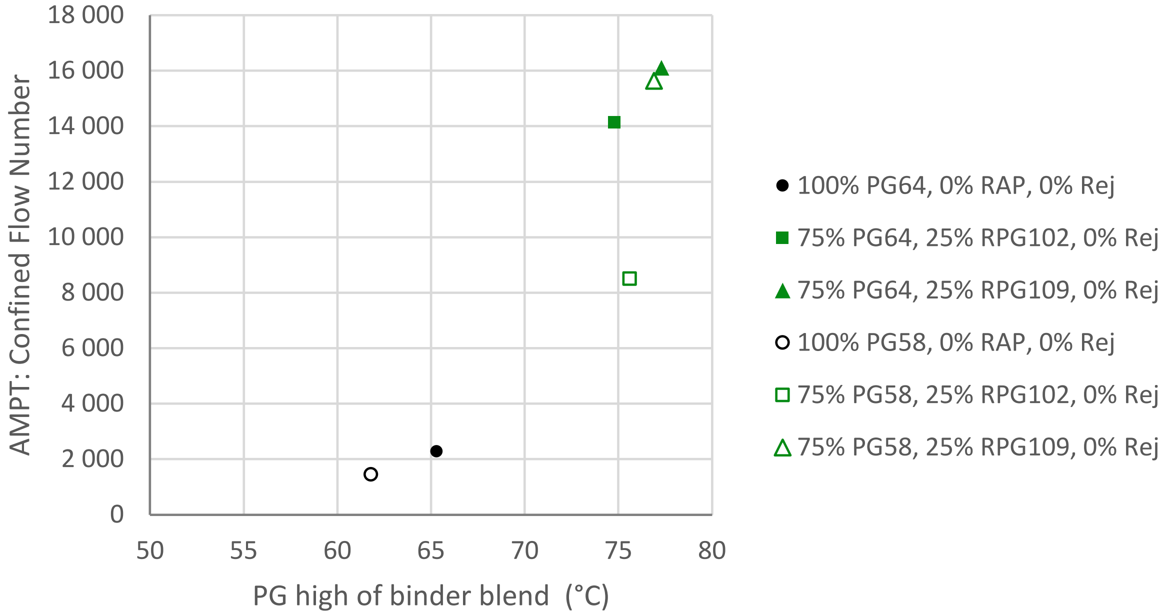


Figure 6.16: Relationship between HMA rutting resistance (AMPT, confined flow number) and binder blend PGH.

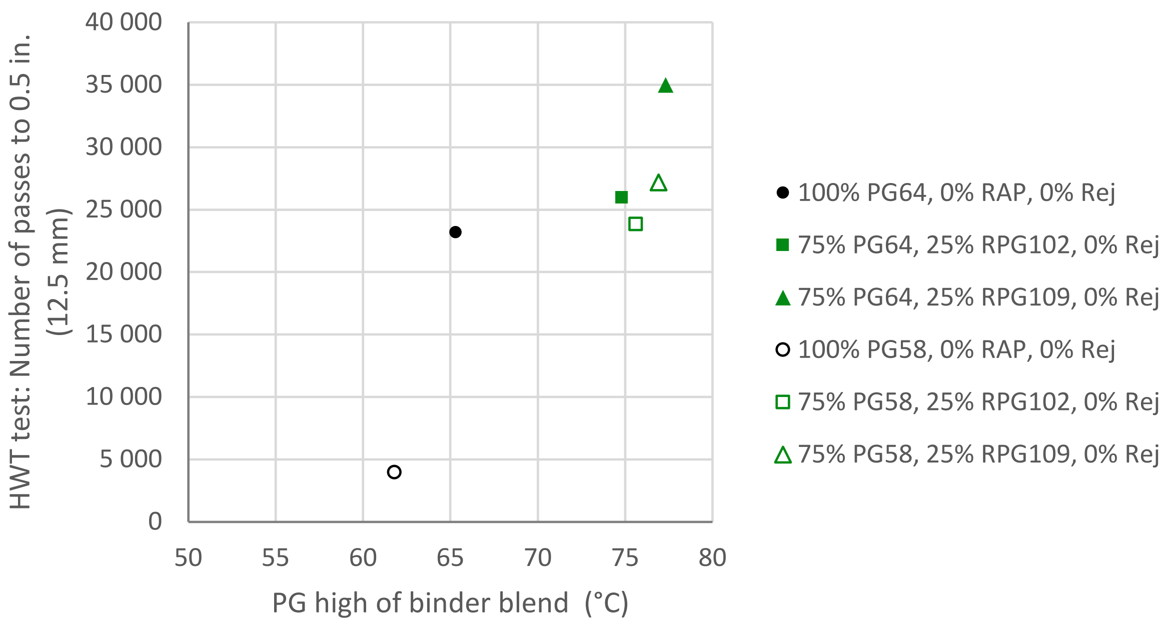


Figure 6.17: Relationship between HMA rutting resistance (HWT test) and binder blend PGH.

6.3 What Are the Effects of the Recycling Agent Addition on the Mechanical Properties of HMA with High RAP Content?

The effects of the recycling agent addition can be evaluated by comparing the mechanical properties of the mixes with recycling agent (either aromatic or tall oil) versus the mechanical properties of the same mixes without recycling agent. Only mixes with 25% binder replacement were tested without recycling agent. The addition of the recycling agent produced the following effects on the HMA:

- **HMA stiffness:** The HMA stiffness decreased due to the recycling agent softening effect (Figure 6.18 and Figure 6.19). As shown in Figure 6.18 and Figure 6.19, the recycling agent addition shifts the dynamic modulus master curve of the HMAs with RAP ("75% PG64, 25% RPG102, 0% Rej" and "75% PG58, 25% RPG102, 0% Rej") to the right, in a manner that is somewhat (although not exactly) opposite to the RAP addition effect.
- **HMA IDEAL-CT test results:** The load-displacement curves contracted in the y-axis direction (lower load), as expected, due to the softening effect of the recycling agent (Figure 6.20 and Figure 6.21). The effect on the x-axis direction varied from mixes with PG 64 binder, where the recycling agent produced a flatter post-peak slope, versus the mixes with PG 58 binder, where the recycling agent reduced the strength but did not have much effect on the post-peak slope. Consequently, while the addition of the recycling agent improved the CT_{Index} of the mixes with PG 64 binder, it did not improve the CT_{Index} of the mixes with PG 58 binder (Figure 6.22).
- **HMA fatigue resistance:** The addition of recycling agent did not produce a considerable change in the 4PB flexural fatigue life of the mix with PG 64 binder (Figure 5.8 and Figure 6.23). This result was not expected, and it is believed to be related to the fact that the RAP addition did not reduce the fatigue life of the control mix without RAP. On the contrary, for the mix with PG 58 binder, the addition of the aromatic recycling agent resulted in an improvement in the 4PB flexural fatigue life (Figure 5.10) compared with the mix with 25% RAP and no recycling agent. The ε_6 increased 25% after adding the aromatic recycling agent (Figure 6.23).
- **HMA rutting resistance:** The addition of the recycling agent did not consistently produce the same effect on the rutting resistance of the HMA with RAP. Depending on the combination of base binder (PG 64 or PG 58), recycling agent (aromatic or tall oil), and test (AMPT confined/unconfined, or HWT test), the rutting resistance increased, decreased, or remained roughly unchanged. (See HWT test results in Figure 6.24 and Figure 6.25.)
- **Difference Between Recycling Agents:** The only clear difference between the two recycling agents was that the aromatic required a higher dose (around 60% higher) than the tall oil to produce similar effects on the HMA mechanical properties. The NCHRP 9-58 study also concluded that the (petroleum-based) aromatic recycling agents required higher dose than the tall oils to produce similar effects on the HMA mechanical properties *(5)*. The difference reported is not as high, likely due to changes in the chemistry of the different recycling agents since the NCHRP project was completed. That project reported a drop in the PGH of the binder blend of 1.38°C and 1.82°C (around 30% higher) for every 1% increase in aromatic and tall oil content, respectively.

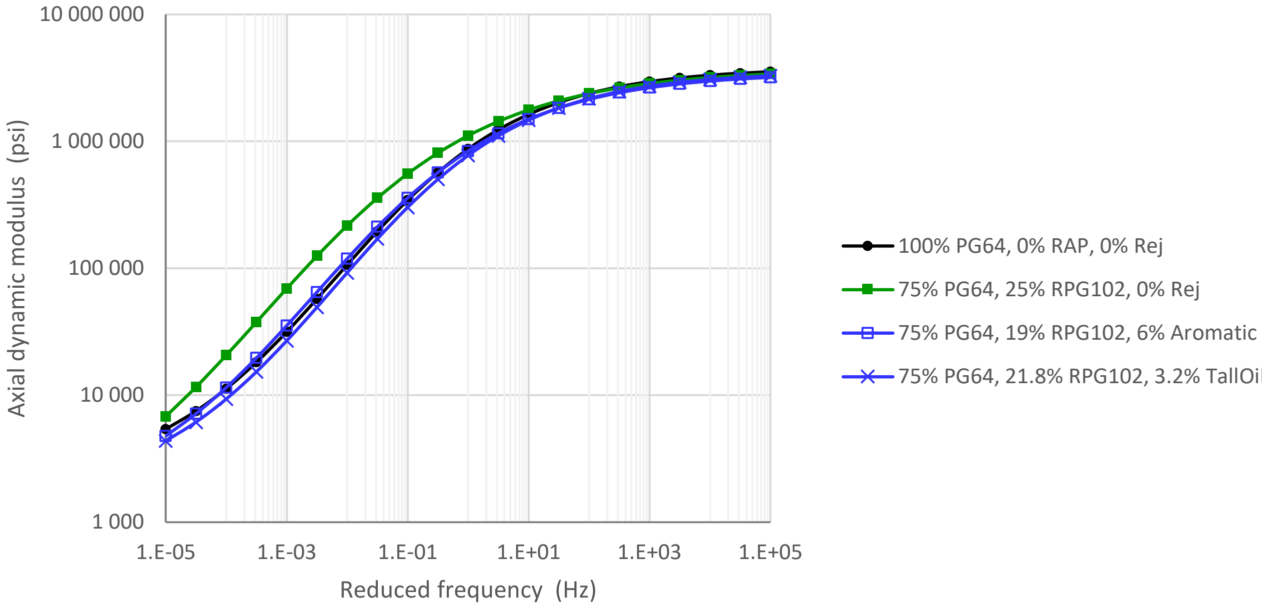


Figure 6.18: Effect of recycling agent addition on HMA stiffness—mixes with PGH 64.

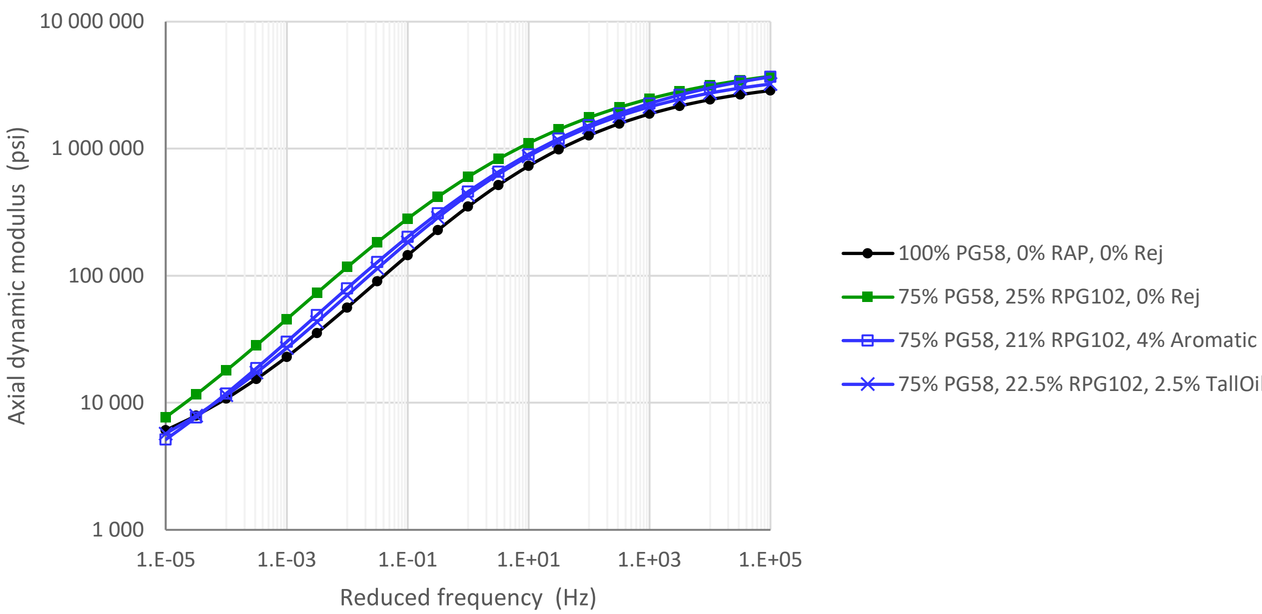


Figure 6.19: Effect of recycling agent addition on HMA stiffness—mixes with PGH 58.

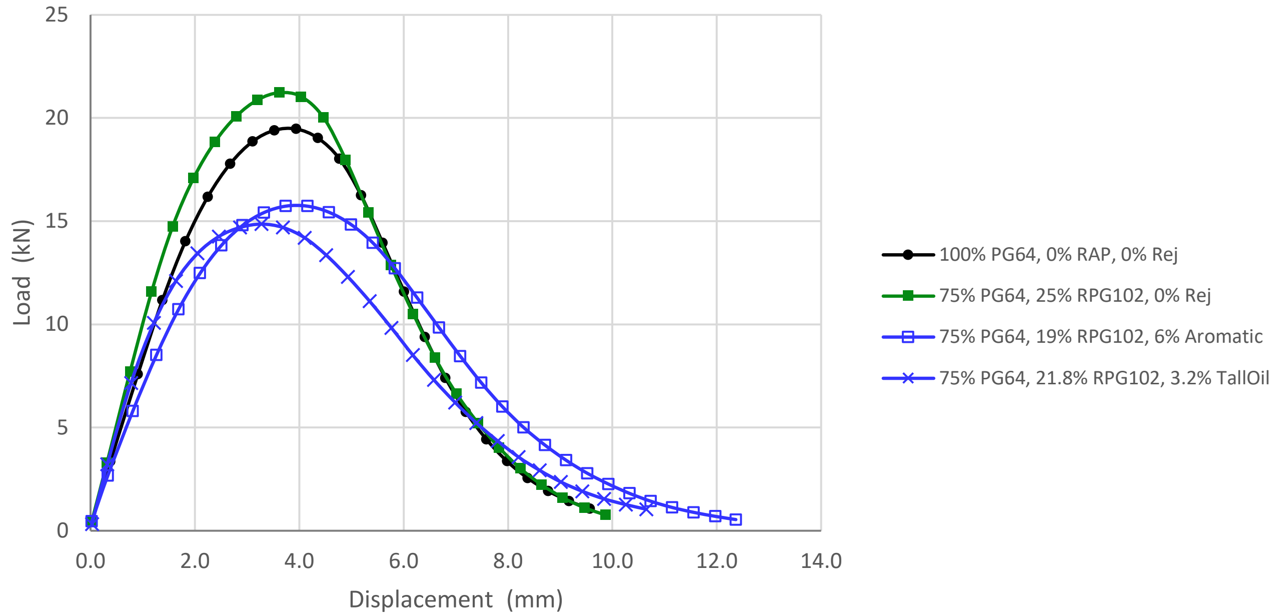


Figure 6.20: Effect of recycling agent addition on HMA IDEAL-CT test results—mixes with PGH 64.

