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RAP and RAS in HMA Pilot Project on SBD 215: Material Testing, Observations, and Findings

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16. ABSTRACT A pilot project for the inclusion of high percentages of reclaimed asphalt pavement (RAP) in hot mix asphalt (HMA) was built on State Route 215 in San Bernardino County in September 2022. Five mixes were included in short test sections: (1) a control mix with no recycled asphalt shingles (RAS) or RAP, (2) a mix with 25% RAP and recycling agent (RA), (3) a mix with 30% RAP and RA, (4) a mix with 35% RAP and RA, and (5) a mix with 40% RAP and RA. A sixth mix, which was a typically used mix with 23% RAP, was used for construction of the rest of the overall project. This technical memorandum presents the laboratory test results from plant mix produced for job mix formula verification and from one or two quality assurance (QA) samples, depending on the test, taken during test section construction as well as observations of plant production and construction. Only the control mix binder consisting of the virgin PG 64-28M base binder and the mix with PG 58-34M, 25% RAP, and RA passed the delta T _c specification. There is FHWA guidance and past UCPRC experience with other polymer-modified Caltrans mixes that indicate delta T _c may not be a good parameter to use with modified binders. The mixes with 30%, 35%, and 40% RAP and RA and the mainline mix did not meet the PG specification low temperature limit. All the mixes easily passed the IDEAL-CT (cracking tolerance) index number. Construction QA sampled binder test results indicated that the PG 58-34M binder was used for the control mix with no RAP instead of the specified PG 64-28M binder. Results are presented for volumetric tests, flexural and axial dynamic modulus tests, repeated load triaxial tests, flexural fatigue tests, Hamburg Wheel-Track tests, and IDEAL-CT tests with reheated and medium-term oven aged samples reported in terms of the IDEAL-CT index and indirect tensile strength.		
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PROJECT OBJECTIVES

This study is part of PPRC Project 4.79 (Guidance, Tests, and Specifications for High RAP/RAS in HMA and RHMA Mixes), which is a continuation of PPRC Project 4.64 (Continued Development of Guidelines for Determining Binder Replacement in High RAP/RAS Content Mixes). The objective of this project is to develop guidelines for determining binder replacement rates in high reclaimed asphalt pavement/recycled asphalt shingles (RAP/RAS) 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 rejuvenators (referred to as recycling agents in this technical memorandum).
- 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 binder replacement and, if applicable, recommendations for accelerated wheel-load testing.

The results presented in this technical memorandum contribute to Tasks 2, 3, 5, and 6 by presenting the results of laboratory testing of binders and mixes for a pilot project on State Route 215 in San Bernardino County (SBD 215), including sampling and testing for job mix formula approval and sampling and testing of plant-sampled materials during construction of the test sections, as well as observations from construction.

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LIST OF ABBREVIATIONS

AMPT	Asphalt mixture performance tester
APCS	Automated pavement condition survey
BBR	Bending beam rheometer
COV	Coefficient of variation
DM	Dynamic modulus test
DSR	Dynamic shear rheometer
FAT	Beam fatigue test
FM	Flexural modulus test
FS	Frequency sweep
FTIR	Fourier transform infrared
FTIR-ATR	Fourier transform infrared spectroscopy with attenuated total reflection
HMA	Hot mix asphalt
HWT	Hamburg Wheel-Tracking
IDEAL-CT	IDEAL cracking tolerance test
JMF	Job mix formula
LAS	Liquid antistrip
MTOA	Medium-term oven aging
NMAS	Nominal maximum aggregate size
nSSP	Non-Standard Special Provision
OLTS	Online Laboratory Testing System
PAV	Pressure aging vessel
PG	Performance grade
QC/QA	Quality control/quality assurance
RA	Recycling agent
RAP	Reclaimed asphalt pavement
RAS	Recycled asphalt shingles
RBR	Recycled binder ratio
RHMA	Rubberized hot mix asphalt

RLT	Repeated load triaxial
RTFO	Rolling thin-film oven
RVE	Representative volume element
SSD	Saturated surface-dry
Superpave	SUperior PERforming asphalt PAVement
TCE	Trichloroethylene

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 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 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)
AASHTO TP 124	Provisional Standard Method of Test for Determining the Fracture Potential of Asphalt Mixtures Using Semicircular Bend Geometry (SCB) at Intermediate Temperature

CONVERSION FACTORS

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

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

1 INTRODUCTION

1.1 Background of the Study

The California Department of Transportation (Caltrans) is interested in finding, developing, and implementing approaches to reduce life cycle cost and improve life cycle environmental performance for maintaining and rehabilitating existing pavements and constructing new ones. 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, meaning mixes containing more than 25% RAP binder replacement with and without the use of recycling agents (RAs). The University of California Pavement Research Center (UCPRC) has been investigating use of higher percentages of RAP in HMA through laboratory testing of laboratory-prepared and field-sampled materials, observations of construction, and mechanistic-empirical simulations using the performance-related test properties for the mixes.

Previous and ongoing research at the UCPRC, working with Caltrans and industry, has identified potential concerns regarding the use of highly aged, stiff RAP. Research is underway at the UCPRC to study the impact of different RAP sources, varying RAP content, and the addition of RAs to engineer the performance-related properties of binders and mixes, considering the properties of highly aged RAP and RAS.

Several performance-related tests have been identified to assess the performance characteristics of these mixes, including rutting, stiffness, and fatigue. These performance-related tests include long-established tests such as the Hamburg Wheel-Tracking (HWT) test, repeated load triaxial (RLT) test, and four-point flexural beam tests. Other recently developed tests, such as the indirect tensile asphalt cracking IDEAL cracking tolerance (IDEAL-CT) test, are also being assessed for their potential to provide a quick and simple indicator of mix performance-related properties for mix design and quality control/quality assurance (QC/QA) purposes.

Limited work had been done on virgin binder replacement with binder in RAS in California by the UCPRC, Caltrans, and industry prior to the program of Caltrans pilot studies of which the pilot study presented in this technical memorandum is a part. 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 RAS source used (1).

This technical memorandum presents project information, materials testing data from tests performed by the UCPRC, and construction observations by the UCPRC from a pilot project on State Route 215 in San Bernardino County (SBD 215) that included six mixes: a control mix with no RAP, a mix with a currently typical amount of RAP, and four mixes with increasing RAP aggregate contents intended to meet binder replacement rates of 25%, 30%, 35%, and 40%.

The following problem statements related to inclusion of RAS and RAP in HMA were identified for this project:

- The degree of blending between RAP, RAP/RAS, and virgin binders could be a significant variable, particularly for mixes using highly aged RAP—typical of Inland Empire, Desert, and High Desert locations in District 8—and RAS. Incomplete blending could alter the properties of the mix because of less available binder and partial activation of the stiff RAP and/or RAS binder. The effects of potentially not achieving full blending need to be better understood to be effectively considered in mix design procedures and performance-related testing. This problem is addressed in this pilot project and technical memorandum.
- Plant-produced mixes subjected to silo storage undergo additional blending and aging, leading to increased stiffness, improved rutting, and reduced cracking and fatigue resistance, dependent on the time spent in the silo. This outcome needs to be factored into mix design procedures and performance-related testing. This problem was not addressed in this pilot project or technical memorandum because all materials were sampled without silo storage. Silo storage is addressed in a separate report (2).
- The impact of long-term aging on the performance of high RAP and RAP/RAS mixes with different RAs needs to be fully investigated using various aging protocols. This problem was addressed with respect to binder aging but not mix aging. Mix aging will be addressed in the future through laboratory mix testing using medium-term oven aging (MTOA) of loose mix and later field sampling of this pilot project and will be documented in a separate report.

1.2 Report Structure

This report includes the following chapters, which address the tasks discussed in Section 1.3:

- Chapter 2 details the test section layout, testing plan, material sampling, mix designs, and test method overview for the SBD 215 pilot project.
- Chapter 3 discusses the results from testing of binders from the pilot project mixes, addressing Task 3 of the project objectives.
- Chapter 4 covers the testing of the mixes from the pilot project, including testing during the job mix formula (JMF) approval process and during construction, addressing Task 2 and setting the baseline for future testing of field-mixed/field-compacted specimens for Task 6.
- Chapter 5 presents initial field construction observations.
- Chapter 6 presents preliminary conclusions from this pilot project.

Appendix A shows the provisional method for MTOA used for laboratory testing. Box sample IDEAL-CT test results are shown plotted in Appendix B, as an addition to the results from bucket sample results shown in the main body of the report. Detailed data tables are not included in this

report. All data are available through the UCPRC Online Testing Service web application or in Excel tables.¹

1.3 Measurement Units

Although Caltrans has returned to the use of US standard measurement units, metric units have always been used by the UCPRC in the design and layout of test tracks, and for laboratory, Heavy Vehicle Simulator, and field measurements and data storage. In this report, both US and metric units (provided in parentheses after the US units) are provided in general discussion. In keeping with convention, metric units are used in laboratory data analyses and reporting, with some US units, where appropriate, to assist the reader. A conversion table is provided on page xv.

¹ Contact the report's authors for access to these resources.

2 TESTING PLAN AND MATERIAL SAMPLING AND TEST METHODS

2.1 Pilot Project Test Sections Overview and Pre-Overlay Observations

The test sections are within Caltrans project 08-1M1104, SBD 215, in San Bernardino County, from 0.1 miles north of 27th Street to 0.1 miles south of Devore Road, in the city of San Bernardino. The beginning and ending post miles of the total project are 10.0 and 17.2. The six test sections make up a portion of the total project in a relatively straight stretch of the interstate freeway in Lane 1 in both directions, with post miles shown in Table 2.1. The plan was for the mixes to be proportioned to meet the binder replacement rates shown in the table. During the mix design process, the mix producer had difficulty proportioning the mixes to exactly hit those binder replacement rates and focused on matching them as closely as possible, using two definitions of binder replacement rate: one including the RA in the virgin binder and the other including it with the RAP binder. The mainline mix with 23% RAP was used throughout the rest of the project, as shown in the table. A mix with RAP and 3% RAS was removed from the project, although it was part of the original plan.

Table 2.1: Pilot Project Test Section Location Lane and Post Miles and Mix Types from Project Special Provisions

Pilot Project Test Sections ^a			
Type ^b	Beginning Post Mile	Ending Post Mile	Lane Number
0% RAP	13.0	13.4	1
23% RAP aggregate (mainline)	10.0	17.2	All
25% RAP binder replacement	13.4	13.8	1
30% RAP binder replacement	13.8	14.2	1
35% RAP binder replacement	14.2	14.6	1
40% RAP binder replacement	14.6	15.0	1

^a See project plans for details. A test section with RAS was originally in the plan but was later removed from the project before construction.

^b Percentages were specified as % binder replacement. However, contractor used replacement by weight of RAP aggregate.

The maintenance project that the test sections are part of primarily consists of a 0.2 ft thick surface removal and new overlay (mill and fill). Approximately 4,330 tons of high RAP mix were placed, split between the innermost lanes (Lane 1) in both directions. Each test section had 433 tons of material placed per direction, or 866 tons combined for the two directions. An estimated 53,080 tons of the mainline mix were placed in the project.

The existing pavement had nearly zero cracking distress in Lane 1 in both directions prior to placement of the overlay but had rut depths of 10 to 12 mm in Lane 1 in both directions where the test sections were placed and nearly 20 mm in Lane 2 in both directions, based on the automated pavement condition survey (APCS) data shown in Figure 2.1 and Figure 2.2. A 12.5 mm (1/2") rut depth is considered a failure in the Caltrans pavement management system because rutting of that severity poses a safety risk. Nearly 25% of the Lane 2 wheel path was cracked in the southbound direction as well.