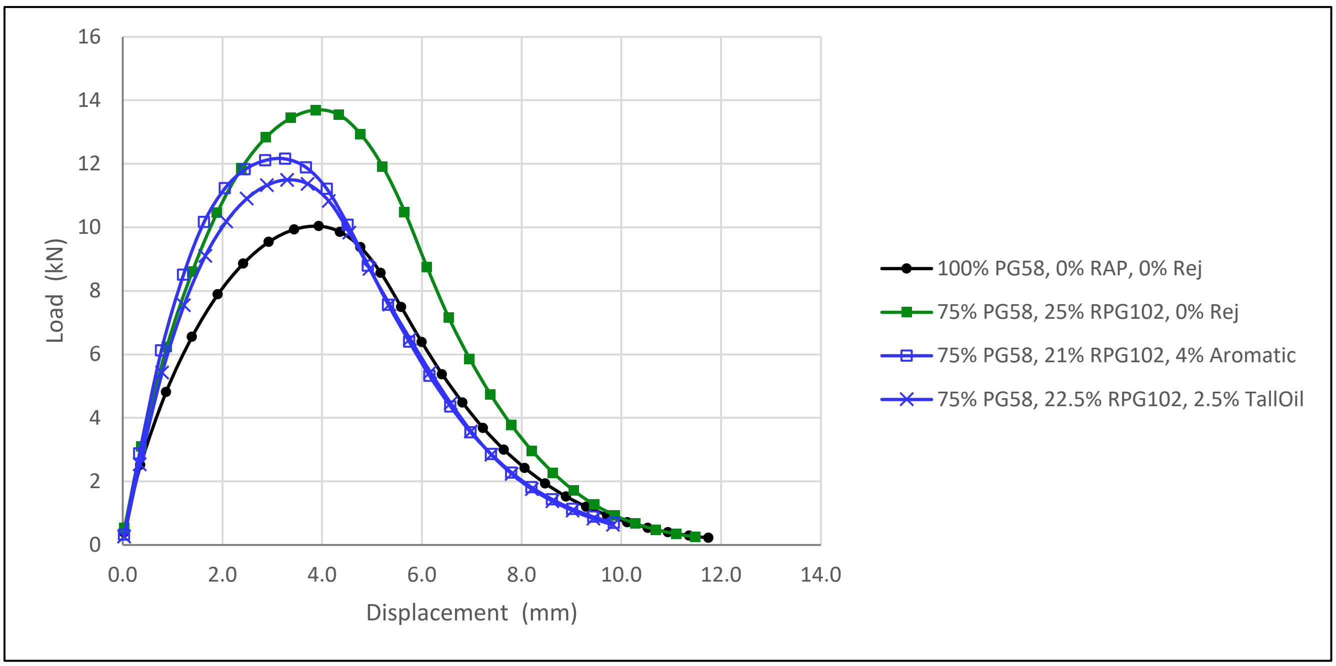


Figure 6.21: Effect of recycling agent addition on HMA IDEAL-CT test results—mixes with PGH 58.

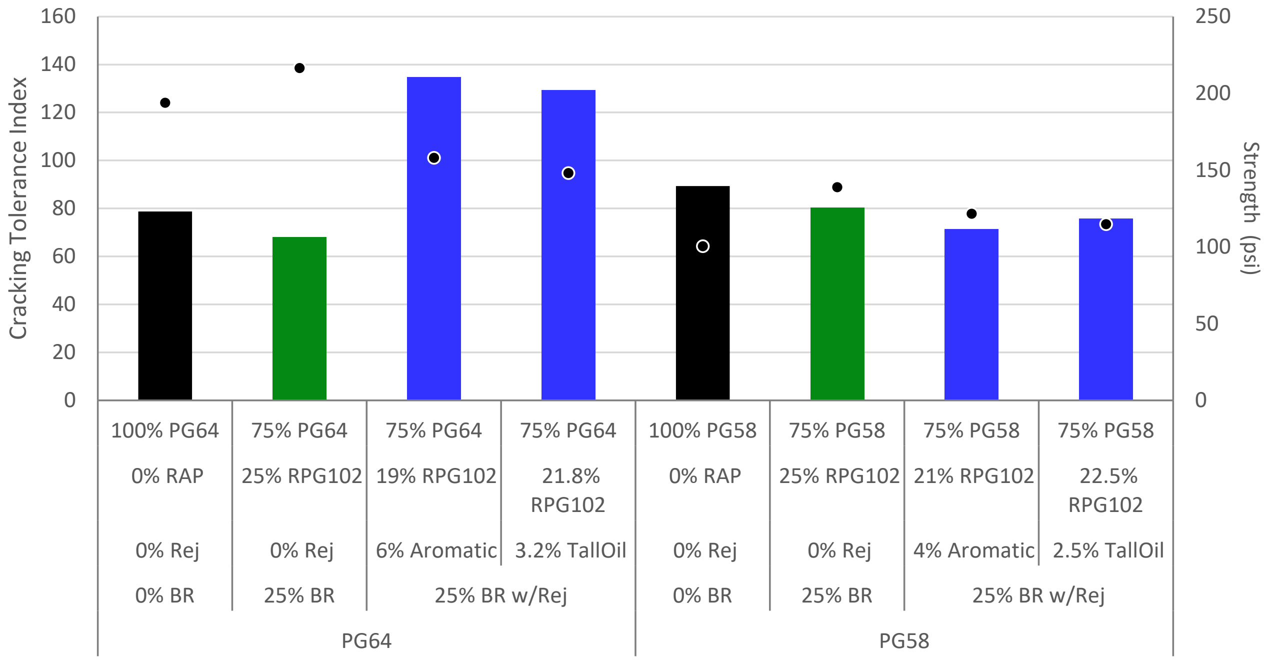


Figure 6.22: Effect of recycling agent addition on HMA IDEAL-CT test results.

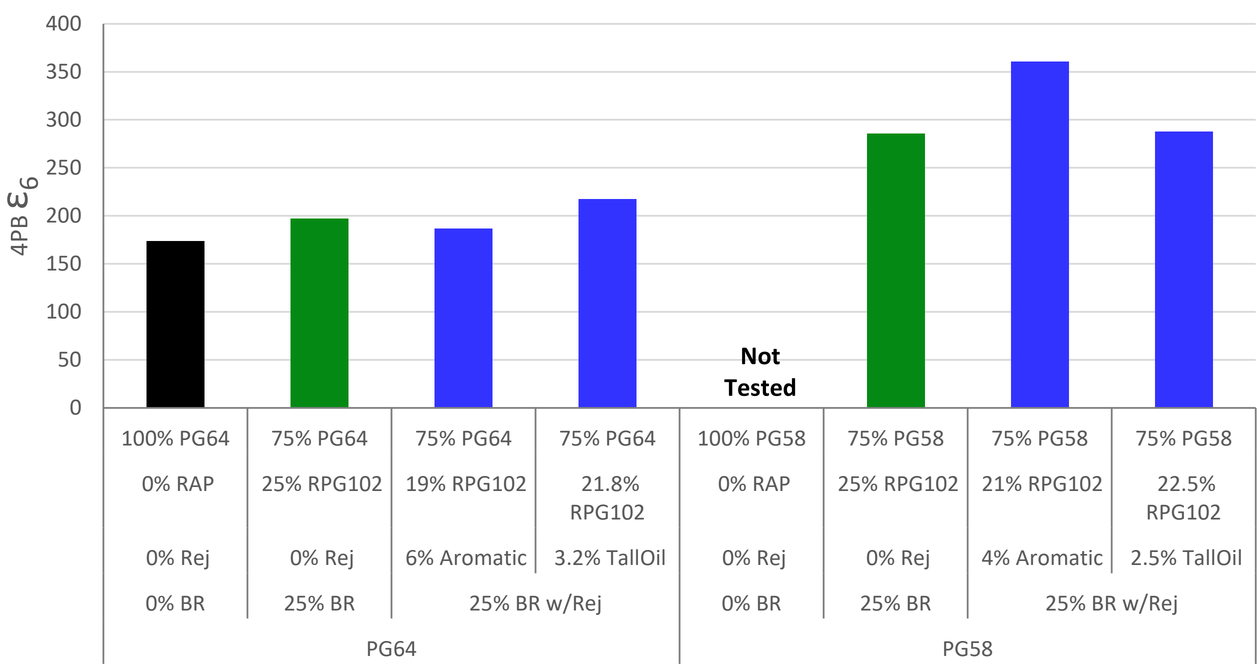


Figure 6.23: Effect of recycling agent addition on HMA 4PB fatigue life.

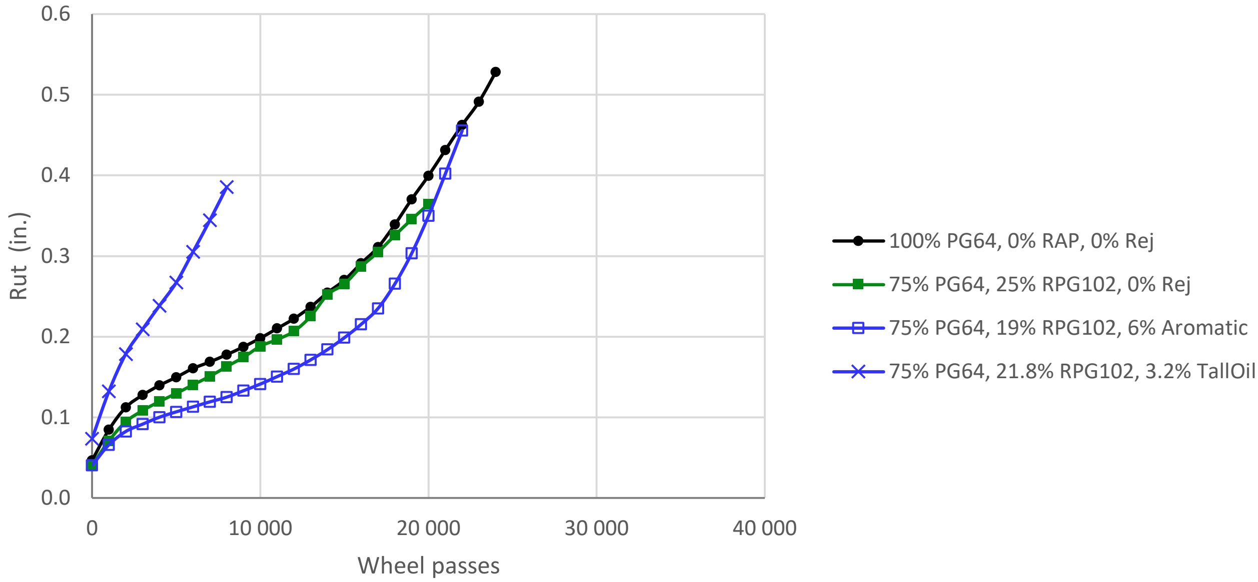


Figure 6.24: Effect of recycling agent addition on HMA rutting resistance (HWT testing)—mixes with PG 64.

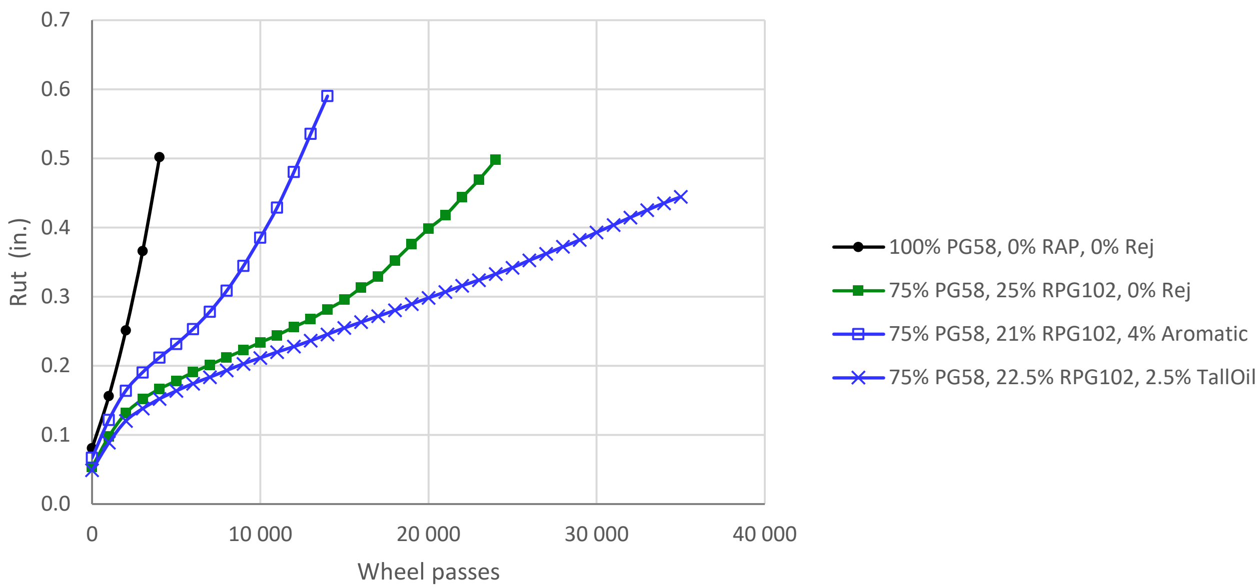


Figure 6.25: Effect of recycling agent addition on HMA rutting resistance (HWT testing)—mixes with PG 58.

6.4 By Using a Recycling Agent, Can the Mechanical Properties of an HMA with High RAP Content Be Restored Back to the Properties of the HMA with Low RAP Content?

The answer to the research question is addressed in the following discussion for each of the two strategies considered in this study: (1) adding recycling agent while maintaining the base binder and (2) adding recycling agent while replacing the base binder with a softer binder.

The first strategy is adding recycling agent while maintaining the base binder (PGH 64). The effects on the HMA are the following:

- **HMA stiffness:** The recycling agent (RA) addition produced an effect on the stiffness of the mix that was roughly the opposite of the RAP addition effect (Figure 6.26). Consequently, by selecting the right amount of recycling agent, the dynamic modulus master curve of the mix with high RAP content can be restored back to the master curve of the control mix with no RAP (or with low or regular RAP content in general). It should be noted that in Figure 6.26 the dynamic modulus of some mixes with RAP and recycling agents are within ±20% of the control mix for most of the reduced frequency range.
- **HMA IDEAL-CT test results:** The RA addition produced an effect on the load-displacement curves that was roughly the opposite of the RAP addition effect (Figure 6.27). Consequently, by selecting the right amount of recycling agent, the IDEAL-CT test parameters (in particular, CT_{Index} and *Strength*) of the mix with high RAP content can be restored back to values similar to the mix with no RAP (or with low or regular RAP content in general). Since CT_{Index} and *Strength* are strongly correlated to the mix stiffness (for a particular mix and binder), the recycling agent dose required to restore the stiffness will be similar to the dose required to restore the IDEAL-CT test parameters.
- **HMA fatigue resistance:** A conclusion could not be reached based on this study’s experimental data as the RAP addition did not reduce the 4PB flexural fatigue life of the mix with PGH 64 binder (Figure 5.8 and Figure 6.23).
- **HMA rutting resistance:** Since the RAP addition improved the rutting resistance, there is no need to restore this property back to the same value of the control mix with no RAP. The caveat is that the recycling agent addition may make the mix rutting susceptible. This issue is discussed in Section 6.6.

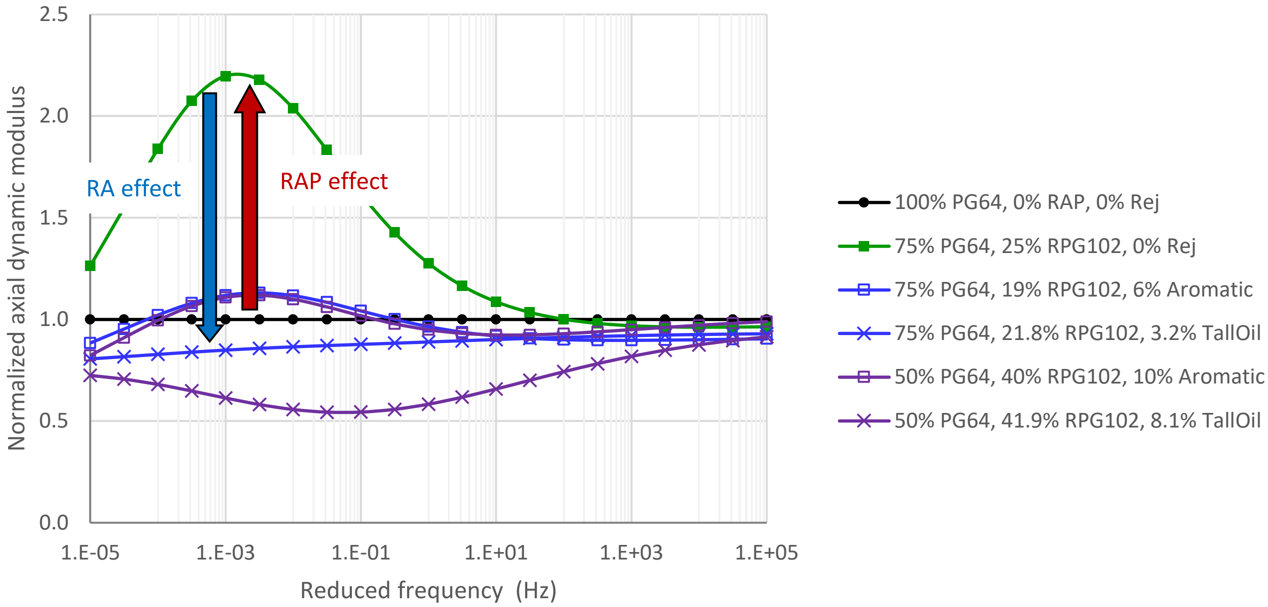


Figure 6.26: Comparison of recycling agent (RA) versus RAP addition effects on the stiffness of the HMA—mixes with PG 64.

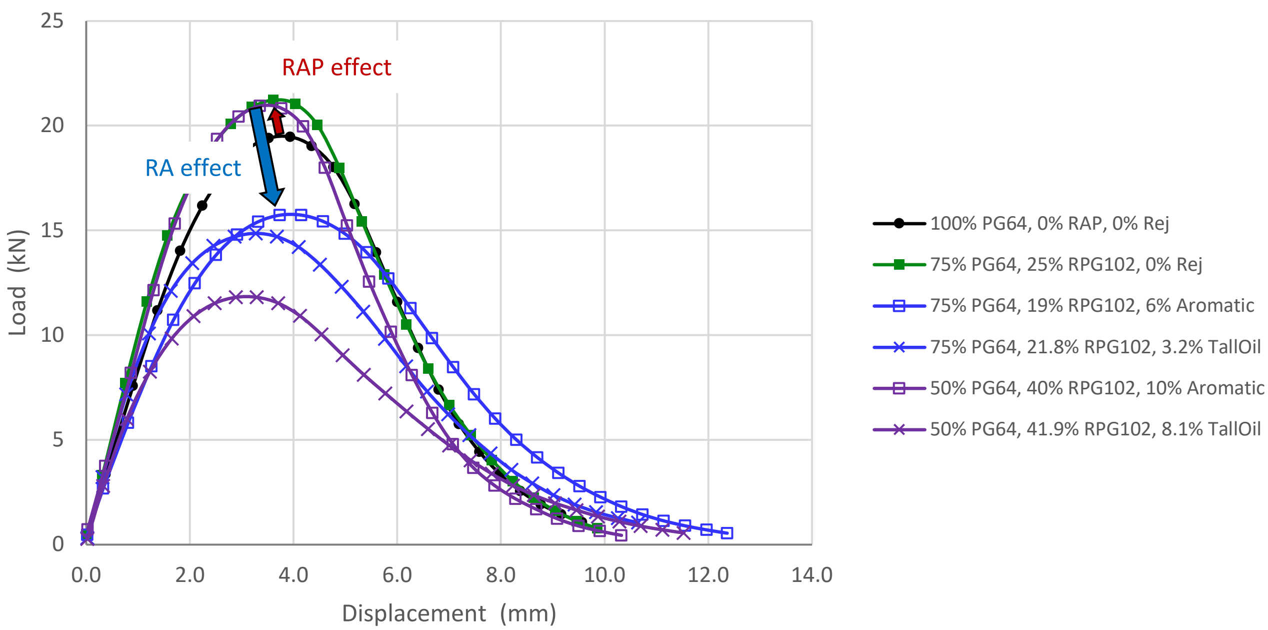


Figure 6.27: Comparison of recycling agent (RA) versus RAP addition effects on the load-displacement curves of the IDEAL-CT test—mixes with PGH 64.

The second strategy is adding recycling agent while replacing the base binder by a softer binder (PGH 58). The effects on the HMA are the following:

- **HMA stiffness:** Both RAP and recycling agent modify the dynamic modulus master curve around the master curve of the mix with PGH 58 binder and no RAP. The RAP shifts the master curve in the direction of decreasing frequencies while the recycling agent shifts it in the direction of increasing frequencies. Since the master curves of the two mixes without RAP differ from each other, PGH 64 versus PGH 58 (Figure 6.28), the master curve of the mixes with PGH 58 binder and RAP and recycling agent will only partially match the master curve of the control mix with PGH 64 and no RAP (Figure 6.29). In other words, the recycling agent brings the master curve back to the master curve of the mix with PGH 58 and no RAP but not to the control mix with PGH 64 and no RAP.
- **HMA IDEAL-CT test results:** Both RAP and recycling agent modify the load-displacement curves around the curve of the mix with PGH 58 binder and no RAP. The RAP shifts the curves in the direction of increasing load while the recycling agent shifts it in the direction of decreasing load. Since the load-displacement curves of the two mixes without RAP differ from each other (PGH 64 versus PGH 58), the load-displacement curve of the mixes with PGH 58 binder, RAP, and recycling agent will only partially match the curve of the control mix with PGH 64 and no RAP (Figure 6.30).
- **HMA fatigue resistance:** A final conclusion could not be reached based on this study's experimental data as the 4PB fatigue life of the mixes with PGH 58 base binder, RAP, and no recycling agent was higher than the 4PB fatigue life of the control mix (PGH 64 binder and no RAP). Nonetheless, the fact that the recycling agent improved the 4PB fatigue life of the mixes with PGH 58 base binder and RAP suggests that restoring the fatigue resistance of a generic control mix by using step-down binder and recycling agent is possible.
- **HMA rutting resistance:** Since the RAP addition improved the rutting resistance, there is no need to restore this property back to the same value of the control mix with no RAP. The caveat is that the recycling agent addition may make the mix rutting susceptible. This issue is discussed in Section 6.6.

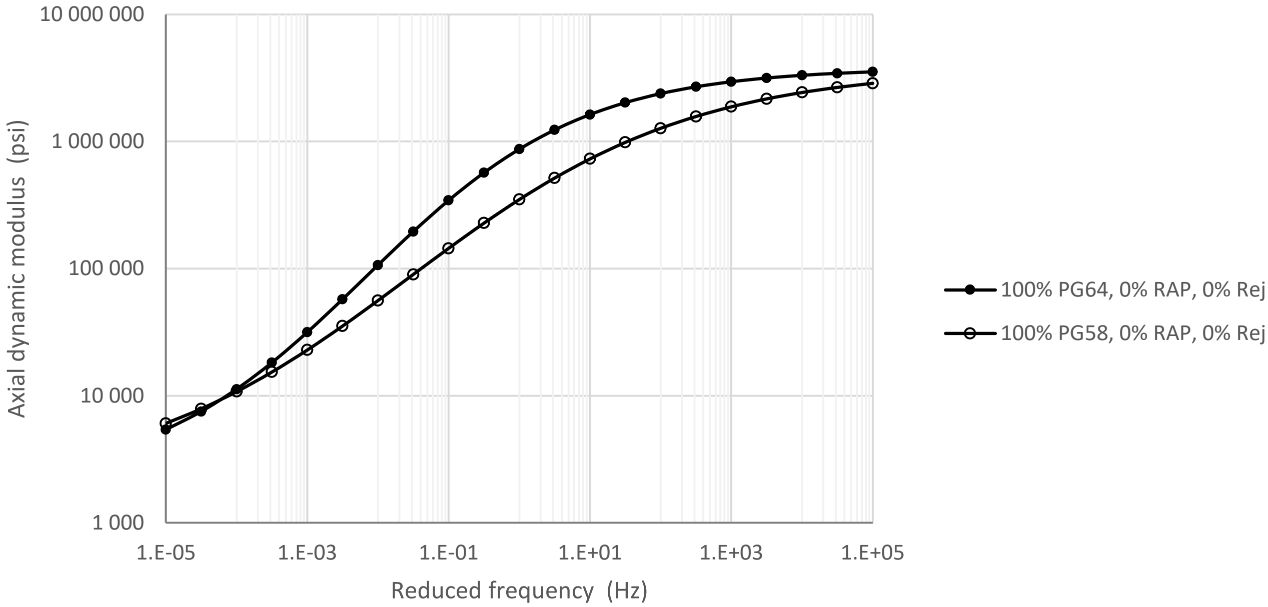


Figure 6.28: Comparison between the stiffness of the two mixes without RAP.

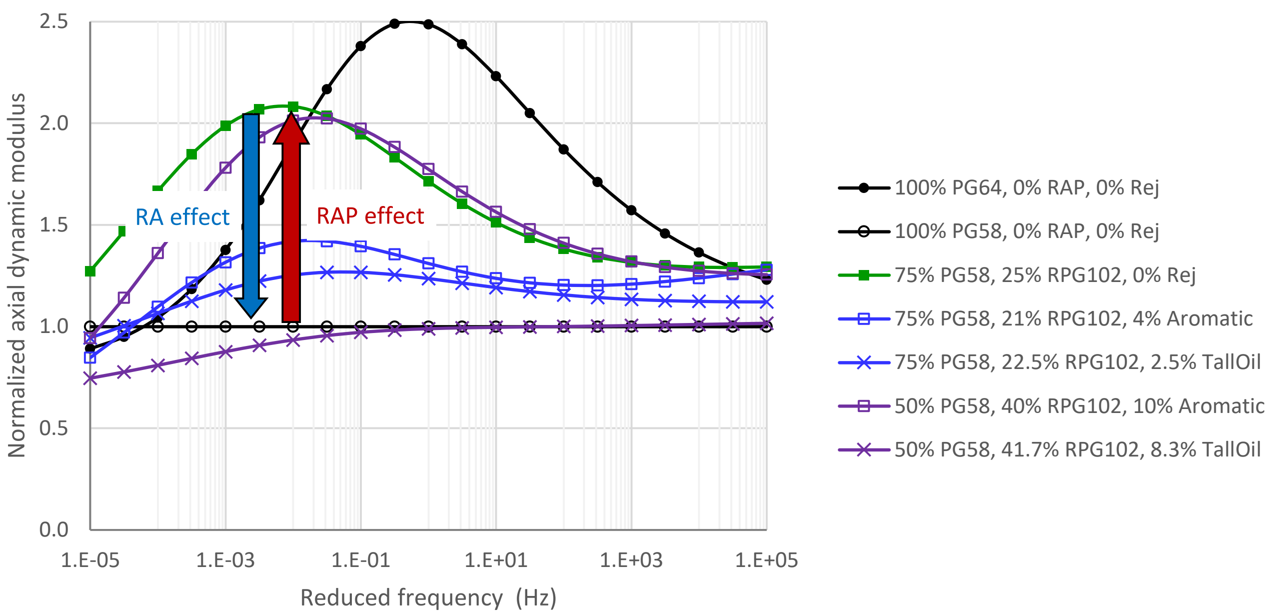


Figure 6.29: Comparison of recycling agent (RA) versus RAP addition effects on the stiffness of the HMA—mixes with PGH 58.

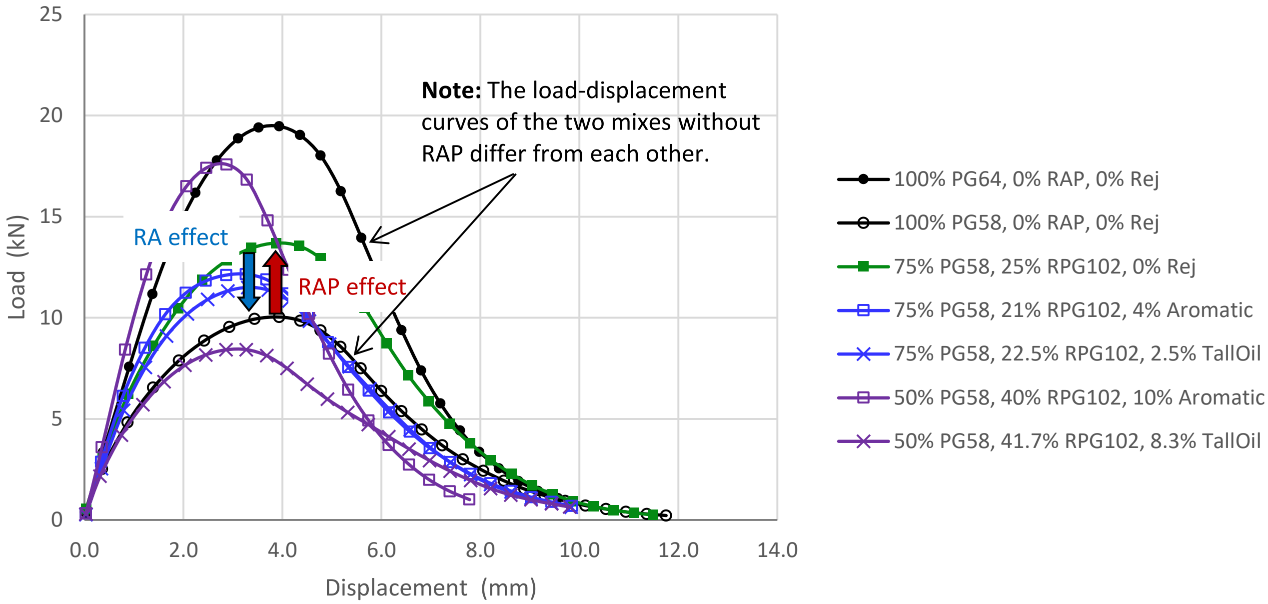


Figure 6.30: Comparison of recycling agent (RA) versus RAP addition effects on the load-displacement curves of the IDEAL-CT test—mixes with PGH 58.