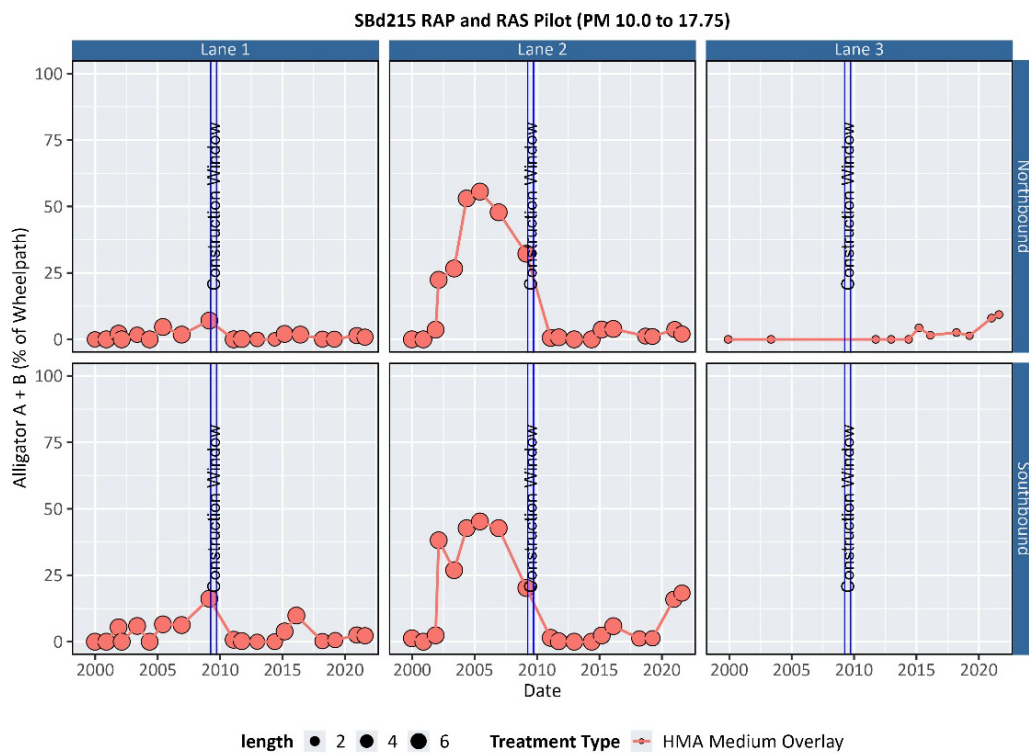


Figure 2.1: Alligator A+B cracking (% of wheelpath) prior to section construction (test sections are in Lane 1 on the left).

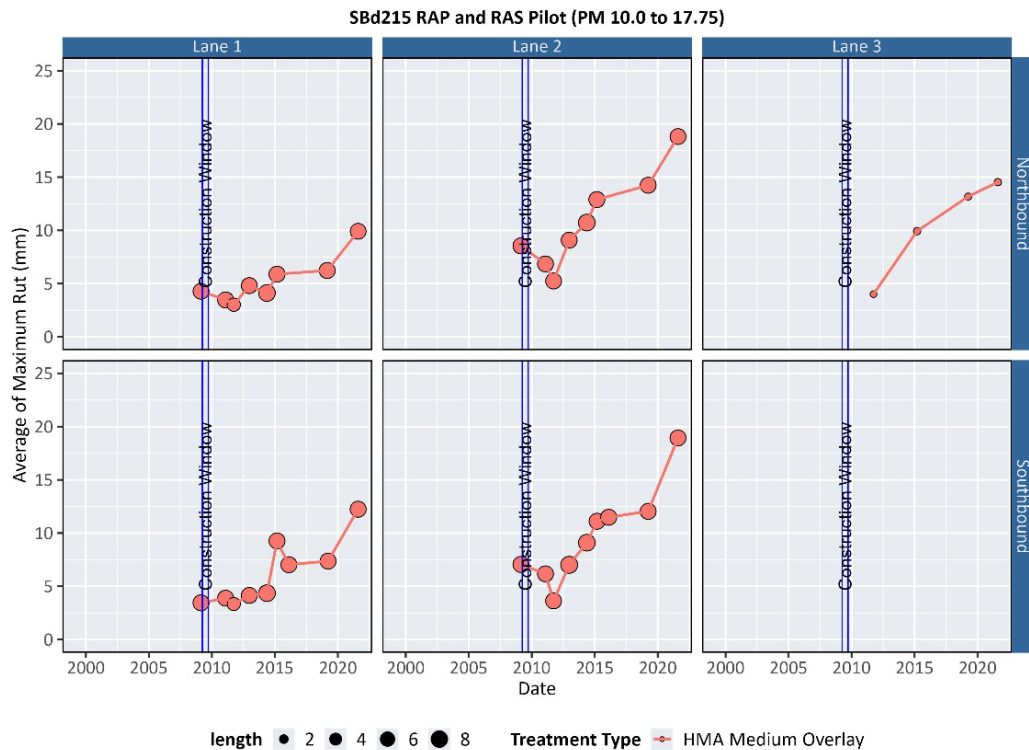


Figure 2.2: Average of maximum rut (mm) prior to section construction (test sections are in Lane 1 at left).

2.2 Mix Designs

The mainline mix with 23% RAP was required to meet Caltrans Standard Specifications for Type A dense-graded HMA. All the mixes were designed to meet Caltrans specifications for 3/4" nominal maximum aggregate size (NMAS), and the specifications for the test section mixes other than the mainline mix were included in the Non-Standard Special Provisions (nSSPs) for the contract. The nSSP requirements are shown in Figure 2.3. The nSSP mix design requirements are the same as those in the Caltrans Standard Specifications, except for the following:

- The gyratory compaction requirements (N_{design} , VMA) and gradation requirements for the mixes with high RAP and RAS are waived (although the RAS mix was later removed from the project).
- The moisture susceptibility test dry strength has a minimum and maximum value, and the wet strength has a minimum ratio.
- The HWT test has a minimum number of cycles to a specified rut depth, and the minimum number of passes at the inflection point was waived for mixes with high RAP or RAS.
- Extracted PG-M binder grade and delta T_c values are specified for all mixes.
- The IDEAL-CT test value of the high RAP mixes must be greater than or equal to that of the virgin mix (with no RAP).
- Flexural fatigue testing and asphalt mixture performance tester (AMPT) RLT testing are required for information only, with testing done by the UCPRC only.

The information from the JMF submittals from the contractor for the 0% RAP control mix, the four high RAP mixes, and the 23% RAP mainline mix are shown in Table 2.2 along with mix codes used throughout the report (Mix E to Mix I for the control and high RAP mixes and Mix Q for the mainline mix). The information in the table comes from the CEM 3511/3512 forms submitted to Caltrans by the contractor prior to the collection of the JMF verification samples.

The nSSP for this project and the other high RAP pilot projects called for setting the RAP content based on percent of binder replacement (25%, 30%, 35% and 40%). However, on this pilot project, the contractor developed the mix designs based on percent of aggregate replacement with RAP and then calculated the recycled binder contents, which the district approved. The contractor was not confident that the binder content of the RAP aggregates would be consistent enough to focus on RAP binder replacement. During production, RAP is controlled based on aggregate replacement rather than binder replacement. Therefore, the specified binder replacement percentages became RAP aggregate replacement percentages of 25%, 30%, 35%, and 40%.

One aggregate source, one RAP source, one liquid antistriper, and one RA source were used by the contractor to produce the mix designs included in the pilot sections. The aggregate was a crushed alluvium (primarily nonmarine sedimentary rocks) from near San Bernardino. The binder grade of the virgin asphalt used in the mixes containing RAP was PG 58-34M, and of the control mix with no

RAP was PG 64-28M. For the mixes with RAP aggregate contents of 25% to 40% (Mix F to Mix I), the contractor used the softer binder and RAs to match the high temperature grade of the control mix. For the mainline mix, the contractor also used the PG 58-34M binder, one grade lower than the PG 64-28M binder specified for the climate region. For the mainline mix on this project, the contractor did not have to meet binder testing results, contrary to Caltrans standard practice for mixes with greater than 15% and less than 25% RAP at the time the mixes were approved. The control mix with 0% RAP and the mainline mix with 23% RAP and no RA (Mix E and Mix Q) both had 0.5% liquid antistrip (LAS) by mass of binder. The 25% to 40% RAP mixes used a tall oil-based RA.

JMF target aggregate gradations are shown in Figure 2.4 for the control mix (Mix E) with no RAP, in Figure 2.5 for the mix with 25% RAP (Mix F), in Figure 2.6 for the mix with 30% RAP (Mix G), in Figure 2.7 for the mix with 35% RAP (Mix H), in Figure 2.8 for the mix with 40% RAP (Mix I), and in Figure 2.9 for the mainline mix with 23% RAP (Mix Q). All the JMF target gradations were in the middle of the Caltrans 3/4" Standard Specifications limits, summarized in Figure 2.10. The binder content of the RAP aggregate used in the calculations was 4.14%, which came from extraction results from the contractor.

39-2.13B(2) Type A Hot Mix Asphalt—High RAP Mix Design

The mix design for Type A HMA—High RAP must comply with the requirements shown in the following table:

Type A HMA—High RAP Mix Design Requirements			
Quality characteristic	Test method	Requirement	
		HMA Virgin Mix and HMA with Up to 25% RAP BR	HMA Mix with RAS or High RAP
Air voids content (%)	AASHTO T 269 ^a	$N_{initial} > 8.0$ $N_{design} = 4.0$ ($N_{design} = 5.0$ for 1-inch aggregate) $N_{max} > 2.0$	Report value at N_{design} gyrations on job mix formula (JMF) submittal form
Gyrations compaction (no. of gyrations)	AASHTO T 312	$N_{initial} = 8$ $N_{design} = 85.0$ $N_{max} = 130$	$N_{initial} = 8$ $N_{design} = 85.0$ $N_{max} = 130$
Voids in mineral aggregate (min, %) ^b Gradation: No. 4 3/8-inch 1/2-inch 3/4-inch 1-inch with NMAS = 1-inch with NMAS = 3/4-inch	MS-2 Asphalt Mixture Volumetrics	16.5–19.5 15.5–18.5 14.5–17.5 13.5–16.5 13.5–16.5 14.5–17.5	Report value on JMF submittal form
Dust proportion	MS-2 Asphalt Mixture Volumetrics	0.6–1.3	0.6–1.3
Hamburg wheel track (min number of passes at 0.5-inch rut depth) Binder grade: PG 58 PG 64 PG 70 PG 76 or higher	California Test 389 ^c	10,000 15,000 20,000 25,000	10,000 15,000 20,000 25,000
Hamburg wheel track (min number of passes at the inflection point) Binder grade: PG 58 PG 64 PG 70 PG 76 or higher	California Test 389 ^c	10,000 10,000 12,500 15,000	10,000 10,000 12,500 15,000
Moisture susceptibility (min, psi, dry strength)	AASHTO T 283 ^d	100	100-300
Moisture susceptibility (min, psi, wet strength)	AASHTO T 283 ^d	70	70
Recovered asphalt from HMA Mix	Must comply with section 92 ^e	Must comply with project specified PG binder	Must comply with project specified PG binder
Delta Tc (°C)	ASTM D7643 ^{g,h}	≥ -5.0	≥ -5.0
IDEAL CT	ASTM D8225	Report only	≥ the virgin mix value
I-FIT	AASHTO TP 124 ⁱ	Report only ^h	Report only ^h

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Bending Beam Fatigue (psi)	AASHTO T 321 ^a	Report only ^h	Report only ^h
Repeated Load Triaxial test (psi)	AASHTO T 378 ^a	Report only ^h	Report only ^h

^aCalculate the air voids content of each specimen using AASHTO T 275, Method A, to determine bulk specific gravity. Use AASHTO T 209, Method A, to determine theoretical maximum specific gravity. Use a digital manometer and pycnometer when performing AASHTO T 209.

^bMeasure bulk specific gravity using AASHTO T 275, Method A.

^cTest plant-produced Type A HMA.

^dFreeze thaw required.

^ePerform binder extraction and recovery for HMA mix with RAS under AASHTO T 164 and ASTM D5404.

^fDelta Tc must be performed on virgin binder and extracted binder from HMA mix with RAP or RAS. For pilot project, run test at 20 hours for information only in addition to 40 hours.

^gContractor to provide and deliver loose mix samples to the Engineer.

^hEmail to High.RAP@dot.ca.gov.

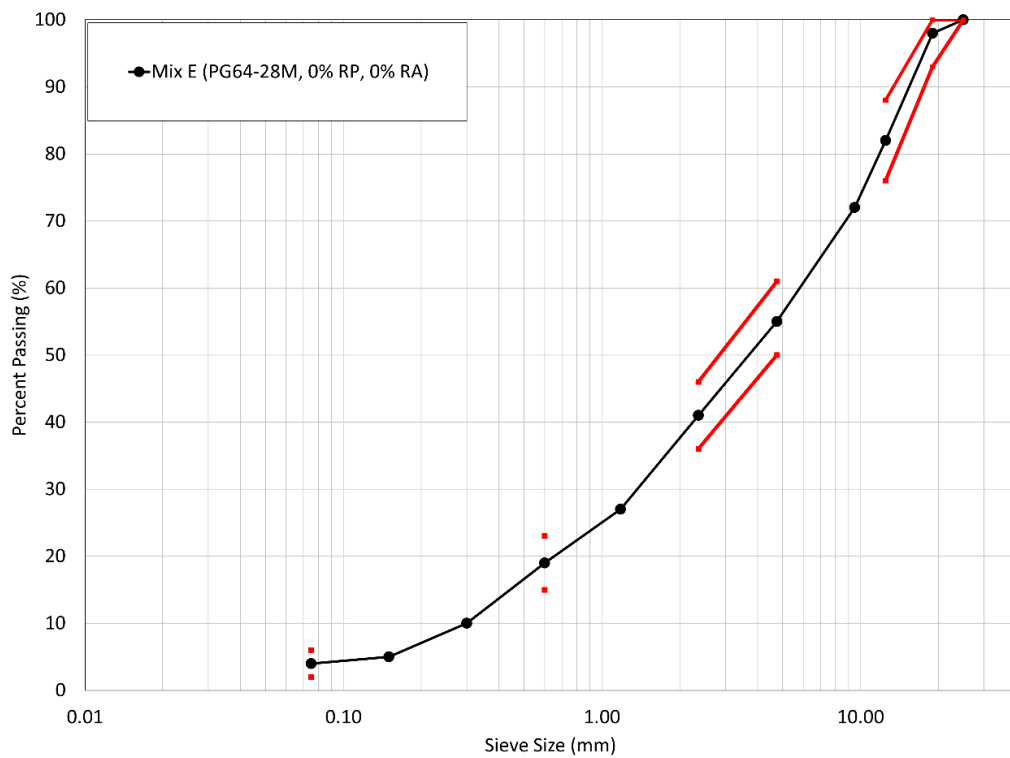
Figure 2.3: Non-standard special provision (nSSP) requirements for the mixes.

Table 2.2 Job Mix Formulas for All Mixes

Parameter		3/4" NMAS											
		Control (Mix E)		High RAP Blend (Mix F)		High RAP Blend (Mix G)		High RAP Blend (Mix H)		High RAP Blend (Mix I)		Mainline Blend (Mix Q)	
		0% RAP		25% RAP		30% RAP		35% RAP		40% RAP		23% RAP	
		JMF Design	JMF Limits	JMF Design	JMF Limits	JMF Design	JMF Limits	JMF Design	JMF Limits	JMF Design	JMF Limits	JMF Design	JMF Limits
Grading (% passing sieve)	1"	100	100-100	100	100-100	100	100-100	100	100-100	100	100-100	100	100-100
	3/4"	98	93-100	98	93-100	98	93-100	98	93-100	98	93-100	98	93-100
	1/2"	82	76-88	82	76-88	82	76-88	80	74-86	80	74-86	81	75-87
	3/8"	72	—	72	—	72	—	70	—	69	—	72	—
	#4	55	50-60	56	51-61	55	50-60	49	44-54	47	42-52	56	51-61
	#8	41	36-46	37	32-42	35	30-40	33	28-38	35	30-40	37	32-42
	#200	4	2.0-6.0	3.8	1.8-5.8	4	2.0-6.0	4.2	2.2-6.2	4.8	2.8-6.8	3.8	1.8-5.8
RAS content (% by weight of aggregate)		0	—	0	—	0	—	0	—	0	—	0	—
RAP content (% by weight of aggregate)		0	—	25	—	30	—	35	—	40	—	23	—
Base asphalt binder performance grade		64-28M	—	58-34M	—	58-34M	—	58-34M	—	58-34M	—	58-34M	—
RA/LAS type		Morlife (LAS)	—	Tall Oil (RA)	—	Tall Oil (RA)	—	Tall Oil (RA)	—	Tall Oil (RA)	—	Morlife (LAS)	—
RA/LAS dosage (% by weight of binder)		0.5	—	2.7	—	3.8	—	5.8	—	8.3	—	0.5	—
Total binder content (% by weight of mix)		4.6	4.2-5.0	4.6	4.2-5.0	4.6	4.2-5.0	4.6	4.2-5.0	4.7	4.3-5.1	4.6	4.2-5.0
Recycled binder content (% binder in mix)		0	—	1.12	—	1.35	—	1.57	—	1.80	—	1.03	—
Estimated binder replacement excluding RA/LAS (% of total binder)		0	—	24.4	—	29.3	—	34.2	—	38.2	—	22.5	—
Estimated binder replacement including RA/LAS (% of total binder)		0.5	—	27.1	—	33.1	—	40.0	—	46.5	—	23.0	—
Number of gyrations		85	85	85	85	85	85	85	85	85	85	85	85

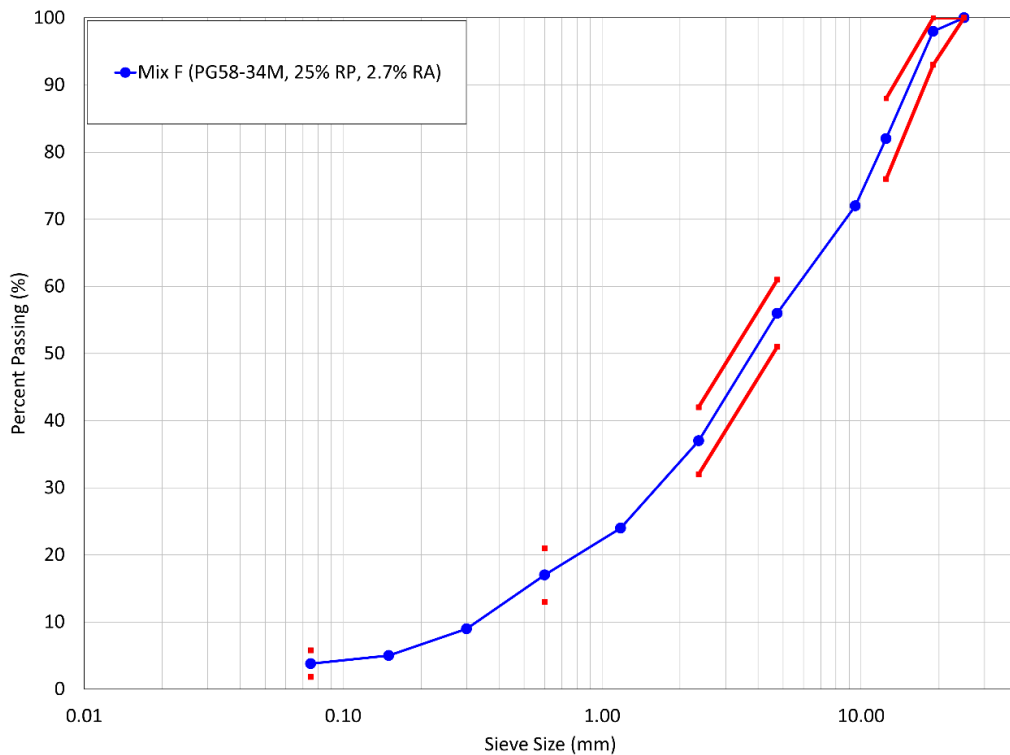
Parameter	3/4" NMAS											
	Control (Mix E)		High RAP Blend (Mix F)		High RAP Blend (Mix G)		High RAP Blend (Mix H)		High RAP Blend (Mix I)		Mainline Blend (Mix Q)	
	0% RAP		25% RAP		30% RAP		35% RAP		40% RAP		23% RAP	
	JMF Design	JMF Limits	JMF Design	JMF Limits	JMF Design	JMF Limits	JMF Design	JMF Limits	JMF Design	JMF Limits	JMF Design	JMF Limits
Air-void content (%)	4.0	2.5-5.5	4.0	2.5-5.5	2.0	0.5-3.5	2.0	0.5-3.5	2.1	0.6-3.6	4.0	2.5-5.5
Voids in mineral aggregate (%)	13.5	12.5-15.5	14.3	12.5-15.5	14.7	Report only	13.6	Report only	12.5	Report only	14.3	12.5-15.5
Dust proportion	1.0	0.6-1.3	0.9	0.6-1.3	0.9	0.6-1.3	1.0	0.6-1.3	1.1	0.6-1.3	0.9	0.6-1.3
Hamburg (rut depth [in.] at 15,000 passes)	0.191	0.5	0.154	0.5	0.199	0.5	0.190	0.5	0.266	0.5	0.154	0.5
Moisture susceptibility, dry strength (psi)	178	100	123	100	128	100	121	100	121	100	123	100
Moisture susceptibility, wet strength (psi)	125	70	90	70	91	70	89	70	81	70	94	70

Notes: LAS: liquid antistrip; RA: recycling agent; the binder content of the RAP aggregate assumed in the calculations from the contractor's mix designs is 4.14%.



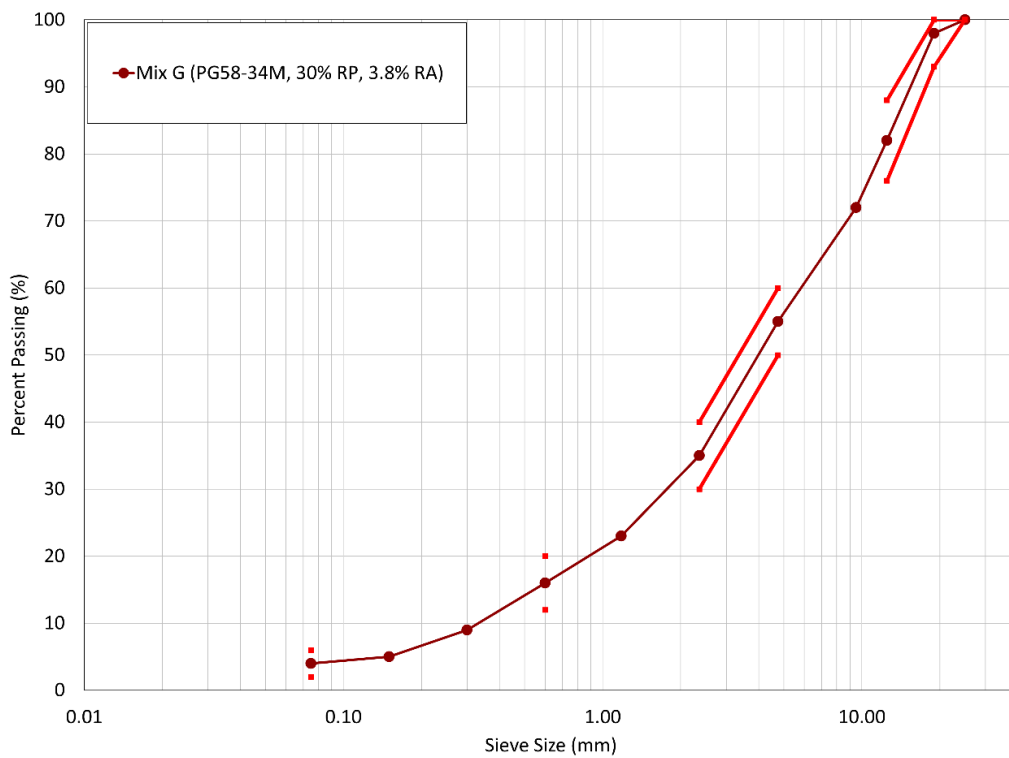
Note: Limits shown are the construction variability range around the target values in the JMF.