6.5 Are There Specific Considerations Required for the Addition of RAS Compared with the Addition of RAP?

The RAS binder is typically much stiffer (harder) than the RAP binder and, consequently, it is expected to produce a bigger impact on the mix mechanical properties than the RAP binder. In this study, the PG of the RAS binder could not be determined as the dynamic shear rheometer loading was not high enough to produce the required testing strain. Nonetheless, the PG of the binder blend with RAS could be determined. The PGH was very high compared with the binder blends with only RAP while the PGI and the PGL were comparable to the binder blends with only RAP.

Overall, the RAS addition effect on the mix mechanical properties was consistent with the higher stiffness (higher PG) of the RAS binder compared with the RAP binder:

- **HMA stiffness:** The RAS effect on mix stiffness at high, intermediate, and low temperatures was consistent with the PGH (Figure 6.31), PGI (Figure 6.32), and PGL (Figure 6.33), respectively, of the binder blend. The RAS effect was particularly relevant at high temperatures.
- **HMA IDEAL-CT test results:** The RAS effect on the IDEAL CT_{Index} and *Strength* was consistent with the PGI of the binder blend (Figure 6.34).
- **HMA fatigue resistance:** The RAS effect on the flexural fatigue life was consistent with the binder replacement ratio (Figure 6.35). As previously explained, the RAP binder alone provided better fatigue resistance than the base binder (PGH 64) used in this study. Based on the fatigue results presented in Figure 6.35, the same applies to the combination of RAP and RAS binders.

- **HMA rutting resistance:** The increase in rutting resistance due to the RAS addition was, overall, high compared with the effect of the RAP addition (Figure 6.36). This outcome is consistent with the high PGH of the binder blend with RAS compared with the binder blends with only RAP.

The addition of the recycling agent produced similar effects on the mix with RAP and RAS compared with the mixes with only RAP: overall reduction of stiffness, contraction of the IDEAL-CT test load-displacement curves in the y-direction with the consequent reduction of strength and expansion in the x-direction with the consequent increase of CT_{Index}, and not much effect on the flexural fatigue life. For the mix with RAP and RAS, the recycling agent addition reduced the rutting resistance.

The dynamic modulus versus PG data shown in Figure 6.31 to Figure 6.33 indicate that the mixes with RAP and RAS follow similar pattern that the mixes with only RAP. The same conclusion can be drawn in terms of the IDEAL-CT test results (Figure 6.34). Overall, other than the high values of the RAP binder PG, no main difference was found between the way that RAS and RAP impact the mechanical properties of the mix.

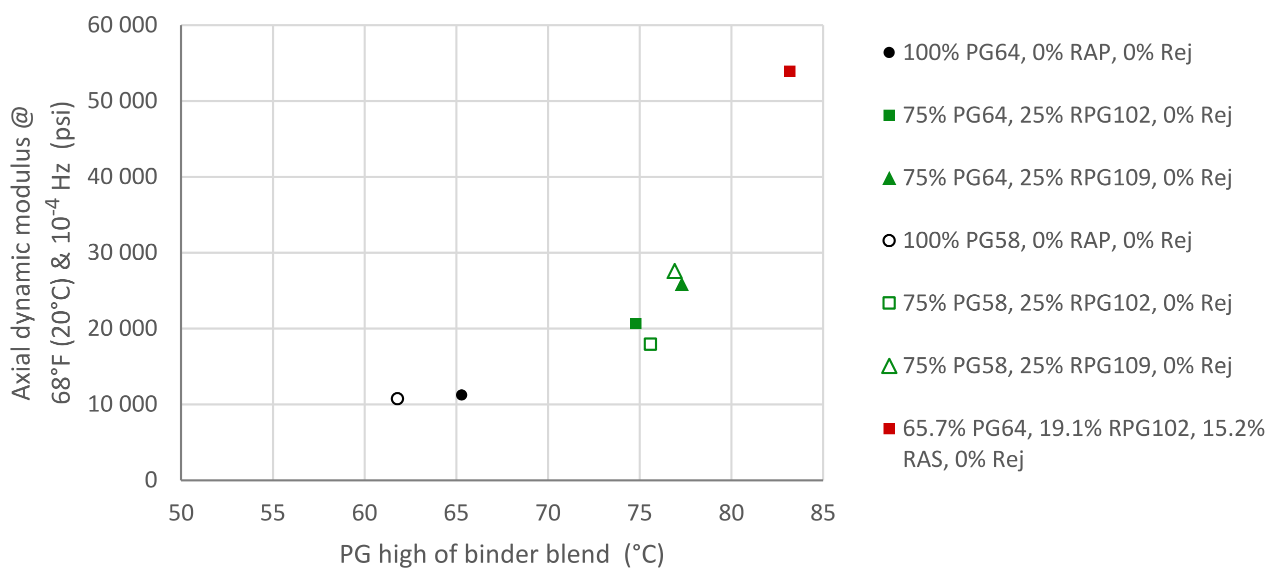


Figure 6.31: Comparison between RAP and RAS effects—HMA stiffness at high temperature (low reduced frequency).

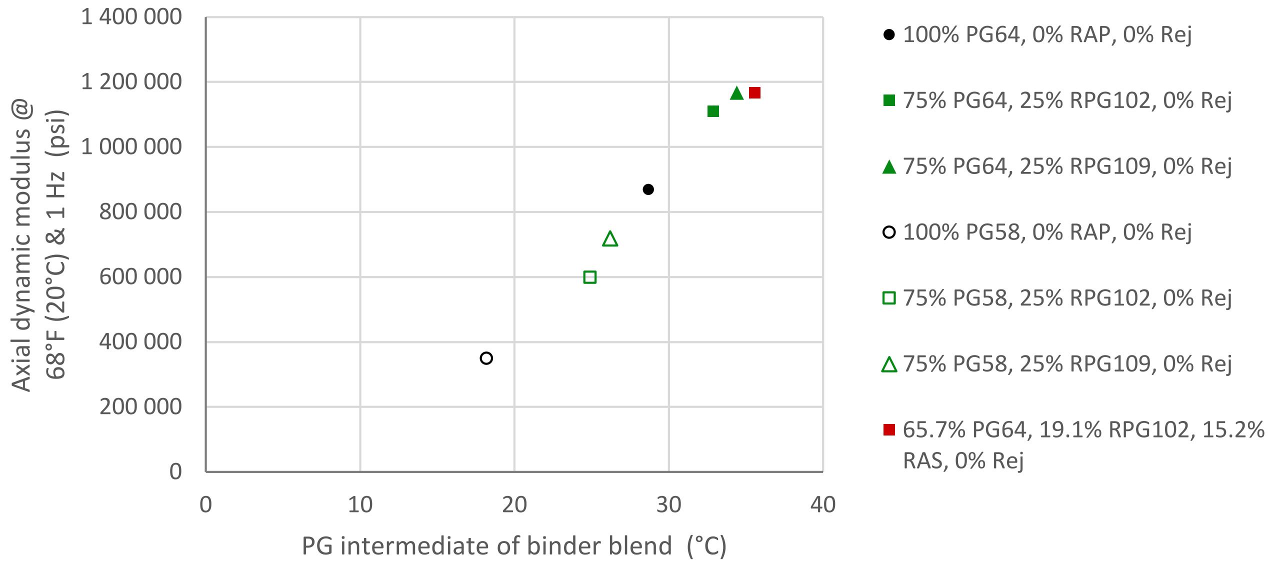


Figure 6.32: Comparison between RAP and RAS effects—HMA stiffness at intermediate temperature (intermediate reduced frequency).

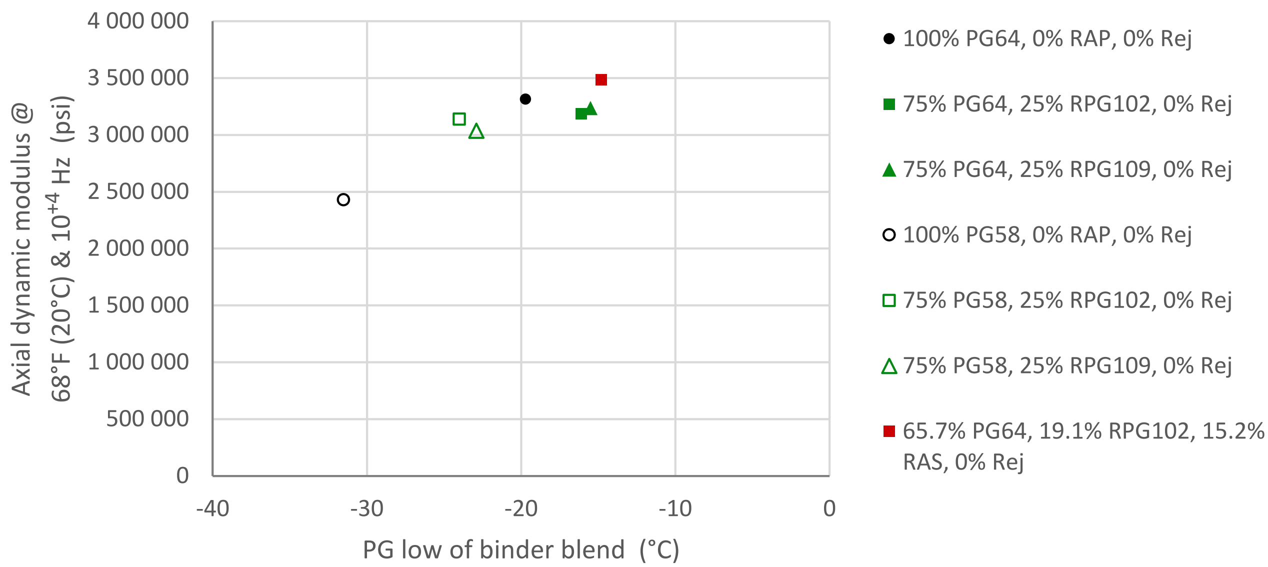


Figure 6.33: Comparison between RAP and RAS effects—HMA stiffness at low temperature (high reduced frequency).

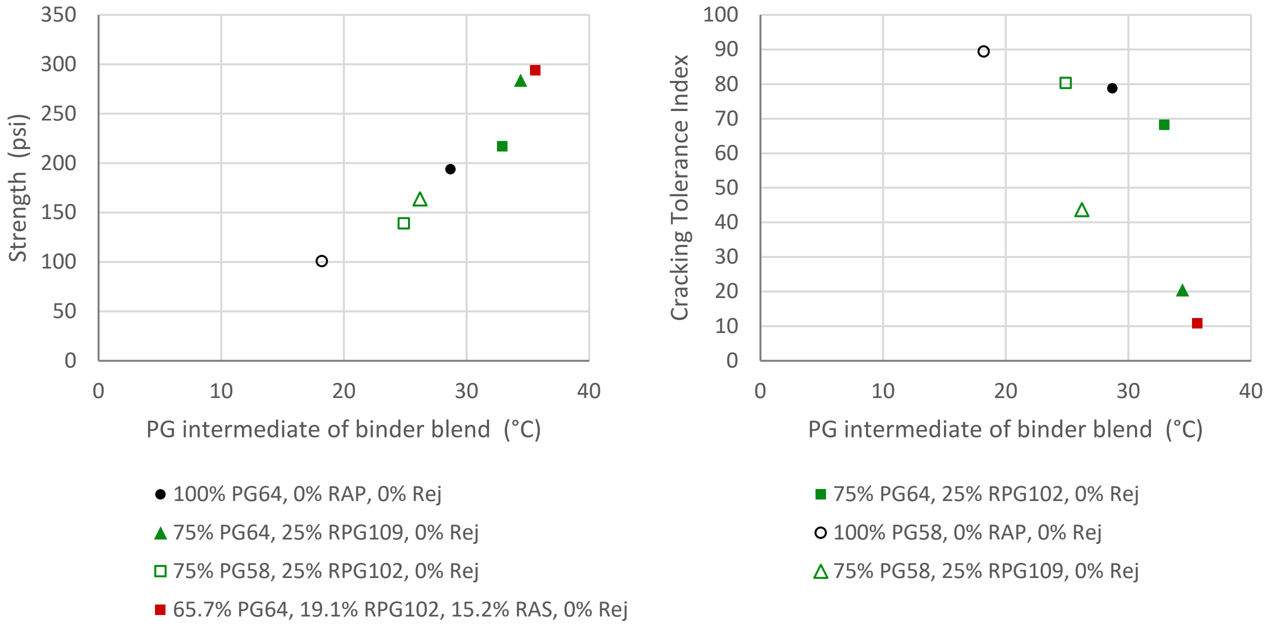


Figure 6.34: Comparison between RAP and RAS effects—IDEAL-CT test results.

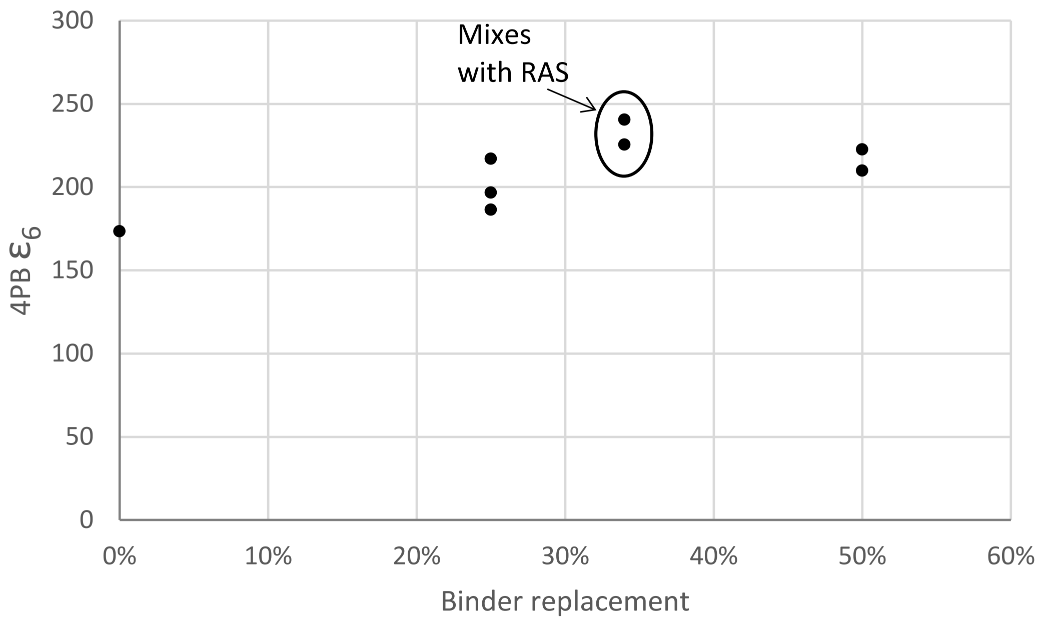


Figure 6.35: Comparison between RAP and RAS effects—flexural fatigue life.