Figure 2.4: Job mix formula target for Mix E-0% RAP.



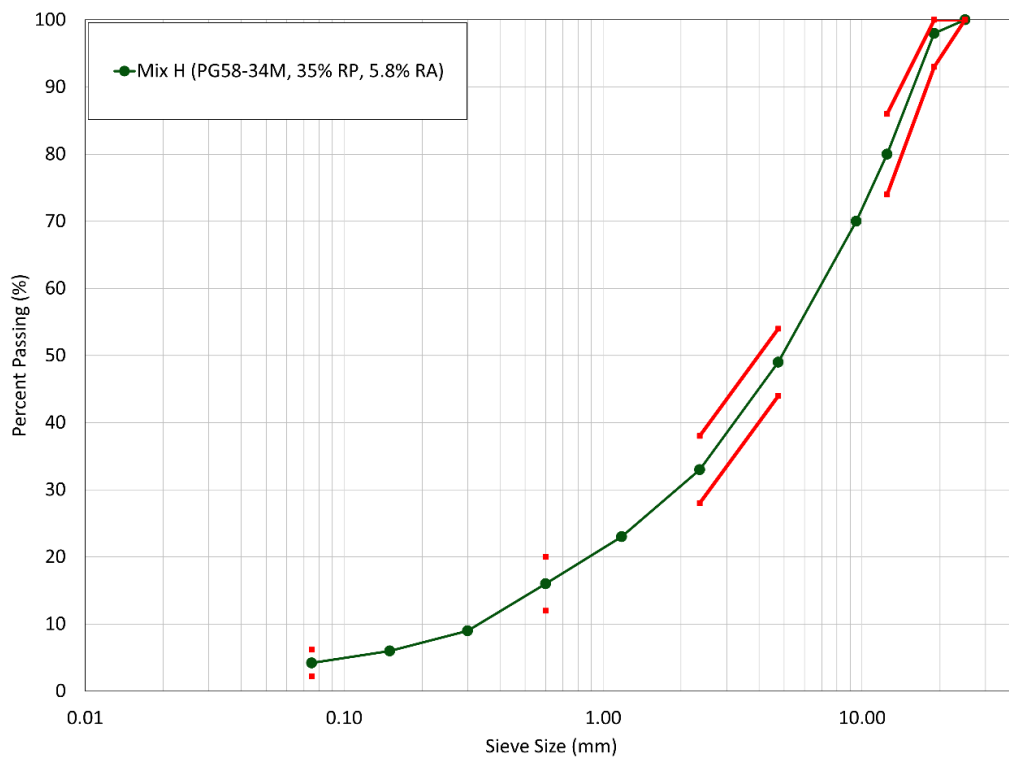
Note: Limits shown are the construction variability range around the target values in the JMF.

Figure 2.5: Job mix formula target for Mix F-25% RAP.



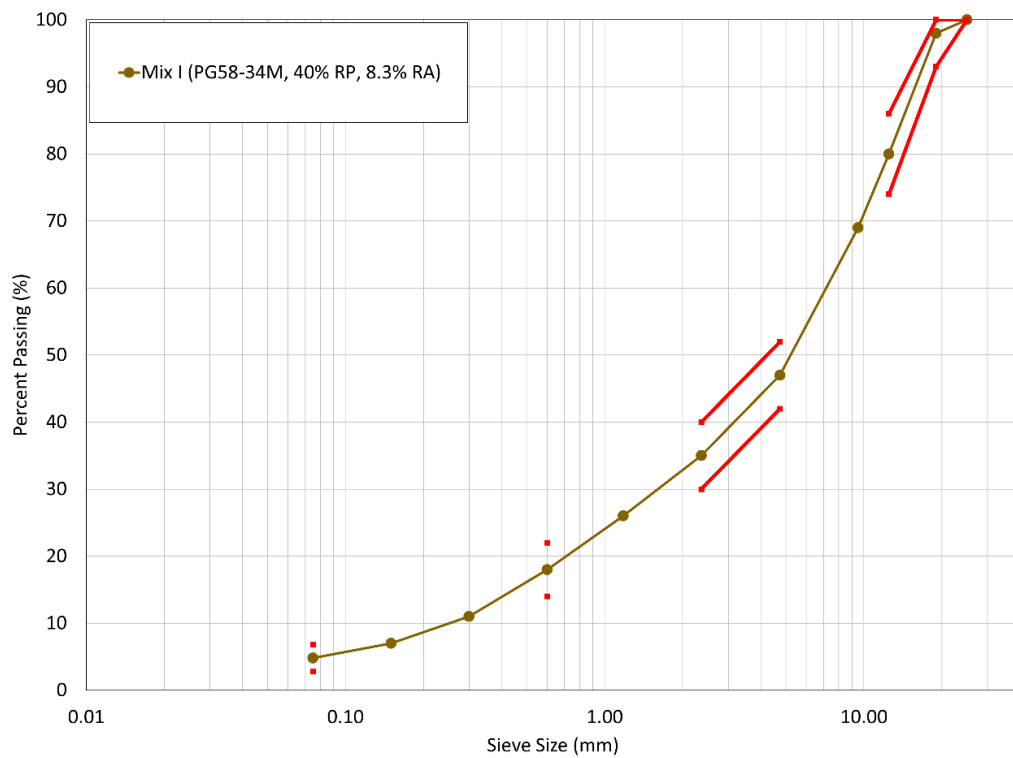
Note: Limits shown are the construction variability range around the target values in the JMF.

Figure 2.6: Job mix formula target for Mix G-30% RAP.



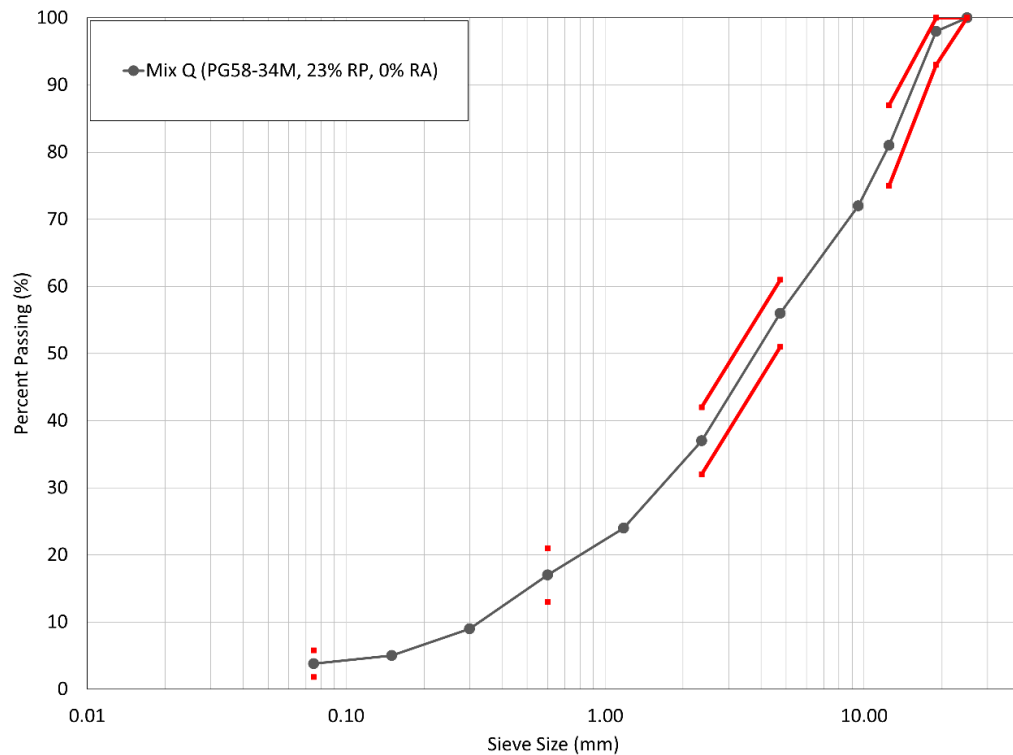
Note: Limits shown are the construction variability range around the target values in the JMF.

Figure 2.7: Job mix formula target for Mix H-35% RAP.



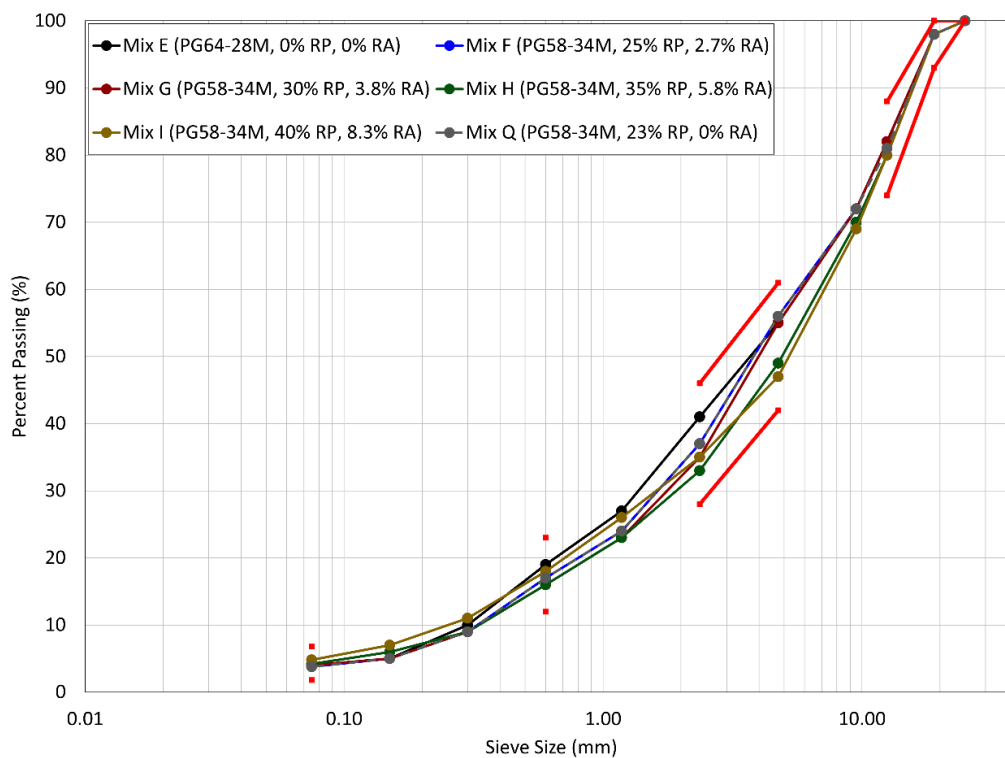
Note: Limits shown are the construction variability range around the target values in the JMF.

Figure 2.8: Job mix formula target for Mix I-40% RAP.



Note: Limits shown are the construction variability range around the target values in the JMF.

Figure 2.9: Job mix formula target for Mix Q-23% RAP.



Note: Limits shown are the construction variability range around the target values in the JMF.

Figure 2.10: Job mix formula target gradation (percent passing for all mixes).

The total binder content consists of the RAP binder, the virgin binder, and the RA. The recycled binder ratio (RBR) is the RAP and/or RAS binder as the percentage of total binder. When RA is included in the mix, the RBR can be calculated both with and without the RA as part of the RAP/RAS component. The nSSP for the pilot project states that only the RAP binder in the total binder blend is counted as reclaimed binder, which indicates that the RA used to change the properties of the RAP/virgin binder blend and that the RAP/RAS/virgin binder blend should be counted as part of the virgin binder. The nSSP also states that LAS, which was not used on this project, is not counted as part of the virgin binder.

Table 2.3 shows the virgin aggregate and RAP aggregate percentages in the JMF designs as percentages of total mass of aggregate. Regarding the binder, the table shows the target total binder content, the reclaimed asphalt binder content, and the resultant target RBR. The inclusion of the RA with the virgin binder content, combined with the fact that the binder content of the RAP was less than the new mix design total binder contents, results in RBR values that are lower than the percentage of virgin aggregate replaced by RAP aggregate. For example, the addition of 40% RAP aggregate in the new mix results in a 35.1% replacement of virgin asphalt binder in the new mix.

Table 2.3: Percentages of Virgin and RAP Binder and Aggregate Contents in Each Mix Design from Job Mix Formula

Average Mix	Virgin Agg (% of TMA)	RAP Agg. (% of TMA)	JMF Target Total AC Content (Pb, % of Tmm)	JMF Target Recycled AC Content (Pb, % of Tmm)	JMF Target RBR^a (% of total binder)
Mix E (PG 64-28M, 0% RP, 0% RA)	100.0	0.0	4.60	0.00	0
Mix Q (PG 58-34M, 23% RP, 0% RA)	77.0	23.0	4.60	0.95	20.7
Mix F (PG 58-34M, 25% RP, 2.7% RA)	75.0	25.0	4.60	1.03	22.4
Mix G (PG 58-34M, 30% RP, 3.8% RA)	70.0	30.0	4.60	1.24	27.0
Mix H (PG 58-34M, 35% RP, 5.8% RA)	65.0	35.0	4.60	1.44	31.3
Mix I (PG 58-34M, 40% RP, 8.3% RA)	60.0	40.0	4.70	1.65	35.1

^a RBR: recycled binder ratio; recycling agent (RA) counted as part of virgin binder; liquid antistrip not counted.

Notes: TMA: total mass of aggregate; Tmm: total mass of mix.

2.3 Material Sampling and Handling

Sampling for JMF verification and quality assurance (QA) was completed in coordination with the contractor's asphalt plant operations and QA groups to ensure safety during sampling and to ensure the validity of materials sampled for representativeness.

2.3.1 Plant-Produced Material Sampling for Job Mix Formula Verification Testing

Five JMF submittals were verified by the UCPRC from June 2022 to August 2022: the control mix with no RAP (Mix E) and four mixes with high RAP (Mixes F, G, H, I). Sampling dates and crews are shown in Table 2.4. Multiple hot drop samples were taken for some mixes as the RA dosage was adjusted to meet the specifications, as shown in Table 2.4. The sixth test section mix, which was the mainline mix used to pave the rest of the project, had <25% RAP (Mix Q), and was previously verified by the Caltrans South Regional Laboratory (SRL). Approximately two tons of material were sampled for UCPRC testing when District 8 sampled for its testing.

Table 2.4: Mix Sampling Dates and Crews for Job Mix Formula Verification Testing by the UCPRC

Mix Type	UCPRC HMA Mix Identifier	Dates Sampled	Location Sampled	Samples Taken By
3/4” Type A HMA – 0% RAP (Control)	4.79-Mix E-R0	6/18/22 7/1/22 7/14/22	Vulcan Materials Company (VMC) – San Bernardino Portable Plant	UCPRC, VMC, and Caltrans staff
3/4” Type A HMA – 23% RAP (Mainline)	4.79-Mix Q-R23	No UCPRC verification		UCPRC and VMC staff
3/4” Type A HMA – 25% RAP Binder Replacement (High RAP nSSP)	4.79-Mix F-R25	6/18/22 7/1/22 7/14/22 7/29/22		UCPRC, VMC, and Caltrans staff
3/4” Type A HMA – 30% RAP Binder Replacement (High RAP nSSP)	4.79-Mix G-R30			UCPRC, VMC, and Caltrans staff
3/4” Type A HMA – 35% RAP Binder Replacement (High RAP nSSP)	4.79-Mix H-R35			UCPRC, VMC, and Caltrans staff
3/4” Type A HMA – 40% RAP Binder Replacement (High RAP nSSP)	4.79-Mix I-R40	6/18/22 7/1/22		UCPRC, VMC, and Caltrans staff

For all samples, the mixes for JMF verification were produced in a continuous, double-barrel drum plant with minimal silo storage (80 tons total capacity) and were loaded from the silo directly into a sampling trailer with a quartermaster. The sampling trailer was then parked in a nearby, safe location, and the material was split through a standard quartermaster into four quadrants, with each bucket receiving half of two opposite, diagonal splits. A similar procedure was followed for the boxes, which were placed below the quartermaster.

The buckets and boxes were brought to the UCPRC laboratory, and then when mix was needed to produce samples for a given type of test, buckets were randomly taken from the total set of buckets, reheated, and combined and re-split in three or more passes using the quartermaster to reach the final amount needed for the number of specimens. The 3.5-gallon buckets were sealed and immediately transported to the UCPRC's Davis laboratory for storage and processing. The materials were labeled and stored in an outdoor, shaded area prior to laboratory processing.

2.3.2 Plant-Produced Material Sampling During Construction

Plant-produced mixes for the six mixes were sampled at the plant during construction. The sampling for the production QA testing was performed similarly to the JMF process (Figure 2.11) and split across four days. The control and high RAP mixes (Mix E to Mix I) were sampled during the week of August 8 to 11, 2022. Mix Q was sampled during mainline construction on July 29, 2022. During production, the boxes of mix for volumetric verification by Caltrans were collected by the contractor at the same time for all parties, with mix for boxes first collected with 3.5-gallon buckets from the quartermaster splitter following CT 125 before being placed in the boxes. Regarding the mix sampled just for UCPRC testing, the materials for determining the performance grades (PGs) of the binders were collected by

bucket from the splitter and then placed in boxes, while all other UCPRC samples were collected and stored in the 3.5-gallon buckets.



Figure 2.11: Sampling from hot drop and placement in buckets and boxes for quality assurance (QA) sampling on SBD 215.

2.3.3 Storage and Reheating to Compaction

As mentioned in the Section 2.3.2 sampling discussion, the mixes were all sampled in sealed 3.5-gallon steel buckets or cardboard boxes. The cardboard boxes for binder extraction were stored inside the asphalt binder laboratory at temperatures between 60°F and 80°F (15°C to 27°C) for up to 60 days prior to extraction (Figure 2.12). The sealed buckets for mix testing were stored in an outdoor, shaded receiving area at temperatures between 50°F and 100°F (10°C to 38°C) for up to 90 days. The buckets for flexural fatigue and stiffness were stored in Richmond at temperatures between 50°F and 75°F (10°C and 25°C) for up to 90 days. Box samples were randomly selected for sharing with Caltrans with the METS headquarters laboratory for performance-related testing.



Figure 2.12: Loose plant mix samples stored in cardboard boxes on SBD 215.

The laboratory reheating-to-compaction procedure was discussed with the contractor, and the procedures labeled as “SBD 215” in Table 2.5 were agreed upon for this project. The AASHTO R30 procedure for conditioning of laboratory-mixed material is included as a reference. AASHTO R30 does not provide specific procedures for reheating for compaction or laboratory aging of plant-produced mix. The procedure used for this project, shown and compared with R30 in Table 2.5, was incorporated into a draft Caltrans test method developed with the METS headquarters laboratory that also covers MTOA. The draft procedure is included in Appendix A.

Table 2.5: Mix Sampling, Storage, and Reheating-to-Compaction Temperature Procedures for SBD 215 Pilot Project Materials, Compared with AASHTO R30

SBD 215 Activity	Procedure Used on SBD 215 and Times	AASHTO R30 Activity	AASHTO R30 Times
Sampling (bucket or box)	Not applicable, plant mixed	Aggregate, asphalt and other components pre-heated	1–4 hours
Mixing	Plant mixed	Laboratory mixing	4 minutes
Transport and storage	Cooled, transported and stored at approximately room temperature ^a	Not applicable, laboratory mixed	—
Bucket/box reheating (workable at 135°C ^b)	4 hours ^c	Conditioned at 135°C ^b	4 hours
Split to compaction mass	0.25 hours	Flipped every hour	—
Loose mix heated in pan to compaction temperature	2±0.25 hours	Loose mix heated in pan to compaction temperature	0.5 hours

^a See details in report text.

^b Material starts at room temperature.

^c Material starts at mixing temperature (140°C or higher).

Compacted and cut flexural beams were stored for 15 to 30 days before testing. After compaction and cutting to final dimensions, specimens for tests other than flexural beam testing were tested within 14 days. All compacted specimens, other than flexural beams, were stored indoors at temperatures between 60°F and 80°F (15°C to 27°C), and flexural beams were stored in a controlled temperature room at 68°F (20°C).

2.3.4 Medium-Term Mix Aging

Medium-term aging to determine mix properties after initial construction was performed based on the draft protocol developed by Caltrans with input from the UCPRC (the draft Caltrans test method is included in Appendix A). Summarizing the protocol, the medium-term aging was performed for the IDEAL-CT test in addition to testing of the reheated plant-sampled mix. MTOA consisted of heating the loose mix for 20 hours at 212°F (100°C) in a pan 1 to 2 inches thick (25 to 50 mm).

2.3.5 Binder Extraction

To determine the PG grade and the delta T_c parameter of each JMF verification and QA subplot, binder was extracted following ASTM D8159 and ASTM D5405 procedures with the use of an automated asphalt extraction unit and rotary evaporator (Figure 2.13 and Figure 2.14). To obtain loose mix, sufficient cardboard sample boxes were minimally reheated to 110°C, and the loose mix was split down to begin processing. The automated extraction process of eight to nine wash cycles for a complete trichloroethylene (TCE) solvent extraction took approximately 90 minutes to run. Extraction was performed on a minimum of four 2,000 to 2,200 g replicates of loose mix to obtain enough recovered asphalt for D7643 PG grading, with 20- and 40-hour pressure aging vessel (PAV) long-term aging.

Following the solvent extraction process, the recovered asphalt binder and TCE solvent solution were stored in 500 mL glass jars for no more than two days prior to recovery. To remove the TCE solvent and recover the asphalt binder, a rotary evaporator was used, following ASTM D5404. The recovery process took approximately 100 minutes in a heated silicone fluid bath under continuously flowing nitrogen gas to minimize oxidation. After all the TCE was removed from the recovered asphalt binder, the glass flask was turned upside down and heated to 163°C to remove all binder. The sample was then transferred to a metal tin, and PG grading began.

The recovered asphalt binder from loose mix produced in the asphalt plant was assumed to have undergone aging similar to that caused by the rolling thin-film oven (RTFO) test (AASHTO T240), and no further short-term aging was applied for PG grading. The 20-hour PAV aging and then 40-hour PAV aging immediately followed, and the delta T_c parameter was calculated per ASTM D7643 using the low temperature bending beam rheometer (BBR) results in either an Excel worksheet or a transmittal database such as StonemontQC.



Figure 2.13: Closed-loop binder extraction system.



Figure 2.14: Placing extraction cylinder with sample into extraction system.

2.4 Test Methods

Binder and mix testing were performed for the materials sampled in the field for JMF approval and during QA to fully characterize the materials. Testing completed by the UCPRC included tests to check specification compliance for JMF approval and QA, as well as additional tests to fully characterize the binder and mix properties.

2.4.1 Binder Testing

JMF verification testing required by the specifications and performed by the UCPRC is shown in Table 2.6. The UCPRC completed additional binder testing, which included the following:

- Performance grade (PG), including calculation of delta T_c
- Frequency sweep (FS) 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 binders extracted from the QA samples, while only PG tests were performed on the binders extracted from the JMF verification samples.

Table 2.6: JMF Verification Testing Performed by UCPRC for Pilot Project

Test Type	Test Method	Material Tested	Goal
Binder true grade with delta T_c	AASHTO R29	Binder extracted from plant-sampled mix	Binder PG grade
IDEAL-CT test	ASTM D8225	Laboratory-compacted plant mix	Intermediate cracking tolerance

An overview of the methods and data interpretation is discussed in the following sections.

Performance Grading

A dynamic shear rheometer (DSR) was used to determine the high and intermediate temperature binder PG. Short-term aging of the binders was not simulated in an RTFO because binders were extracted from mixes that were plant-produced. Long-term aging of the binder was simulated in a PAV following the AASHTO R 28 method for 20 hours, and additional PAV specimens were aged for 40 hours. The low temperature PGs were determined on PAV-aged binders using a BBR, following AASHTO T 313.