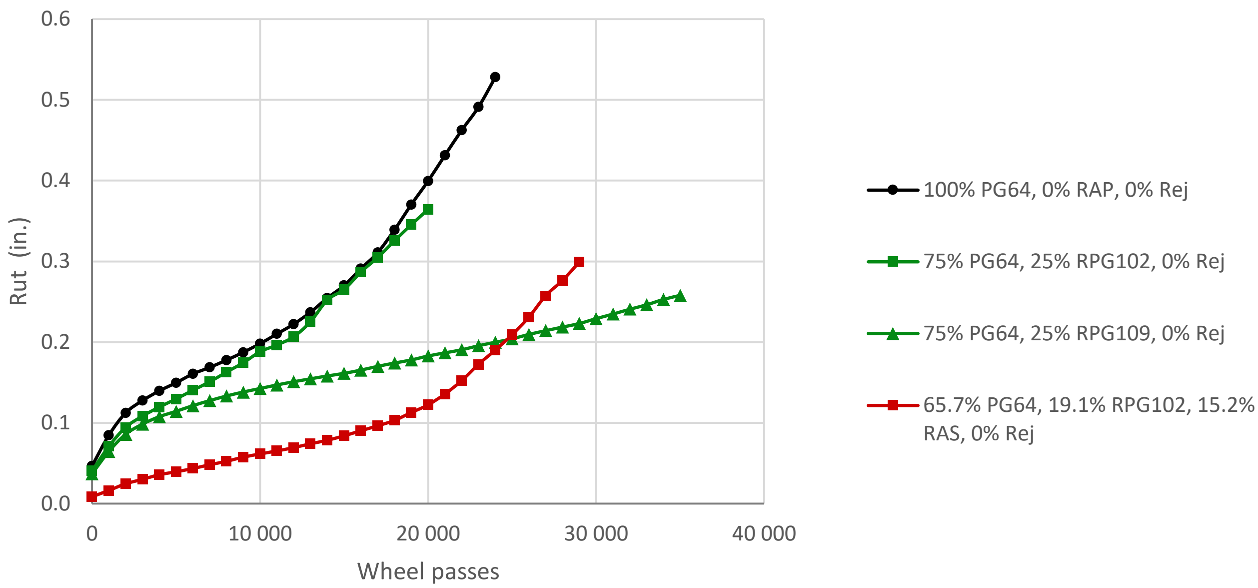


Figure 6.36: Comparison between RAP and RAS effects—HWT test rutting resistance.

6.6 Can Mixes with 50% RAP Content and/or RAS Be Engineered to Have Desired Properties for Different Applications in the Pavement Structure?

As has been discussed throughout this report, different types of properties are desired for different applications of HMA. For thinner (less than 0.2 ft. or, in some cases, 0.25 ft.) overlays on cracked asphalt pavement or full-depth recycled pavement, the generally desired properties are rutting resistance and fatigue resistance versus tensile strain, without great concern about stiffness at intermediate temperatures. As overlays become thicker than 0.25 ft. on cracked asphalt pavement or concrete pavement, or new asphalt in reconstructed pavement, the HMA layers below the top 0.15 to 0.25 ft. surface layer generally will produce better pavement performance as they become stiffer, provided the fatigue resistance versus tensile strain property is not reduced too much by the increased stiffness. As was found with the control PG 64 binder used in this study, stiffness and fatigue resistance are not highly correlated, and for some PG 64 binders poor fatigue resistance results even when they are tested in mixes without RAP or RAS.

To find the required thicknesses for the combination of these variables for a given project's context, Caltrans designers use pavement fatigue and reflective cracking simulation to determine the predicted performance, considering the complex interactions of stiffness, fatigue resistance, pavement asphalt layer thicknesses, the rest of the pavement structure below the asphalt, climate, and truck traffic. The use of high RAP contents and/or RAS adds some further complexity but also add new tools to the designer's toolbox. RAP and RAS can be tools to engineer mixes that have increased stiffness for the layers below the surface, but the effects of the stiffness on fatigue need to be considered as well as the appropriate risks of rutting, fracture cracking, and moisture damage at these greater depths.

The question formulated in this section of the report is addressed for surface layers and for layers below the surface as follows:

- **Surface layers:** Many of the mixes in this study were engineered to have blended base binder, RAP and/or RAS, and recycling agent resulting in the same PGH as the PG 64 control base binder, with the intent of matching mix stiffness and fatigue properties of the mix with only the base binder and no RAP or RAS. The binder and mix testing results from this study, presented in Section 6.4, for the mixes designed to meet that objective show that this extreme case can be engineered using a recycling agent potentially combined with changes in the base binder PG grade.
- **Layers below the surface layer:** The results for mixes with the PG 64 base binder and the PG 58 base binder and 25% RAP show that increased stiffness can be engineered using RAP and a base binder source and low PG, with or without use of a recycling agent (Figure 6.1). The results also show that fatigue resistance can be engineered using RAP (Figure 6.4 and Figure 6.5) and using RAP, a recycling agent, and changes in base binder (Figure 6.6). As shown in Figure 6.4 and Figure 6.5 for RAP and in Figure 6.35 for RAS, replacing the base binder with RAP and/or RAS binder should not be assumed to always result in reduced fatigue resistance versus tensile strain. The overall answer is that the stiffness and fatigue properties of the mix depend on the properties of the base binder source (and not just the PG of the base binder), and the RAP and/or RAS source and their properties, and these properties can be engineered using these tools to achieve desired outcomes.

It must be noted that these conclusions are based only on short-term aged materials, and additional work to evaluate medium-term aging stiffness and fatigue properties should be done to reach final recommendations. It should also be noted that the best combinations of stiffness and fatigue resistance for layers below the surface should be determined using *CalME* simulations and trying different mixes to find the most economical combination in the different asphalt layers to achieve the required design life for a given application.

6.7 What Is the Recommended Approach to Determine the Recycling Agent Dose?

6.7.1 Initial Considerations

6.7.1.1 What Is the Goal of Adding the Recycling Agent?

The standard goal of adding the recycling agent is restoring the properties of the mix with high RAP/RAS content back to the properties of the control mix with either no RAP/RAS or low/standard RAP/RAS content. This is the goal of Approach 1 is outlined in Section 6.7.2. Underlying this goal is the assumption that the RAP/RAS addition is a detriment to the mechanical properties of the mix. This outcome is not necessarily true within the framework of the balanced mix design (BMD), where the goal is optimizing the mix mechanical properties to maximize pavement performance. In the BMD context and in certain scenarios (e.g., non-surface layers of relatively thick asphalt pavements), the increase in stiffness associated with the RAP/RAS addition may result in improved pavement performance even if the RAP/RAS addition also results in loss of fatigue cracking resistance at a given strain level as measured in the 4PB fatigue test. Optimizing mix properties within the BMD framework is the goal of Approach 2 outlined in Section 6.7.3.

6.7.1.2 What Mix Mechanical Properties Should Be Considered?

The mechanical properties to consider for determining the recycling agent dose are the properties that have a relevant effect on pavement performance:

- Properties of short-term oven aged (STOA) mix (or mix as sampled from the plant):
  - Rutting resistance
- Properties of medium-term oven aged (MTOA) mix (20 hours at 100°C):
  - Stiffness
  - Fatigue cracking resistance

While the research presented in this report does not consider medium-term aged mixes, the two approaches for determining recycling agent dose (Sections 6.7.2 and 6.7.3) do consider these mixes.

The resistance to moisture-induced damage, not evaluated in this research, is another relevant mix property that the two proposed approaches consider.

6.7.1.3 Does the Current Method of Determining Recycling Agent Result in Overdosing?

A common approach for determining the recycling agent dose, including the approach recommended in the draft AASHTO standard developed in NCHRP 9-58 *(5)* and the approach adopted in this study, consists of restoring the PGH of the binder blend back to the PGH of the base binder. Nonetheless, there is no benefit from keeping the PGH of the binder blend at the PGH of the base binder, since PGH is intended to address rutting at high temperatures and a higher PGH will usually result in better rutting resistance. The assumption of this approach is that by keeping the blended binder PGH at the base binder PGH, a commensurate maintenance of the intermediate and low temperature properties of the blended binder will also occur. This approach is graphically shown in Figure 6.37 and Figure 6.38.

The first issue with this approach is that it unnecessarily increases the cost and may also increase the environmental impact of the mix by requiring more of the relatively expensive and environmentally impactful recycling agent than is needed. The second issue with this approach is that it may unintentionally result in a PGI that is too low and, consequently, in a mix that is too soft at intermediate temperatures. Such a mix would perform poorly as part of a thicker structure when used as the intermediate or bottom layer and, if the stiffness is particularly low, it may result in poorer performance for a thin overlay. This outcome is referred in this report as “overshooting” as it indicates that the dose of recycling agent was more than needed. The overshooting is due to the RAP/RAS binder and recycling agent not producing exactly opposite effects on the blended binder PG.

For example, consider the binders for the mixes with PGH 64 base binder and 50% binder replacement, shown on the right side of Figure 6.37. The RAP addition results in a PGH increase of around 17°C above that of the base binder; the dose of tall oil required to bring the PGH back to 64°C is 8.1%. Such a relatively high dose makes the PGI drop to around 6°C below the PGI of the base binder. The same problem can be seen for the binder in the PGH 58 mixes, shown in Figure 6.38. The consequence is that the stiffness of the mixes with RAP and recycling agent are too low at intermediate temperatures, around 50% the stiffness of the control mix (Figure 6.39) for some of the mixes with either PG 64 or PG 58 base binder. The intent is that the intermediate temperature stiffnesses should match that of the of the control mix, indicated by the black line in Figure 6.39.

The same figure also shows that the current practice of stepping down the base binder from PG 64 to PG 58 for the 25% RAP binder replacement mixes resulted in overshooting at intermediate temperatures, which were reduced by approximately 30% compared with the control mix. These mixes that have significantly reduced stiffnesses compared with the control mix would perform poorly in terms of fatigue and reflective cracking if used as an intermediate or bottom layer of an asphalt overlay or pavement that is thicker than about 0.2 to 0.25 ft. (62 to 75 mm) and—most likely—in quite a few other scenarios.

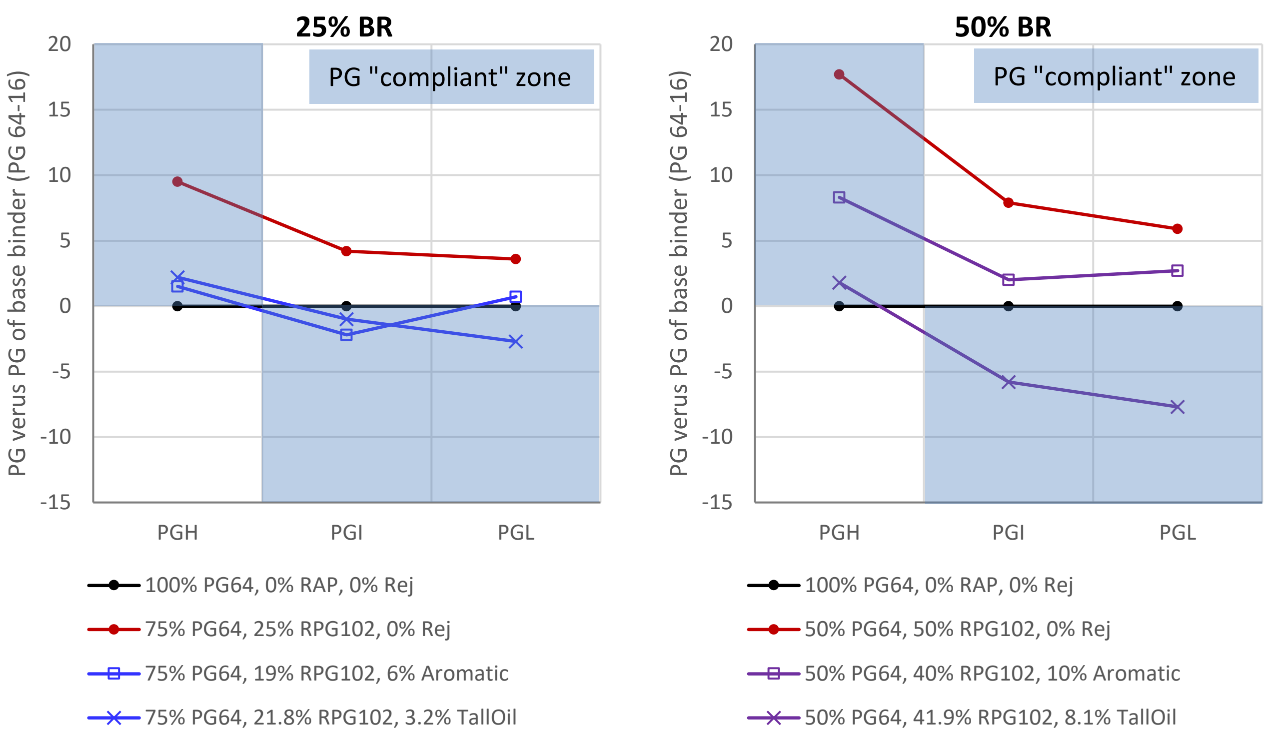


Figure 6.37: Recycling agent dose overshooting in terms of PG—mixes with PGH 64.

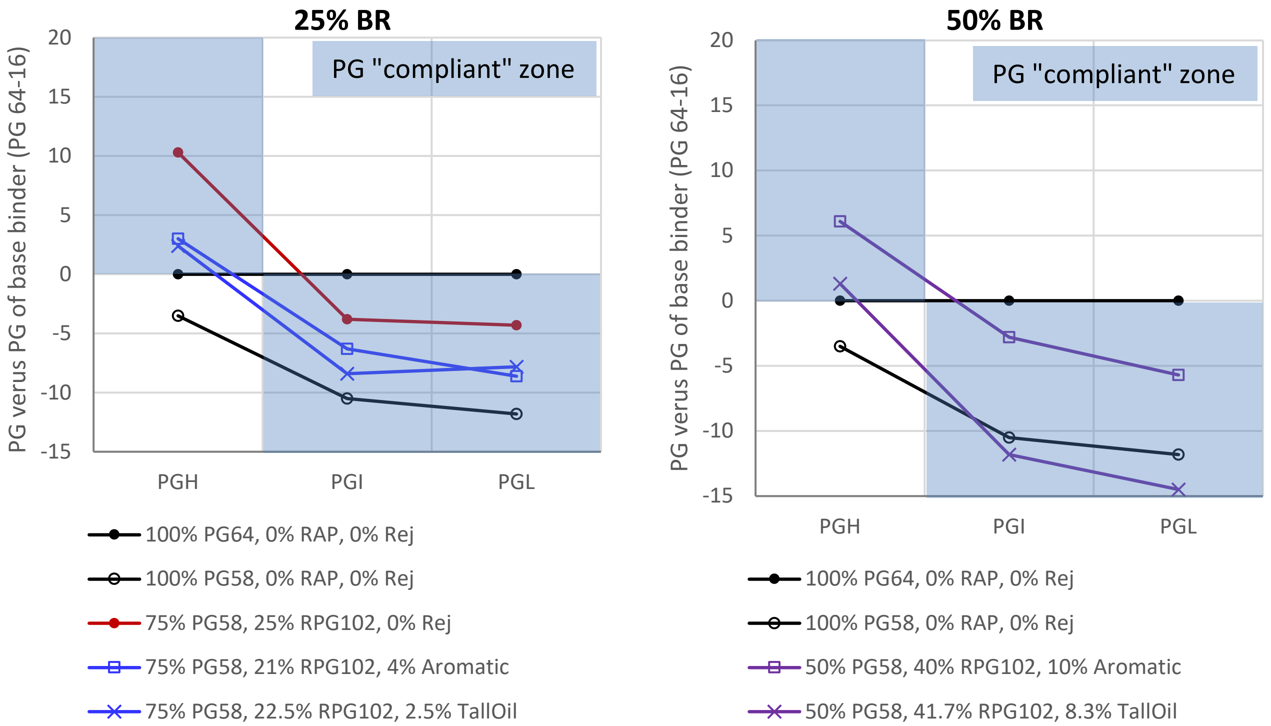


Figure 6.38: Recycling agent dose overshooting in terms of PG—mixes with PGH 58.