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 2.1 (3). The midpoint of the temperature testing range was selected as the reference temperature (i.e., 40°C):

$$\log|E^*| = \delta + \frac{\alpha}{1 + e^{\beta + \gamma \log \omega f_r}} \quad (2.1)$$

Where:

$|E^*|$ = magnitude of complex modulus (kPa)

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

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

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

ω = frequency (Hz)

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

Equation 2.1 can be used to generate a binder master curve by substituting the complex modulus (E^*) with the shear complex modulus (G^*). The reduced frequency can be calculated using the Arrhenius equations (Equation 2.2 and Equation 2.3), which are based on the time-temperature superposition (1):

$$\log f_r = \log f + \log \alpha_T \quad (2.2)$$

$$\log \alpha_T = \frac{E_a}{R(\ln 10)} \left(\frac{1}{T} - \frac{1}{T_r} \right) \quad (2.3)$$

Where:

f = frequency sweep test loading frequency (Hz)

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

E_a = 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 (a_T) can be determined using the solver function in Excel by minimizing the sum of squares error between the predicted and measured dynamic moduli. Figure 2.15 and Figure 2.16 show examples of the fitting procedure.

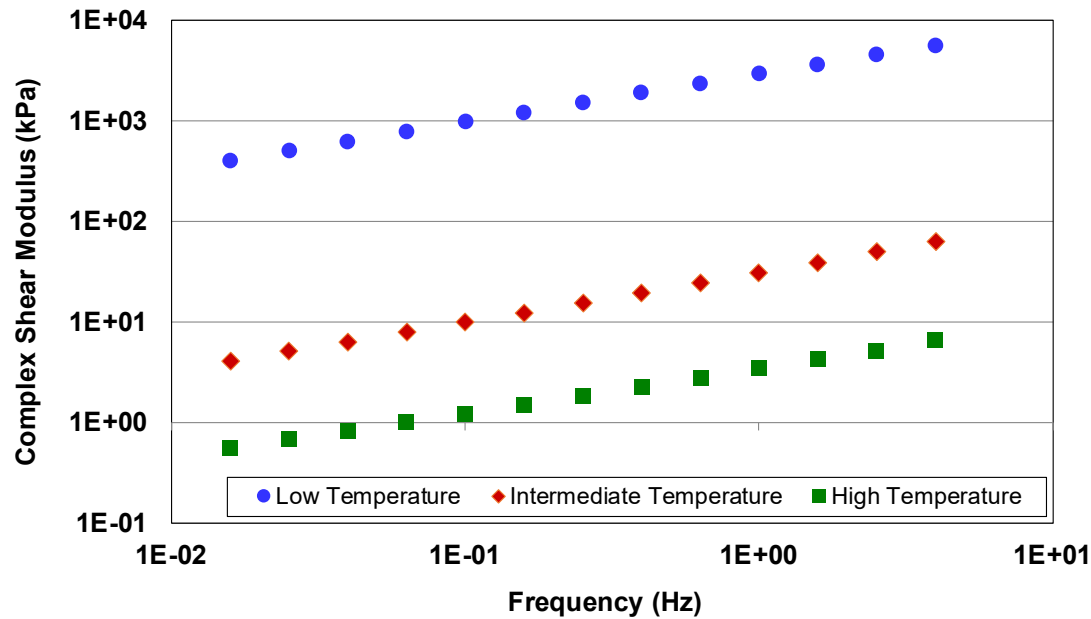


Figure 2.15: Example of modulus master curves (plotted by frequency at tested temperature).

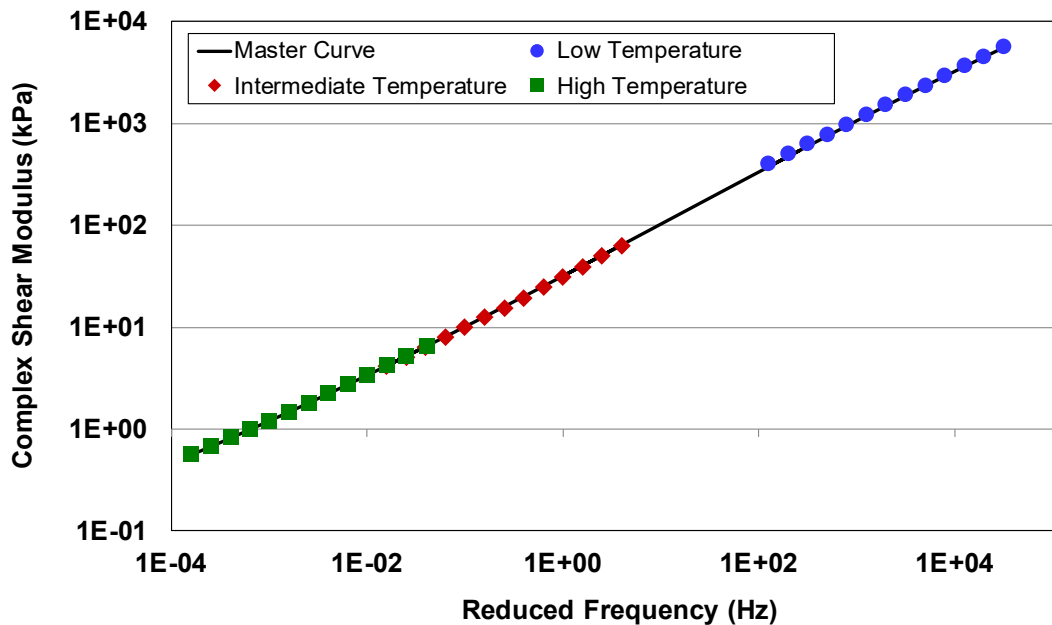


Figure 2.16: Example of modulus master curves (plotted by shifted frequency).

Fourier Transform Infrared Spectroscopy

Chemical component changes in the control and blended binders were evaluated using Fourier transform infrared spectroscopy with attenuated total reflection (FTIR-ATR). The spectra measured by the FTIR were recorded in 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} (4-7). 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 (8). The chemical component area index was then integrated from the normalized spectra using Equation 2.4 (7). Figure 2.17 shows an example of a spectrum and the respective component.

$$I_i = \int_{w_{l,i}}^{w_{u,i}} a(w)dw - \frac{a(w_{u,i}) + a(w_{l,i})}{2} \times (w_{u,i} - w_{l,i}) \quad (2.4)$$

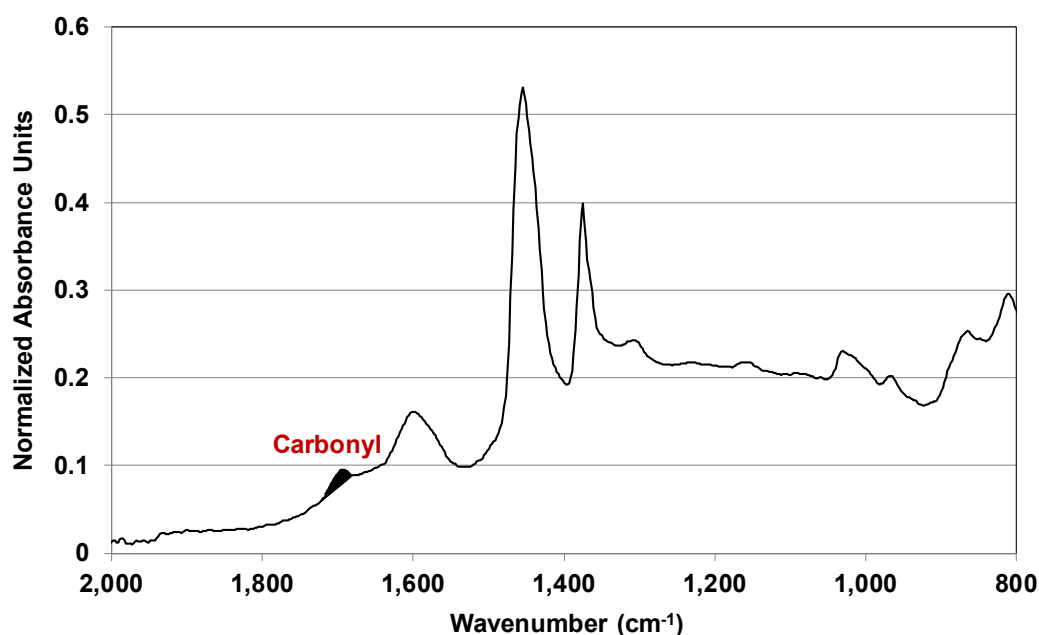
Where:

I_i = index of area i

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

$w_{u,i}$ = upper wavenumber integral limit of area i

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



Note: Plot shows tangential integration with carbonyl areas.

Figure 2.17: Example of normalized FTIR absorbance spectrum.

2.4.2 Mix Testing

Mix testing included the following:

- Dynamic modulus (DM, AASHTO T 378; specimens prepared in a gyratory compactor)
- Flexural modulus (FM, AASHTO T 321; specimens prepared using a rolling wheel compactor)
- Repeated load triaxial (RLT, flow number, AASHTO T 378; specimens prepared in a gyratory compactor)
- Beam fatigue (FAT, AASHTO T 321; specimens prepared using a rolling wheel compactor)
- IDEAL-CT test (IDEAL-CT, ASTM D 8225; specimens prepared in a gyratory compactor)

An overview of the methods and data interpretation is discussed in the following sections.

Test Specimen Air-Void Contents

The bulk densities of the IDEAL-CT test specimens were determined according to AASHTO T 166 (saturated surface-dry [SSD] method). The bulk densities of the beam, asphalt mix performance tester (AMPT), and semicircular bend test specimens were determined according to AASHTO T 331 (CoreLok). Theoretical maximum specific gravity (G_{mm}) 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.

Triaxial Dynamic Modulus

Triaxial dynamic modulus testing followed AASHTO T 378 using an AMPT with specimens prepared in a gyratory compactor. Specimens were tested at 4°C, 21°C, 38°C, and 54°C and at frequencies between 25 and 0.1 Hz. Measured dynamic moduli and phase angles were horizontally shifted into a master curve at 20°C using Equation 2.2, Equation 2.3, and the Williams-Landel-Ferry shift function (9) in Equation 2.5.

$$\log(\alpha_T) = \frac{-C_1(T-T_r)}{C_2+(T-T_r)} \quad (2.5)$$

Where:

α_T = shift factor as a function of temperature T

T = test temperature in Kelvin (°K)

T_r = reference temperature in Kelvin (°K)

C1 and C2 = fitting parameters

Flexural Dynamic Modulus

Flexural beam frequency sweep testing followed AASHTO T 321 using a four-point flexural beam fatigue apparatus and beams prepared using a rolling wheel compactor. Specimens were tested at 10°C, 20°C, and 30°C and at frequencies between 15 and 0.01 Hz. A sine wave frequency was applied to produce a tensile strain of 100 µstrain on the longitudinal surface of the beam. The measured stiffnesses and phase

angles were horizontally shifted into master curves at 20°C using Equation 2.2, Equation 2.3, and Equation 2.5. Flexural stiffnesses were used in the *CalME* simulations discussed in Chapter 8.

Fatigue Cracking Resistance

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 a temperature of 20°C. The fatigue life for each strain level was selected by multiplying the maximum stiffness value for that strain level by the number of cycles at which that stiffness value occurred. The tensile strains shown are peak to peak.

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 2.6). 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.

$$\ln(N) = A + B \times \ln(\varepsilon) \quad (2.6)$$

Where:

N = fatigue life (number of cycles)

ε = strain level (μ strain)

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* simulation when taking into consideration that laboratory test results will generally correspond with field fatigue or reflective cracking performance for overlays thinner than about 62 mm (0.2 ft.) but may not correspond with expected field performance for thicker layers of asphalt. For thicker layers, the interaction of the pavement structure, traffic loading, temperature, and mix stiffness with the controlled-strain beam fatigue results needs to be simulated using mechanistic analysis to rank mixes for expected field performance.

Rutting Resistance

Permanent deformation resistance testing followed AASHTO T 378 using an AMPT with specimens prepared in a gyratory compactor. The RLT parameters assessed included flow number and the number of cycles to reach 3% permanent axial strain. Specimens were tested with no confinement and

a deviator stress of 70 psi (483 kPa) and also with a confining stress of 5 psi (35 kPa) and the same deviator stress of 70 psi (483 kPa) (10–12). HWT testing was also performed, which provides information regarding both rutting resistance and moisture sensitivity by measuring the development of rutting in laboratory specimens under a steel wheel underwater at 50°C (122°F).