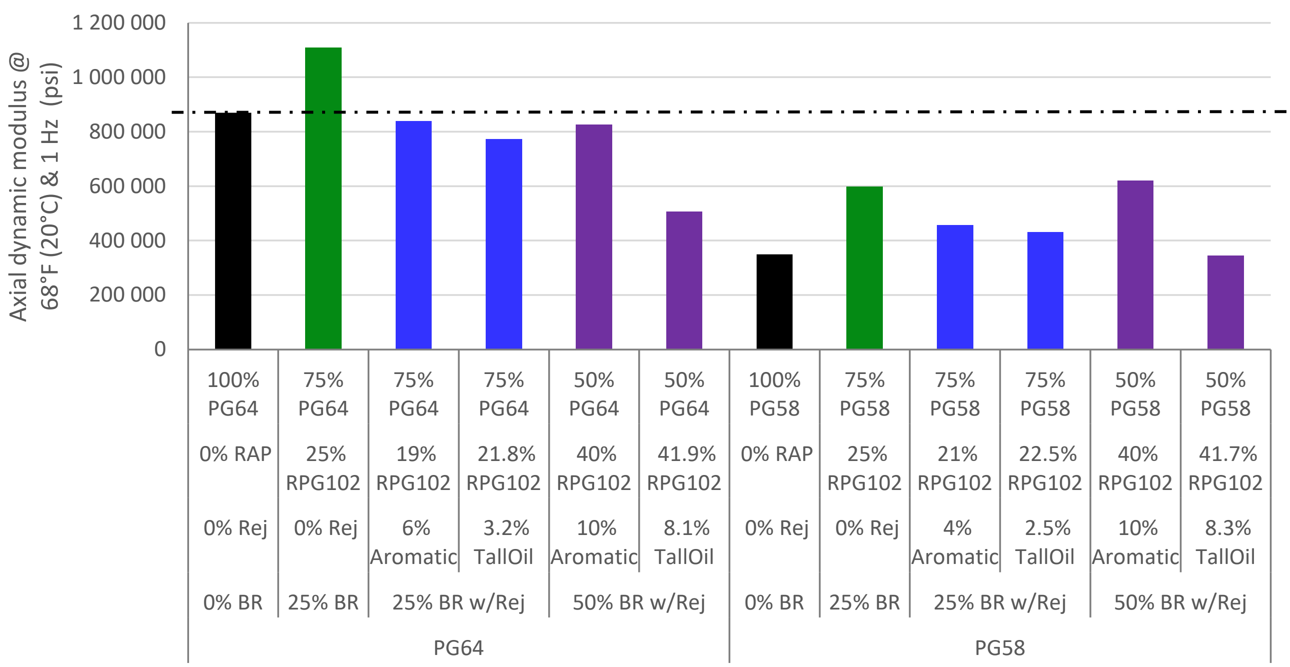


Figure 6.39: Recycling agent dose and base binder PG step-down overshooting in terms of HMA stiffness at intermediate temperature.

6.7.1.4 Does RAP/RAS Binder Fully Blend with the Virgin Binder and Recycling Agent?

The question of whether the RAP/RAS binder fully blends with the virgin binder and recycling agent is not easy to answer as there is no test to directly measure the degree of blending between RAP/RAS and base binders. One approach to answer this question is to compare a property measured in the binder blend, where full blending is certain, and a similar property measured in the actual mix where full blending is questionable, such as dynamic stiffness (flexural or axial) or the IDEAL-CT test *Strength*, which is highly correlated with mix stiffness. Figure 6.40 and Figure 6.41 show the stiffness and *Strength* of the mix, where the extent of blending is unknown, versus the PGI of the binder blend, where full blending is certain. The mixes with 0%, 25%, and 50% binder replacement using RAP all follow the same pattern of a linear correlation between stiffness or strength versus the PGI true temperature, which suggests that the RAP binder fully blended with the virgin binder and, where used, with the recycling agent during the mixing and short-term laboratory conditioning (four hours at 275°F [135°C] followed by two hours at compaction temperature). The mixes with 34% BR (with RAP and RAS) follow the same pattern as the mixes with only RAP, which suggest that the RAS binder fully blended with the virgin binder and, where used, with the recycling agent. Mixes with less than complete blending would be expected to exhibit deviations from this straight line relationship because the binder blend in the mix would not have the same recycled binder content and to a lesser extent because the active binder content in the mix would be reduced.

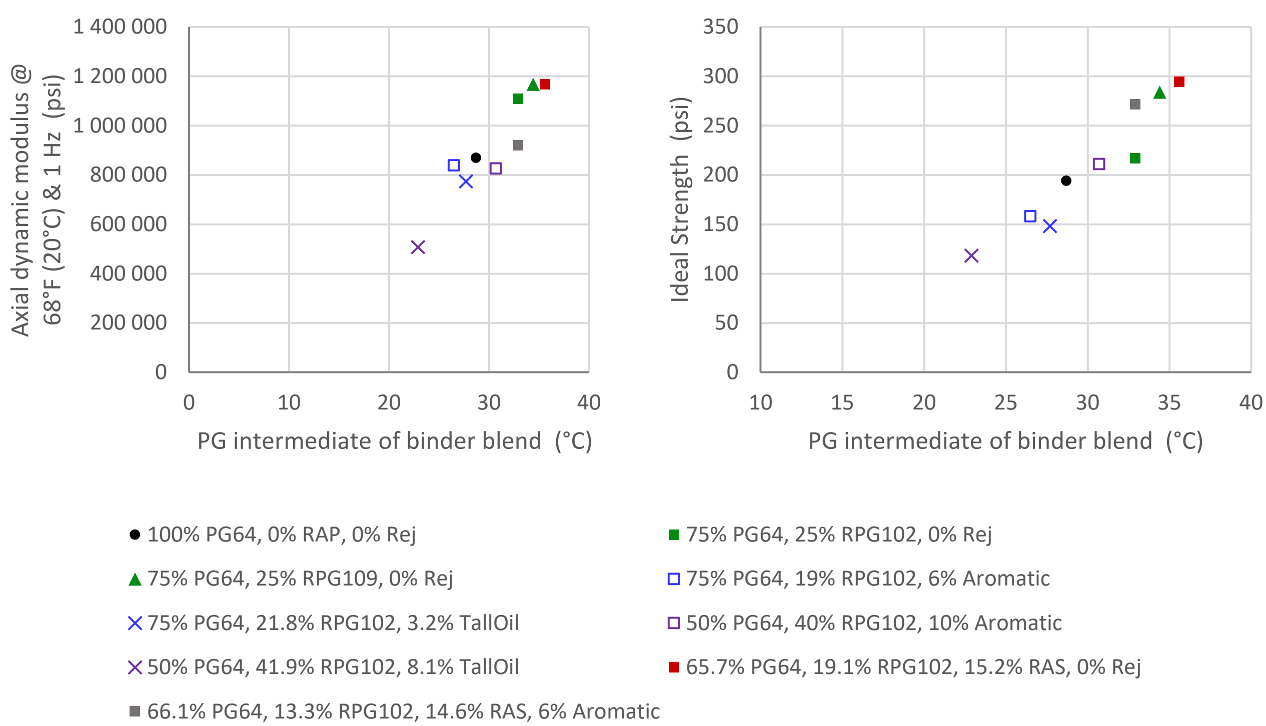


Figure 6.40: Mix stiffness and IDEAL *Strength* versus PGI of the binder blend—mixes with PG 64 base binder.

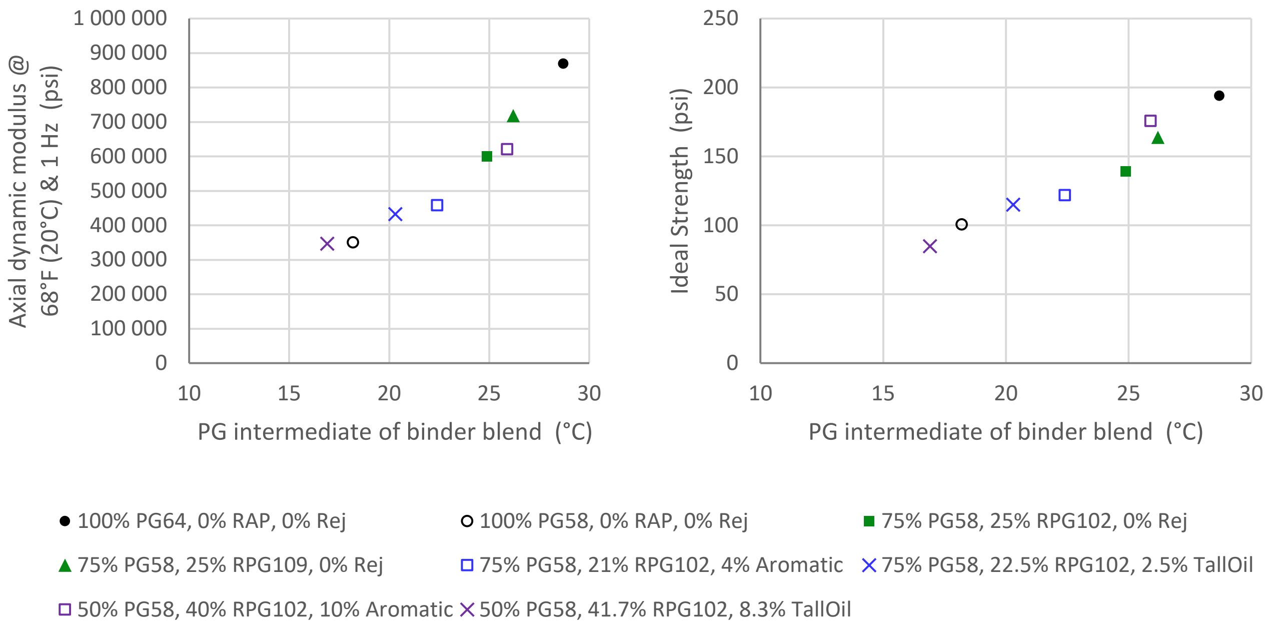


Figure 6.41: Mix stiffness and IDEAL *Strength* versus PG Intermediate of the binder blend—mixes with PG 58 base binder.

6.7.1.5 Does Meeting High Performance Grade Ensure Meeting Hamburg Wheel-Tracking Test Requirements?

While there is a good correlation between the PGH of the binder blend and the rutting performance of the mix (Figure 6.15 to Figure 6.17), meeting the PGH requirement does not ensure meeting the HWT rutting requirement, shown in Figure 6.42 (PG 64 mixes) and Figure 6.43 (PG 54 mixes). There is one case in each figure where the binder blend meets the PGH requirement (>64°C) while the mix fails the Caltrans HWT test requirement (at least 15,000 passes to 0.5 in. rut). The mix with PG 58 base binder and no RAP or RAS also fails the specification.

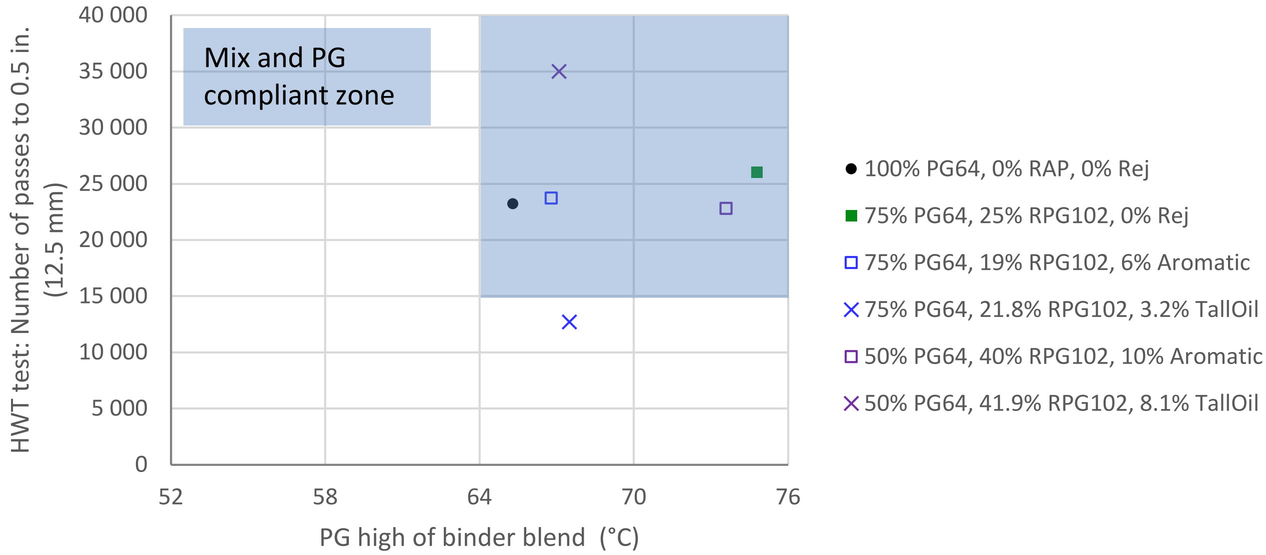


Figure 6.42: Relationship between HMA rutting resistance (HWT test) and binder blend PG high—mixes with PGH 64.

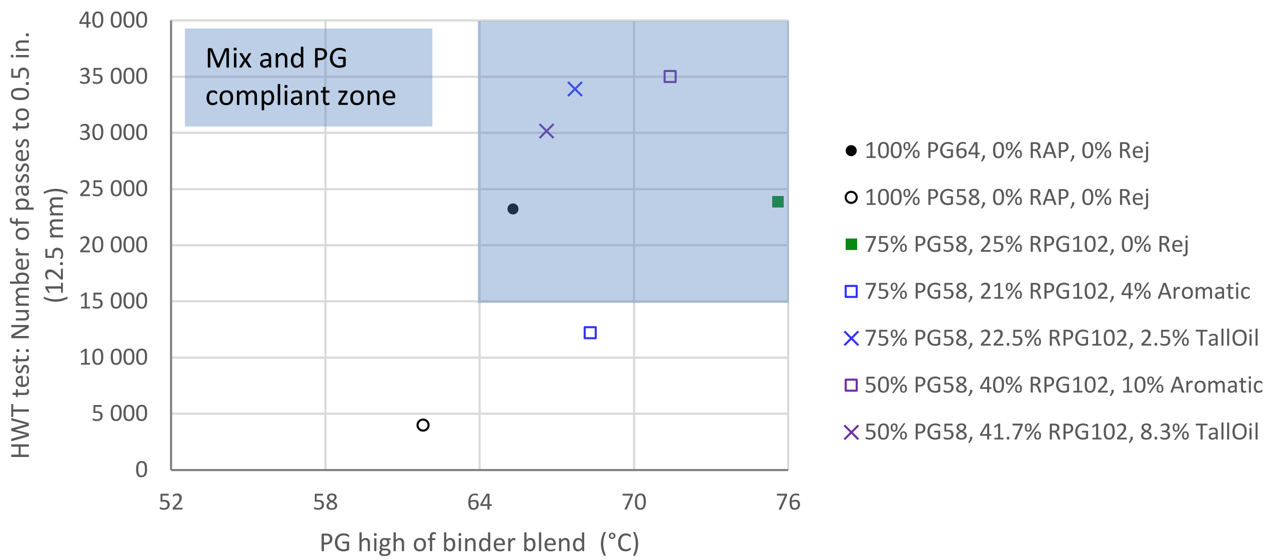


Figure 6.43: Relationship between HMA rutting resistance (HWT test) and binder blend PG high—mixes with PGH 58.