2.4.3 Indirect Tensile Cracking Resistance IDEAL-CT

The IDEAL-CT test uses a loading apparatus and specimen fixture, shown in Figure 2.18. 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 2.19.

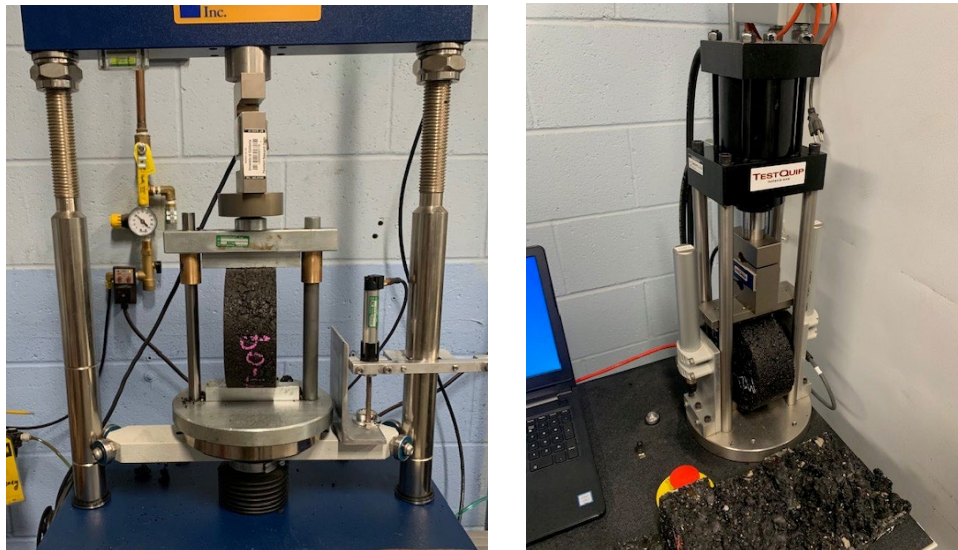


Figure 2.18: Testing machine for IDEAL-CT test with a specimen.

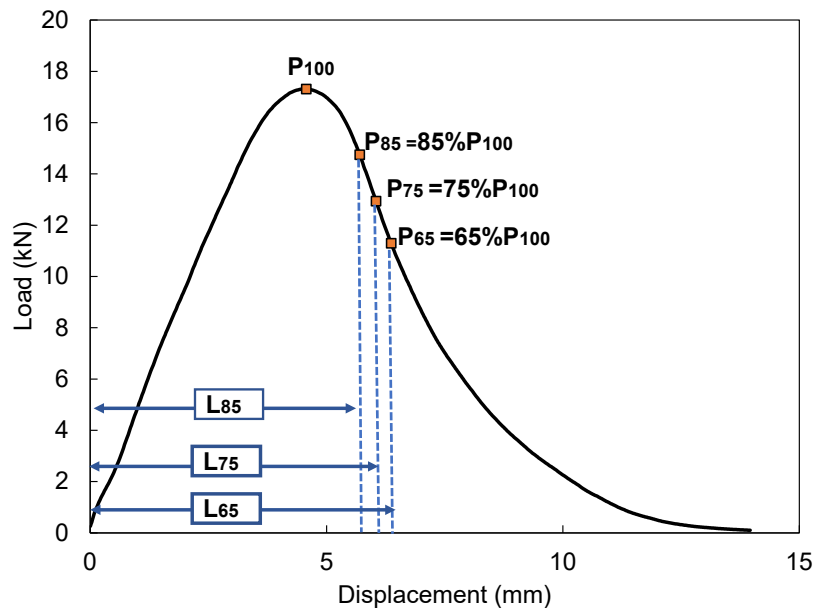


Figure 2.19: Example load-displacement curve from IDEAL-CT test.

Fracture parameters obtained from the IDEAL-CT test are shown in Table 2.7, along with definitions. The two parameters of primary interest are the CT_{Index} (referred to in this report as the IDEAL-CT number), 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 IDEAL-CT strength parameter, which has also been found to have a strong correlation with flexural stiffness but half the test variability of CT_{Index} .

Table 2.7: Fracture Parameters from IDEAL-CT Test

Parameters	Equations
$ m_{75} $: post-peak slope (N/m)	$ m_{75} = \left \frac{P_{85} - P_{65}}{I_{85} - I_{65}} \right $ Where: P_{85} = 85% of peak load P_{65} = 65% of peak load I_{85} = deformation at P_{85} I_{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 (referred to in this report as IDEAL-CT)	$CT_{Index} = \frac{t}{62} \times \frac{l_{75}}{D} \times \frac{G_f}{ m_{75} } \times 10^6$
Strength	$Strength = \frac{Peak\ load}{2rt}$

2.4.4 Testing Done by Caltrans

Testing for volumetric properties for JMF verification and during QA was completed by Caltrans. These results are not included in this technical memorandum.

3 BINDER TESTING RESULTS

3.1 Introduction

This chapter discusses the binder testing results on the blended binders extracted from the five mixes, including extracted binders from the mixes sampled during JMF verification and extracted binders from the two samples from each mix during construction QA. The mainline mix (Mix Q) included for reference contained only one sample set during both JMF and construction QA. QA summary plots are presented in the text, while more detailed, tabulated results are available in the UCPRC Online Laboratory Testing System (OLTS). It should be noted that binder extracted from mixes results in complete blending of the virgin binder, RAP binder, and RA and that this complete blending may not have occurred in the mix at the time of sampling.

3.2 Binder Testing Results for JMF Verification Mix Samples

3.2.1 PG Grading

Table 3.1 summarizes the true grades of the binders for the samples taken during JMF verification and during QA at high, intermediate, and low temperatures, and for low temperatures at a non-standard 40 hours of PAV aging. The JMF verification samples were taken for the mixes that were labeled as follows: Mix E (PG 64-28M, 0% RP, 0% RA) (the control), Mix F (PG 58-34M, 25% RP, 2.7% RA), Mix G (PG 58-34M, 30% RP, 3.8% RA), Mix H (PG 58-34M, 35% RP, 5.8% RA), Mix I (PG 58-34M, 40% RP, 8.3% RA), and Mix Q (PG 58-34M, 23% RP, 0% RA), where RP is RAP content by mass of total mix and RA is RA content by mass of total binder. Mix E is the control mix with 0% RAP and 0% RA, while Mix Q is the reference mainline mix used on the rest of the project outside of the test sections.

The continuous high temperature grade is defined as the temperature where the unaged binder's $G^*/\sin(\delta)$ value equals 1.00 kPa, and the RTFO-aged binder's $G^*/\sin(\delta)$ value equals 2.20 kPa. For the JMF verification and QA testing performed for the pilot project, the binder was extracted from a plant-produced mix. Therefore, there were no virgin binder test results for the blend, and "plant-produced" results are presented in place of RTFO-aged results. Intermediate temperature grading is defined as the temperature where the 20-hour PAV-aged binder $G^* \times \sin(\delta)$ values equal the maximum allowable stiffness of 5,000 kPa, as specified in AASHTO M 320. The low temperature grading is defined as the warmest of the following two temperatures using 20-hour PAV-aged binder: (1) the temperature where the creep stiffness (300 MPa) occurs or (2) the temperature where the lowest minimum allowable m-value (0.300) occurs.

The following are comments regarding the results shown in Table 3.1 and the figures that are called out below:

- As shown in Table 3.1, the base binder used in Mix E is a PG 64-28M, while Mixes F, G, H, I, and Q use a PG 58-34M. The switch from PG 64-28M to PG 58-34M is done to reduce both the high and low PG grade temperatures in an attempt to compensate for the increasing percentages of RAP and RA in Mixes F, G, H, and I. This is done to help them meet the specification for the

test sections that the binder extracted from the mix must meet the PG requirements of the control mix as well as a delta Tc value.

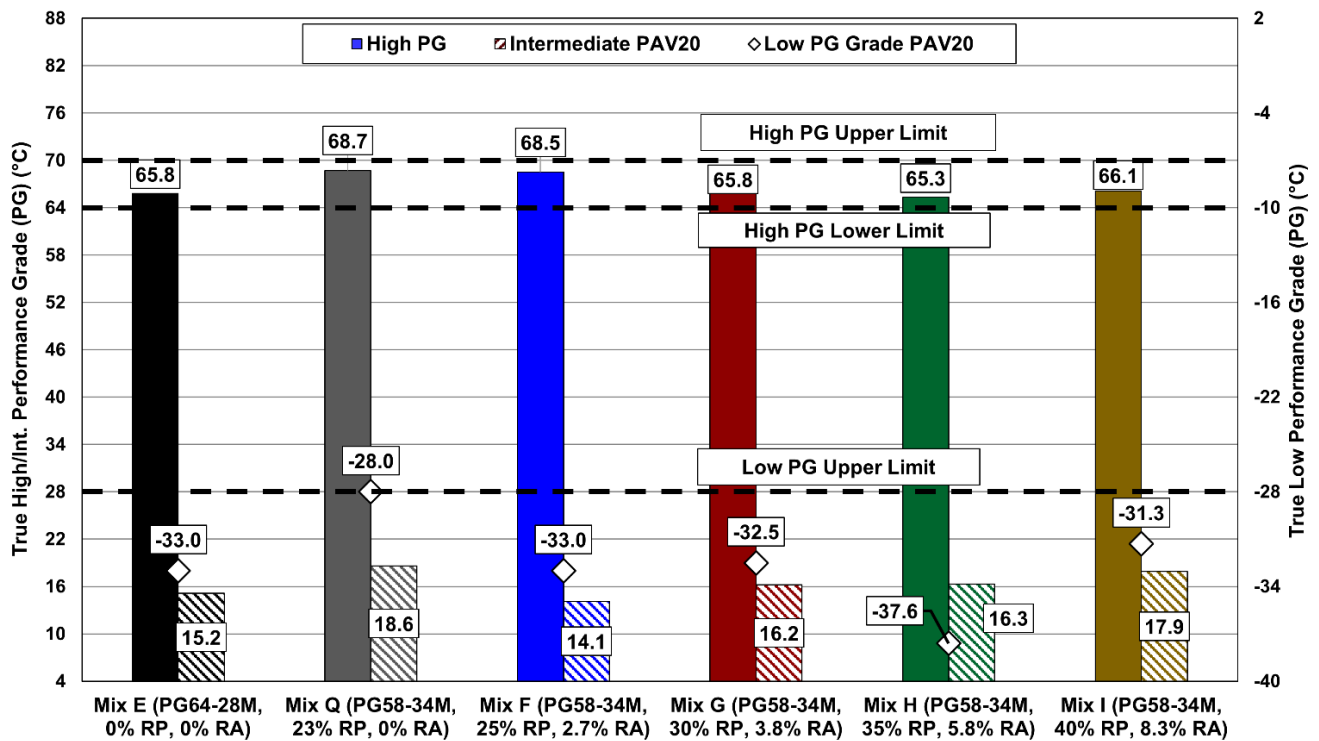
- From the JMF results in Table 3.1 and the plot of JMF results in Figure 3.1, all the mixes met the specification requirement to have a high temperature grade within the range for a PG 64 binder (between 64° and 70°C).
- Mix H, with 35% RAP and 5.8% RA, had the lowest high temperature true grade, while Mix Q, with 23% RAP and no RA, had the highest. Mixes E, F, G, and I fell in between. The change in RA dosage compensated for the increase in RAP binder content for Mixes F, G, H, and I. Table 3.1 shows details of the RA dosage by percentage of binder mass of each mix.
- All the binders met the low temperature binder specification of -28°C. As shown in the Table 3.1 JMF verification results and Figure 3.1, the Mix H binder had the lowest average true grade low temperature, nearly 10°C below the specification limit, followed by Mixes E, F, G, I, and Q. Mix Q, with 23% RAP and no RA, just met the PG 64-28M low temperature specification. According to current Caltrans specifications, mixes with less than 25% RAP only need to use a one-grade-lower binder, in this case PG 58-34M, without any requirement for blended binder testing. The difference between Mix H and Mix Q is 9.4°C.
- The low true grades for the high and low temperature PG results of Mix H may be attributed to a dose of RA that is more than required to just meet the high temperature PG specification (true grade below 70°C). In addition to more RA than was needed to achieve the high temperature requirement, the dose resulted in intermediate and low temperature continuous grades far below what is required. Another recent UCPRC study found that using the high temperature PG grade to determine dosage rates results in excessively low intermediate and low temperature true grades (13).
- For the intermediate temperature true grade for standard 20-hour aging, the Table 3.1 JMF verification results and Figure 3.1 show a narrow range of results, with rank order from softest to stiffest of Mix F, Mix E (PG 64-28M, no RAP), Mix G, Mix H, Mix I, and Mix Q (PG 58-34M with 23% RAP and no RA). The difference in intermediate temperature grade between Mix F and Mix Q is 4.5°C for standard 20-hour PAV aging.
- For the intermediate temperature true grade for 40-hour aging, the Table 3.1 JMF verification results and Figure 3.2 also show a narrow range of results, with rank order from softest to stiffest of Mix F, Mix E, Mix Q, Mix G, and Mix H and Mix I with the same value. The difference in intermediate temperature grade between Mix F and Mix H/Mix I is 5.5°C for 40-hour PAV aging.
- For thin overlays less than about 0.2 to 0.25 ft. (60 to 75 mm) thick (such as the thickness of the overlays in these test sections), softer binders at intermediate temperatures will tend to provide longer fatigue and reflective cracking lives. The opposite is true as overlay or new asphalt layer thicknesses increase above about 0.2 to 0.25 ft., with stiffer binders generally providing increasingly better fatigue and reflective cracking lives as the thickness increases.