6.7.1.6 Does a High ΔTc Ensure Meeting Requirements for Cracking?

The parameter ΔTc is the difference between the binder critical low temperatures for stiffness and slope, determined following AASHTO T 313. ΔTc has been recommended for limiting the risk of age-related cracking related to poor relaxation properties of the asphalt mix *(15)*, and it has been proposed that it also provides information regarding reflective cracking and top-down fatigue cracking *(15,20,21,23,24,25)*. A minimum ΔTc of -5°C after 20-hour PAV aging has been suggested *(15,20,21)*. Nonetheless, the experimental data collected in this study do not support these recommendations.

Figure 6.44 and Figure 6.45 compare the results of the two cracking tests, fracture cracking under monotonic loading at intermediate temperatures (IDEAL-CT test) and flexural fatigue under repeated loading (4PB), respectively, versus the ΔTc of the binder blend. There is almost no correlation between CT_{Index} and ΔTc and, in two cases, the RA addition resulted in a drop in ΔTc (Figure 6.44, left). This outcome does not correspond with the expected change in ΔTc. For the mixes with PG 64 base binder (Figure 6.44), ΔTc was negatively correlated to ε_6, which again does not correspond with the presumed relationship between fatigue and ΔTc discussed in the studies cited here.

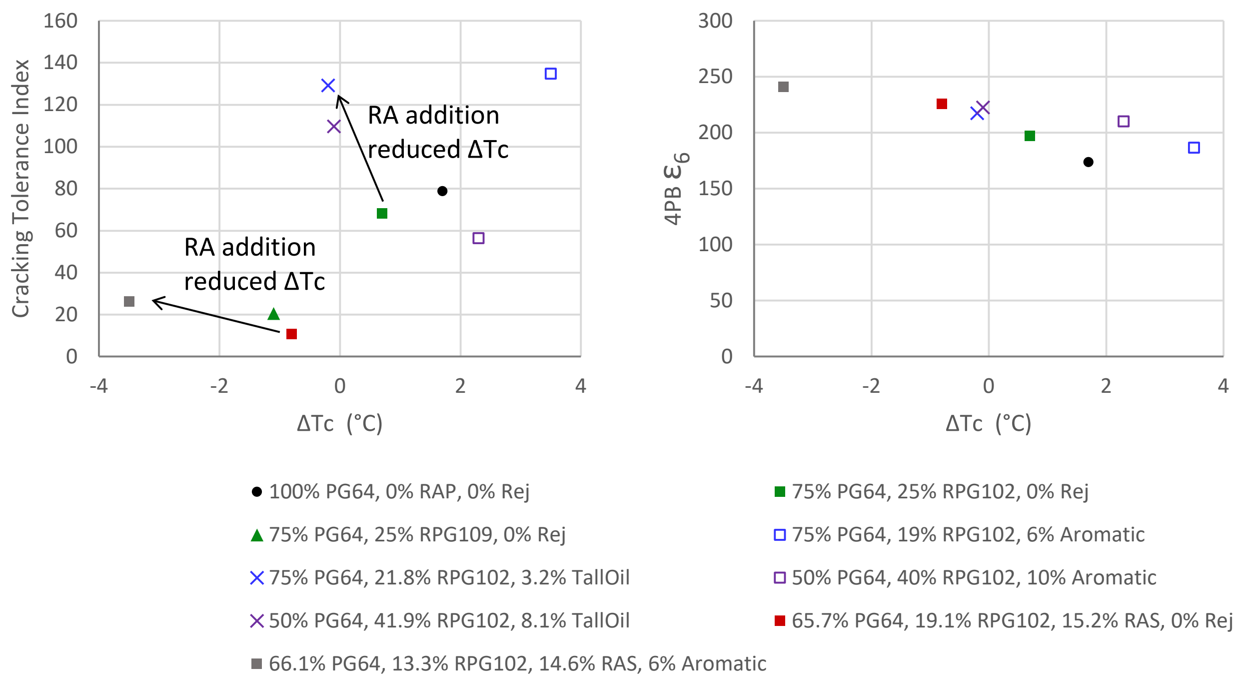


Figure 6.44: Relationship between cracking test results and ΔTc of the binder blend—mixes with PG 64 base binder.

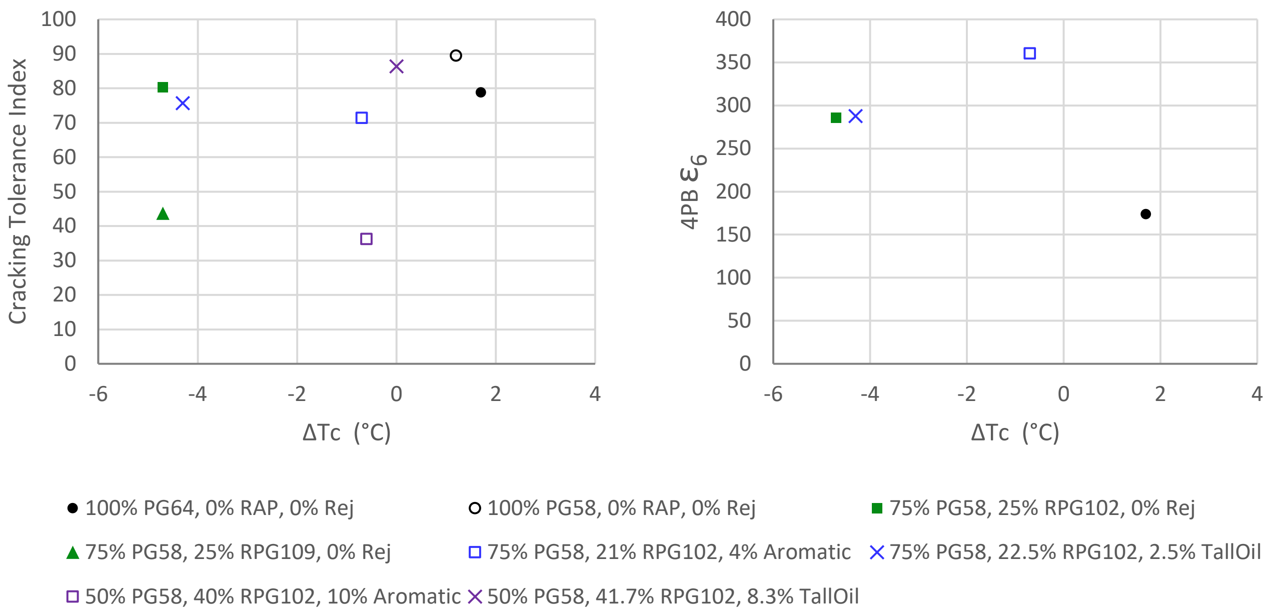


Figure 6.45: Relationship between cracking test results and ΔTc of the binder blend—mixes with PG 58 base binder.

6.7.2 Draft Specification Approaches for Mixes Containing RAP and/or RAS

The following are two draft approaches for specifying binders and mixes with up to 50% RAP and/or RAS binder replacement. The specification is applicable to any binder replacement from 15% to 50%. Note that use of the HWT as the rutting test is for illustration purposes. The ability of the HWT test to adequately identify mixes with poor rutting performance is being investigated in an ongoing study for Caltrans (2023-2026), based on observed field and/or accelerated pavement testing performance.

6.7.2.1 Approach 1: Engineering Desirable Mechanical Properties of the Control Mix

This approach assumes that there is a control mix whose indirect tensile strength (*Strength*) after STOA (if the mix will be placed more than 0.5 ft. [152 mm] below the pavement surface) or MTOA (if the mix will be placed within 0.5 ft .[152 mm] of the pavement surface) has been determined using the IDEAL-CT test. The *Strength* is regarded a surrogate for mix stiffness. The *Strength* results of the STOA and MTOA control mix are referred as $Strength_{\mathrm{T}}^{\mathrm{STOA}}$ and $Strength_{\mathrm{T}}^{\mathrm{MTOA}}$, respectively, while the CT_{Index} of the STOA and MTOA control mix are referred as $CTI_{\mathrm{T}}^{\mathrm{STOA}}$ and $CTI_{\mathrm{T}}^{\mathrm{MTOA}}$, respectively. Note that the subscript "T" stands for "Target." It is also assumed that there are PG requirements for the binder (PGH_R, PGI_R, and PGL_R) and rutting and moisture sensitivity requirements for the mix (e.g., based on the HWT test and AASHTO T283, respectively). A note that the subscript "R" stands for "Required."

The recycling agent dose and the base binder shall be selected to restore the stiffness of the mix at intermediate temperature:

- Based on binder testing: restore PGI of the binder blend (virgin binder + RAP binder + recycling agent) to PGI_R

- Based on mix testing:
    - If the mix will be used within 0.5 ft. (150 mm) of the pavement surface: restore the *Strength* of the MTOA mix to $Strength_{\mathrm{T}}^{\mathrm{MTOA}}$
    - If the mix will be placed more than 0.5 ft (150 mm) below the pavement surface: restore the *Strength* of the STOA mix to $Strength_{\mathrm{T}}^{\mathrm{STOA}}$

Checks after recycling agent dose is determined:

- Binder blend:
    - $PGH \geq PGH_R$
    - $PGI \leq PGI_R$ (if recycling agent dose determination was based on mix testing)
    - $PGL \leq PGL_R$
- STOA mix or mix as sampled from the plant (if the mix will be placed less than or equal to 0.5 ft. below the pavement surface, or heavy vehicle truck traffic is expected prior to placement of the succeeding lifts):
    - Mix passes rutting requirements
- MTOA mix (if the mix will be used within 0.5 ft. of the pavement surface):
    - *Strength* within ±15% $Strength_{\mathrm{T}}^{\mathrm{MTOA}}$ (if recycling agent dose determination was based on binder testing)
    - CT_{Index} within ±15% $CTI_{\mathrm{T}}^{\mathrm{MTOA}}$
- STOA mix or mix as sampled from the plant (if the mix will be placed more than 0.5 ft below the pavement surface):
    - *Strength* within ±15% $Strength_{\mathrm{T}}^{\mathrm{STOA}}$ (if recycling agent dose determination was based on binder testing)
    - CT_{Index} within ±15% $CTI_{\mathrm{T}}^{\mathrm{STOA}}$
- Wet-conditioned mix (mix conditioning as indicated in the corresponding testing procedure):
    - Mix passes moisture-sensitivity requirements

For relevant projects (those that have more than 100,000 tons of HMA), an additional check based on 4PB fatigue testing may be introduced at job mix formula verification. This check may include considering setting the fatigue test result based on the *CalME* simulation to include the combined effect of stiffness and fatigue resistance. In an ongoing study for Caltrans (2023-2026), a suitable fatigue test that is faster, less costly, and easier than the current 4PB fatigue test is being investigated for use in BMD performance-related specifications (PRS) projects.

6.7.2.2 Approach 2: Optimize Mix Properties Within Balanced Mix Design Framework

This approach is based on the assumption that there are PRSs for the mix based on IDEAL-CT test results, in addition to rutting and moisture sensitivity requirements (e.g., based on the HWT test and AASHTO T283, respectively), within the framework of BMD. A preliminary version of such a specification is shown in Table 6.1 (the proposal of the BMD PRS is the goal of an ongoing Caltrans research project). It is also assumed that there are PG requirements for the binder (PGH_R, PGI_R, and PGL_R).

Table 6.1: Draft Routine Balanced Mix Design Performance-Related Specifications Framework for Controlling Stiffness, Rutting, and Moisture Sensitivity

New Asphalt Lifts in Pavement Structure	Lift	Short-Term Oven Aging (STOA) IDEAL Strength	Short-Term Oven Aging (STOA) IDEAL CT_{Index}	Medium-Term Oven Aging (MTOA) IDEAL CT_{Index}	Hamburg Wheel-Tracking (HWT)	Moisture Sensitivity
One or two lifts	Surface	100-175 psi[a]	≥ 50[a]	≥50% STOA[a]	Sect. 39[b]	Sect. 39[b]
	Below surface	≥ 150 psi	≥ 40	≥50% STOA	Sect. 39[b]	Sect. 39[b]
Three or more lifts	Surface	125-175 psi[a]	≥ 50[a]	≥50% STOA[a]	Sect. 39[b]	Sect. 39[b]
	Below surface and ≤0.5 ft. from surface	≥ 175 psi	≥ 35	≥50% STOA	Sect. 39[b]	Sect. 39[b]
	Below surface and >0.5 ft. from surface	≥ 175 psi	≥ 35	Not required	Sect. 39 if will be subjected to truck traffic[b]	Sect. 39[b]

Note: Test values are preliminary.
[a] Assuming conventional HMA as surface lift; values would change if HMA-PM or RHMA-G surface layer.
[b] As prescribed in Caltrans Standard Specifications Section 39.

The combination of the base binder and the recycling agent dose shall be the minimum dose that results in meeting the specifications shown above for the mix and that results in meeting the following binder specifications for the binder blend (virgin binder + RAP binder + recycling agent):

1. $PGH \geq PGH_R$
2. $PGL \leq PGL_R$

For relevant projects (those with more than 100,000 tons of HMA), an additional check based on 4PB fatigue testing may be introduced at job mix formula verification. This check may include considering setting the fatigue test result based on the *CalME* simulation to include the combined effect of stiffness and fatigue resistance. A suitable fatigue test that is faster, less costly, and easier than the current 4PB fatigue test is being investigated for use in BMD PRS projects.

7 SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

7.1 Summary

The goal of the research presented in this report is to study how the mechanical properties of HMA change with the addition of high RAP content and RAS resulting in between 25% and 50% binder replacement and how the resulting changes on stiffness at different temperatures and frequencies and resistance to fatigue, rutting, and monotonic cracking can be engineered by using recycling agents and changing the base binder stiffness. To achieve the goal, 16 mixes and the corresponding binders were fabricated and tested in the laboratory. The set of mixes included a control gradation (0.5 in. NMAS), two virgin binders (PG 64-16 and PG 58-28), two RAPs with different levels of aging (PG high of 102°C and 109°C), one RAS, and two recycling agents (a petroleum-derived aromatic and a tall oil). The testing of the binders included PG grading, shear stiffness, and FTIR spectroscopy. The mix testing included stiffness (AMPT axial dynamic modulus and 4PB flexural dynamic modulus), flexural fatigue resistance (4PB), rutting resistance (AMPT repeated load testing [RLT] and HWT), and IDEAL-CT test to determine the CT_{Index} and *Strength*.

7.2 Conclusions

The conclusions are summarized in the following discussion, and they have been grouped to address the main questions this research intended to answer.

1. What are the effects of the addition of high RAP content on the mechanical properties of the HMA?
   - As expected, the addition of RAP resulted in higher stiffness, particularly at high temperatures, and higher *Strength*, higher rutting resistance, and lower CT_{Index}.
   - Unexpectedly, the addition of RAP to the control mix with PG 64-16 virgin binder did not reduce, but instead improved, the 4PB fatigue resistance at a given tensile strain. This unexpected outcome was related to the poor fatigue performance of the binder source used in this study. In fact, the fatigue performance of the RAP and RAS (aged) binders was better than the fatigue performance of the PG 64-16 virgin binder.
2. Can the RAP addition effects be predicted based on testing of the blended binder?
   - The effects of RAP addition on HMA stiffness, rutting resistance, and IDEAL *Strength* were strongly related to the effect on the PG of the binder blend at similar temperatures as the mix testing. Mix stiffness at high temperatures and rutting resistance were correlated to PGH, mix stiffness at intermediate temperatures and ITS were correlated to PGI, and mix stiffness at low temperatures was correlated to PGL. PGH, PGI, and PGL are the PG high, intermediate, and low, respectively, of the binder blend, with the binder blend being virgin binder plus RAP binder and recycling agent, if used.

- On the contrary, the effects of RAP and recycling agent on 4PB fatigue life and IDEAL CT_{Index} did not correlate well with any blended binder property.

3. What are the effects of the recycling agent addition on the mechanical properties of HMA with high RAP content?

    - As expected, the recycling agent produced an overall softening (decrease in stiffness and IDEAL *Strength* and increase in IDEAL CT_{Index}) of the mix. The effect was somewhat the opposite to the RAP addition.
    - The addition of the recycling agent did not consistently produce the same effect on the rutting resistance of the HMA with RAP.
    - As expected, the addition of the recycling agent resulted in an improvement in the 4PB fatigue life for the mix with PG 58-28 binder. Unexpectedly, the addition of the recycling agent did not improve the 4PB fatigue life for the mix with PG 64-16 binder. This unexpected outcome was believed to be related to the poor fatigue performance of the virgin base binder source used in this study.
    - The main difference between the two recycling agents was that the aromatic required a higher dose (around 60% higher) than the tall oil to produce similar effects on the HMA mechanical properties. Another difference is that—for a similar effect on the PGH—the aromatic produced a higher improvement in ΔTc (more positive ΔTc) than the tall oil.

4. By using a recycling agent, can the mechanical properties of an HMA with high RAP content be restored back to the properties of the HMA with low RAP content?

    - The answer to this question is that, overall, yes. By using a recycling agent, the stiffness of the mix with high RAP content can be restored back to the stiffness of the mix with low or no RAP content, and the same applies to IDEAL *Strength*, CT_{Index}, and fatigue resistance.
    - The negative impact of the recycling agent on the rutting performance of the HMA is a possibility that must be considered and tested accordingly by conducting a rutting performance on the HMA with high RAP content and recycling agent.

5. Are there specific considerations required for the addition of RAS compared with the addition of RAP?

    - The effects of adding RAS on the mix mechanical properties was consistent with the higher stiffness (higher PG) of the RAS binder compared with the RAP binders. Further, the addition of recycling agent produced similar effects on the mix with RAP and RAS as the effects on the mixes with only RAP.
    - No reason was found to treat mix designs with RAS differently from mix designs with RAP other than the facts that RAS PGH is typically much higher than RAP PGH and that RAS binder content is typically three to five times higher than RAP binder content. Because of the high binder content of the RAS compared with the RAP, the mass amount of RAS to achieve a similar binder replacement to RAP is three to five times lower.

6. Can mixes with 50% RAP content and/or RAS be engineered to have desired properties for different applications in the pavement structure?
    - It was demonstrated that mixes with both 25% and 50% RAP (or RAS and RAP) can be engineered to have generally the same properties for a surface mix as a mix with the same base binder and no RAP.
    - It was also demonstrated that the addition of RAP and/or RAS can be used to stiffen a mix used below the surface mix for use in thicker overlays and new pavement.
    - Mechanical properties for either application can be engineered using different binder replacement rates, different base binders, different RAP and/or RAS sources, and recycling agent.
7. What is the recommended approach to determine the recycling agent dose?
    - The approach followed in this research study, recommended after NCHRP 9-58, which consists of restoring the PGH of the binder blend back to the PGH of the control binder, may result in unnecessarily high recycling agent doses and the consequent over-softening of the mix. The high recycling agent dose will increase cost and greenhouse gas emissions. Further, the soft mixes will underperform in many scenarios, particularly when used as layers below the surface in overlays or new pavements with more than one lift of new HMA.
    - Two approaches have been proposed for dosing the recycling agent: Approach 1 and Approach 2.
        - Approach 1 focuses on engineering the mechanical properties of the mix with high RAP/RAS content to match the properties of a control mix with either no RAP/RAS or low/standard RAP/RAS content. The dosing goal is to match the stiffness of the HMA at intermediate temperatures, based on either binder or mix testing (PGI and ITS are used as surrogates for HMA stiffness). The resulting mix and/or the extracted binder is then tested for low and high temperatures performance verification.
        - Approach 2 focuses on meeting the required PRSs within the BMD framework by changing the base binder and/or using the minimum amount of recycling agent.

Other questions addressed in this study are the following:

8. Does RAP/RAS binder fully blend with the virgin binder and recycling agent?
    - Based on the comparison of mix test results, for which full bending is unknown, versus binder test results, for which full bending is guaranteed, it appears that the RAP and RAS binders fully blended or nearly fully blended with the virgin binder. This result was found for mixes prepared with laboratory mixing and short-term oven aging conditioning (four

hours at 135°C followed by two hours at 138°C compaction temperature). Blending level will increase as the mix ages.

9. Does meeting PGH ensure meeting HWT test requirements?
    - While there is a good correlation between PGH of the binder blend and rutting performance of the mix, meeting the PGH requirement does not ensure meeting the HWT rutting requirement.
10. Does a high ΔTc ensure meeting requirements for fracture and fatigue cracking?
    - As expected, ΔTc becomes more negative upon RAP/RAS addition. Nonetheless, no correlation was found between ΔTc of the binder blend and IDEAL CT_{Index} or 4PB fatigue. Further, the addition of the tall oil recycling agent resulted in worse ΔTc (more negative) than the petroleum-based recycling agent in some cases.

7.3 Recommendations

It is recommended that Caltrans moves forward with pilot implementation of high RAP content HMA, up to 50% binder replacement, in the field. It is recommended that Approach 1 is followed for determining the recycling agent dose in the beginning. Once Caltrans implements a BMD approach for HMA, the use of Approach 2 for determining the recycling agent dose would be recommended. No specific recommendation was formulated regarding the type of recycling agent.

Further research is recommended to address several topics not considered in this study:

- The long-term effectiveness of the recycling agent.
- The effect of RAP/RAS and recycling agent on the moisture sensitivity of the mix.
- Volumetric limits, if applicable, for HMA with greater than 25% RAP/RAS.
- A maximum amount of 10% recycling agent was adopted in this research, where the percentage refers to the sum of virgin binder, recycled binder, and recycling agent. Further research is required to set the limits for each recycling agent type.
- Neither CT_{Index} not ΔTc showed correlation with the fatigue resistance of the mix, as determined in the 4PB test. Further research is needed to select a simple performance-related test that can be used in QC/QA of regular asphalt concrete paving projects.
- Completion and piloting of BMD limits for the recommended categories of HMA use (surface layers, layers below the surface to a depth of 0.5 ft. and layers below the surface and deeper than 0.5 ft.).
    - IDEAL *Strength* and CT_{Index} for 3/8”, 1/2", 3/4”, and 1” nominal aggregate sizes.
    - Validation of HWT test or an alternative simple rutting test for QA/QC in production.
- Life cycle assessment (LCA) and life cycle cost analysis (LCCA) to quantify the benefits of using high RAP/RAS content in HMA while considering performance and the economic and environmental costs of the recycling agent.

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APPENDIX A BINDER TEST RESULTS

Complete mix design and performance-related test results are available by request and stored in the UCPRC transmittal databases (Internal Online Lab Tracking System [OLTS] and Stonemont Solutions Mix Design and QC Management System).

Table A.1: Summary Glover-Rowe Values for All Binder Blends

Blend ID	Corresponding Mix Number	GR (kPa)		
		Unaged	RTFO-Aged	PAV 20-Aged
RAP(A)	Not Tested	3.25E+03	1.20E+04	2.85E+04
RAP(B)	Not Tested	2.16E+04	2.56E+04	4.51E+04
PG64 Virgin	#1	4.34E-02	9.22E-01	5.39E+01
PG58 Virgin	#2	1.74E-01	3.18E+00	6.99E+01
PG64+R15(A)	Not Tested	3.45E+00	7.19E+00	2.63E+02
PG64+R25(A)	#3	7.67E+00	7.12E+01	6.38E+02
PG58+R25(A)	#4	4.64E+00	3.58E+01	2.38E+02
PG64+R25(B)	#5	4.95E+00	3.57E+01	4.92E+02
PG58+R25(B)	#6	5.72E+00	4.28E+01	2.36E+02
PG64+R19(A)+RJ6(a)	#7	2.47E-01	4.39E+00	6.52E+01
PG58+R21(A)+RJ4(a)	#8	1.40E+00	1.71E+01	1.14E+02
PG64+R21.8(A)+RJ3.2(b)	#9	5.61E-01	2.77E+00	3.47E+01
PG58+R22.5(A)+RJ2.5(b)	#10	1.10E+00	1.16E+01	6.73E+01
PG64+R50(A)	Not Tested	2.39E+02	8.71E+02	2.54E+03
PG64+R40(A)+RJ10(a)	#15	4.34E+00	3.94E+01	3.05E+02
PG58+R40(A)+RJ10(a)	#16	3.34E+00	3.42E+01	1.25E+02
PG64+R41.9(A)+RJ8.1(b)	#17	9.32E-02	7.00E-01	1.21E+01
PG58+R41.7(A)+RJ8.3(b)	#18	1.69E-01	2.07E+00	2.91E+01
PG64+R19.1(A)+RAS15.2	#23	2.30E+02	6.62E+02	1.99E+03
PG64+R13.3(A)+RAS14.6+RJ6(a)	#24	2.05E+01	1.05E+02	7.54E+02

Notes: R(A): Southern California RAP(A) (high PG of 102°C); R(B): Inland Valley RAP(B) (high PG of 109°C); RAS: reclaimed asphalt shingles; RJ(a): aromatic-based recycling agent; RJ(b): tall oil-based recycling agent.

Table A.2: Summary FTIR Test Results for All Binder Blends

Blend ID	Corresponding Mix Number	CA Index			SUL Index		
		Unaged	RTFO-Aged	PAV-Aged	Unaged	RTFO-Aged	PAV-Aged
RAP(A)	Not Tested	2.95	3.04	3.58	9.28	8.32	8.34
RAP(B)	Not Tested	3.07	3.12	3.45	7.90	9.87	8.19
PG64 Virgin	#1	0.18	0.47	1.14	0.63	1.85	4.08
PG58 Virgin	#2	0.12	0.40	1.03	0.60	1.24	3.86
PG64+R15(A)	Not Tested	0.57	0.94	1.60	1.83	2.37	4.64
PG64+R25(A)	#3	0.84	1.05	1.70	2.94	2.77	4.85
PG58+R25(A)	#4	0.79	1.04	1.62	2.66	2.63	4.50
PG64+R25(B)	#5	0.80	1.05	1.60	3.05	2.94	5.25
PG58+R25(B)	#6	0.78	1.06	1.57	2.88	3.10	4.85
PG64+R19(A)+RJ6(a)	#7	0.79	1.14	1.55	2.17	2.26	4.59
PG58+R21(A)+RJ4(a)	#8	0.70	1.05	1.55	2.67	3.20	4.21
PG64+R21.8(A)+RJ3.2(b)	#9	0.29	0.50	1.25	2.73	2.73	5.00
PG58+R22.5(A)+RJ2.5(b)	#10	0.41	0.64	1.38	2.49	2.53	4.86
PG64+R50(A)	Not Tested	1.54	1.76	2.24	4.96	4.76	6.15
PG64+R40(A)+RJ10(a)	#15	1.35	1.59	2.12	4.67	4.23	5.68
PG58+R40(A)+RJ10(a)	#16	1.24	1.52	2.08	4.04	4.00	5.69
PG64+R41.9(A)+RJ8.1(b)	#17	0.41	0.61	1.23	3.97	3.36	5.10
PG58+R41.7(A)+RJ8.3(b)	#18	0.45	0.68	1.25	4.06	3.30	5.10
PG64+R19.1(A)+RAS15.2	#23	1.33	1.55	2.04	2.55	2.97	4.19
PG64+R13.3(A)+RAS14.6+RJ6(a)	#24	1.24	1.53	2.07	2.21	2.65	4.15

Notes: R(A): Southern California RAP(A) (high PG of 102°C); R(B): Inland Valley RAP(B) (high PG of 109°C); RAS: reclaimed asphalt shingles; RJ(a): aromatic-based recycling agent; RJ(b): tall oil-based recycling agent.

Table A.3: Modified Carbonyl Area (CAmod) Indices for All Binder Blends

Blend ID	Corresponding Mix Number	CA Index			CAmod Index		
		Unaged	RTFO-Aged	PAV-Aged	Unaged	RTFO-Aged	PAV-Aged
RAP(A)	Not Tested	2.95	3.04	3.58	2.95	3.04	3.58
RAP(B)	Not Tested	3.07	3.12	3.45	3.07	3.12	3.45
PG64 Virgin	#1	0.18	0.47	1.14	0.18	0.47	1.14
PG58 Virgin	#2	0.12	0.40	1.03	0.12	0.40	1.03
PG64+R15(A)	Not Tested	0.57	0.94	1.60	0.57	0.94	1.60
PG64+R25(A)	#3	0.84	1.05	1.70	0.84	1.05	1.70
PG58+R25(A)	#4	0.79	1.04	1.62	0.79	1.04	1.62
PG64+R25(B)	#5	0.80	1.05	1.60	0.80	1.05	1.60
PG58+R25(B)	#6	0.78	1.06	1.57	0.78	1.06	1.57
PG64+R19(A)+RJ6(a)	#7	0.79	1.14	1.55	0.67	1.02	1.40
PG58+R21(A)+RJ4(a)	#8	0.70	1.05	1.55	0.62	0.98	1.44
PG64+R21.8(A)+RJ3.2(b)	#9	0.29	0.50	1.25	0.29	0.50	1.25
PG58+R22.5(A)+RJ2.5(b)	#10	0.41	0.64	1.38	0.41	0.64	1.38
PG64+R50(A)	Not Tested	1.54	1.76	2.24	1.54	1.76	2.24
PG64+R40(A)+RJ10(a)	#15	1.35	1.59	2.12	1.17	1.39	1.86
PG58+R40(A)+RJ10(a)	#16	1.24	1.52	2.08	1.05	1.32	1.83
PG64+R41.9(A)+RJ8.1(b)	#17	0.41	0.61	1.23	0.41	0.61	1.23
PG58+R41.7(A)+RJ8.3(b)	#18	0.45	0.68	1.25	0.45	0.68	1.25
PG64+R19.1(A)+RAS15.2	#23	1.33	1.55	2.04	1.33	1.55	2.04
PG64+R13.3(A)+RAS14.6+RJ6(a)	#24	1.24	1.53	2.07	1.12	1.41	1.92

Notes: R(A): Southern California RAP(A) (high PG of 102°C); R(B): Inland Valley RAP(B) (high PG of 109°C); RAS: reclaimed asphalt shingles; RJ(a): aromatic-based recycling agent; RJ(b): tall oil-based recycling agent.

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