- The average delta T_c results for 20-hour and 40-hour PAV-aged specimens can be seen in Figure 3.1 and Figure 3.3 for the JMF samples. The results show that only the control mix with no RAP (Mix E) and the mix with 25% RAP and RA (Mix F) met the delta T_c specification of having a value equal to or more positive than -5°C with 20 hours of PAV aging. Control Mix E had less negative delta T_c values than the mixes with RAP, indicating that its low temperature performance is controlled more by creep rate than by stiffness compared with the mixes with RAP. The asphalt binder literature considers a delta T_c value that is more controlled by creep rate than by stiffness to be an indication of better performance regarding long-term age-related low temperature and block cracking. The delta T_c alone is not a preferred method to predict binder performance, particularly due to challenges with rubber and polymer modification, and how the Glover-Rowe parameter proposed by Rowe provides a stronger predictive power of low temperature block cracking potential in the asphalt binder (14).
- Additional PAV aging to 40 hours to simulate very long-term aging performance showed that Mix Q, with 23% RAP and no RA, suffered the most from the detrimental effects of very long-term aging. Only Mix E and Mix F from the JMF verification sampled binders met the specification for a delta T_c value greater than -5.0 for 20-hour PAV aging, while only Mix E, the control mix with PG 64-28M binder and no RAP, met the specification for 40-hour PAV aging. Based upon FHWA guidance, the delta T_c parameter is not applicable to modified binders where the failure temperature is not directly measured and therefore was waived in this project (16).
- Figure 3.4 shows PG true grade temperatures (including PAV aging for 20 hours following PG specifications) normalized to those of the control Mix E (PG 64-28M binder and no RAP), showing that all mixes had similar high temperature true grades; most had similar low temperature true grades, except for Mix H (35% RAP, high dose of RA), which had a much better true grade, and Mix Q (23% RAP, no RA), which had a much worse true grade; and all except Mix F had slightly better intermediate temperature true grades (for a thin overlay application). Figure 3.5 shows PG true grade temperatures normalized to Mix E after 40 hours of PAV aging. The trends are similar to those with 20 hours of PAV aging, except for the low temperature true grade for Mix H (35% RAP, high dose of RA).
- Figure 3.6 and Figure 3.7 show the variability of the high and intermediate temperature true grades, providing an indication of test variability, as well as showing that there was high variability for the Mix H intermediate temperature true grade with 20 hours of PAV aging.

Table 3.1 Continuous Binder Grading Results for JMF and QA Samples

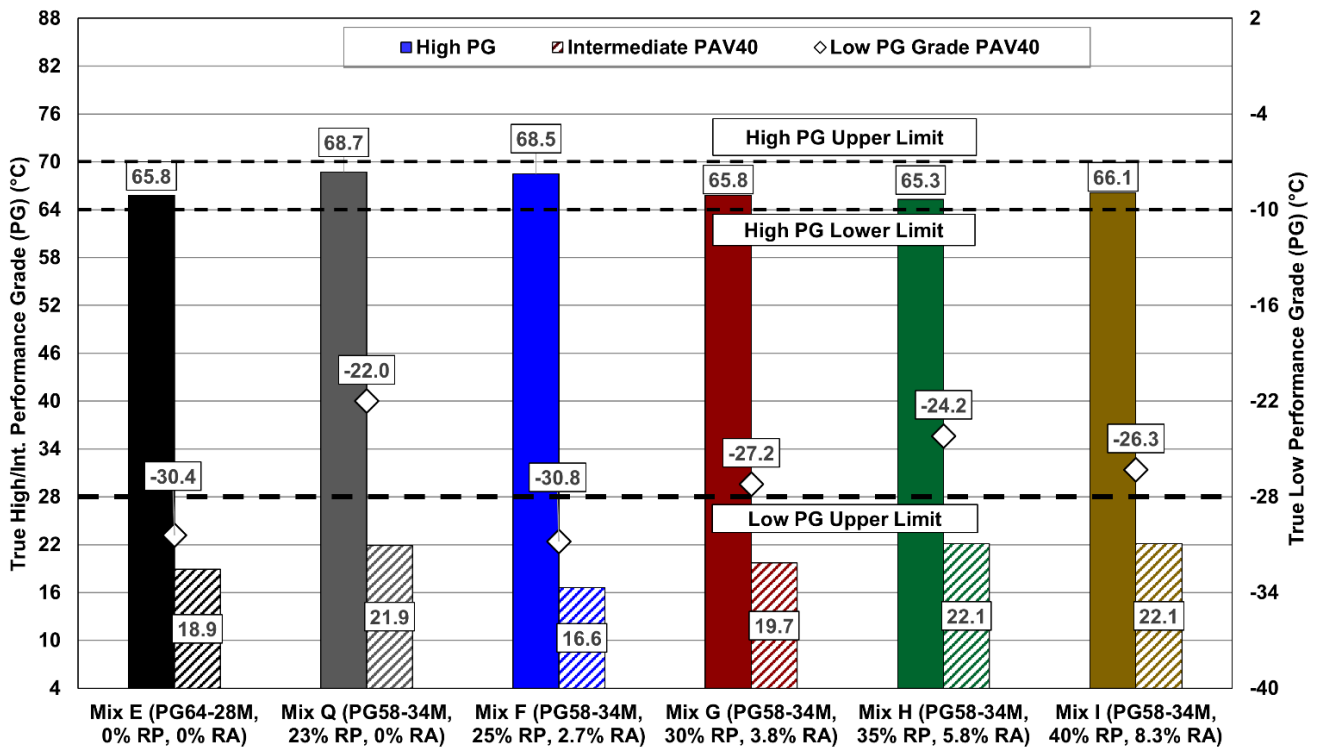
Mix Sample	Sample Type	PG Grade (20-Hour PAV)	PG Grade (40-Hour PAV)	PG True Grade (20-Hour PAV) ^a	ΔTc (°C) (20-Hour PAV)	PG True Grade (40-Hour PAV)	ΔTc (°C) (40-Hour PAV)	ΔTc (°C) (Change from 20- Hour to 40- Hour PAV)
Mix E (PG 64-28M, 0% RP, 0% RA)	JMF	PG 64-28	PG 64-28	CG 65.8-33.0 (15.1)	-1.3	CG 65.8-30.4 (18.9)	-3.5	2.2
Mix Q (PG 58-34M, 23% RP, 0% RA)	JMF	PG 64-28	PG 64-22	CG 68.6-28.0 (18.6)	-6.5	CG 68.6-22.0 (21.9)	-10.9	4.4
Mix F (PG 58-34M, 25% RP, 2.7% RA)	JMF	PG 64-28	PG 64-28	CG 68.5-33.0 (14.1)	-4.8	CG 68.5-30.8 (16.6)	-9.1	4.3
Mix G (PG 58-34M, 30% RP, 3.8% RA)	JMF	PG 64-28	PG 64-22	CG 66.0-32.5 (16.2)	-6.4	CG 66.0-27.2 (19.7)	-11.2	4.8
Mix H (PG 58-34M, 35% RP, 5.8% RA)	JMF	PG 64-34	PG 64-22	CG 65.3-37.6 (16.3)	-7.3	CG 65.3-24.2 (22.1)	-9.6	2.3
Mix I (PG 58-34M, 40% RP, 8.3% RA)	JMF	PG 64-28	PG 64-22	CG 66.1-31.3 (17.9)	-5.6	CG 66.1-26.3 (22.1)	-8.3	2.7
Mix E (PG 64-28M, 0% RP, 0% RA)	QA Sample 1 (SL1)	PG 58-34	PG 58-28	CG 63.2-34.6 (11.5)	-5.2	CG 63.2-29.6 (14.6)	-8.0	2.8
Mix E (PG 64-28M, 0% RP, 0% RA)	QA Sample 2 (SL2)	PG 58-34	PG 58-28	CG 62.4-34.4 (13.1)	-4.1	CG 62.4-29.2 (15.7)	-7.8	3.7
Mix Q (PG 58-34M, 23% RP, 0% RA)	QA Sample 1 (SL1)	PG 64-22	PG 64-18	CG 69.1-25.6 (18.6)	-7.5	CG 69.1-19.9 (22.0)	-12.2	4.7
Mix F (PG 58-34M, 25% RP, 2.7% RA)	QA Sample 1 (SL1)	PG 64-28	PG 64-22	CG 67.6-30.6 (14.6)	-4.3	CG 67.6-27.5 (17.9)	-7.9	3.6
Mix F (PG 58-34M, 25% RP, 2.7% RA)	QA Sample 2 (SL2)	PG 64-28	PG 64-28	CG 68.8-31.9 (15.1)	-5.7	CG 68.8-28 (18.5)	-7.6	1.9
Mix G (PG 58-34M, 30% RP, 3.8% RA)	QA Sample 1 (SL1)	PG 64-28	PG 64-22	CG 69.3-32.4 (16.2)	-3.3	CG 69.3-26.2 (19.3)	-8.9	5.6
Mix G (PG 58-34M, 30% RP, 3.8% RA)	QA Sample 2 (SL2)	PG 64-28	PG 64-22	CG 66.4-30.5 (17.7)	-6.3	CG 66.4-25.7 (20.2)	-8.1	1.8
Mix H (PG 58-34M, 35% RP, 5.8% RA)	QA Sample 1 (SL1)	PG 70-28	PG 70-22	CG 70.5-28.3 (20.5)	-6.2	CG 70.5-22.7 (22.9)	-9.8	3.6
Mix H (PG 58-34M, 35% RP, 5.8% RA)	QA Sample 2 (SL2)	PG 70-28	PG 70-22	CG 70.6-30.0 (19.2)	-5.8	CG 70.6-25.4 (23.3)	-8.9	3.1
Mix I (PG 58-34M, 40% RP, 8.3% RA)	QA Sample 1 (SL1)	PG 70-22	PG 70-18	CG 72.6-25.5 (21.5)	-6.5	CG 72.6-21.6 (23.3)	-9.1	2.6
Mix I (PG 58-34M, 40% RP, 8.3% RA)	QA Sample 2 (SL2)	PG 64-28	PG 64-22	CG 69.8-29.2 (20.2)	-6.0	CG 69.8-23.8 (24.6)	-9.0	3.0

^a Also known as continuous grade (CG), shown as [high temperature, low temperature, (intermediate temperature)].



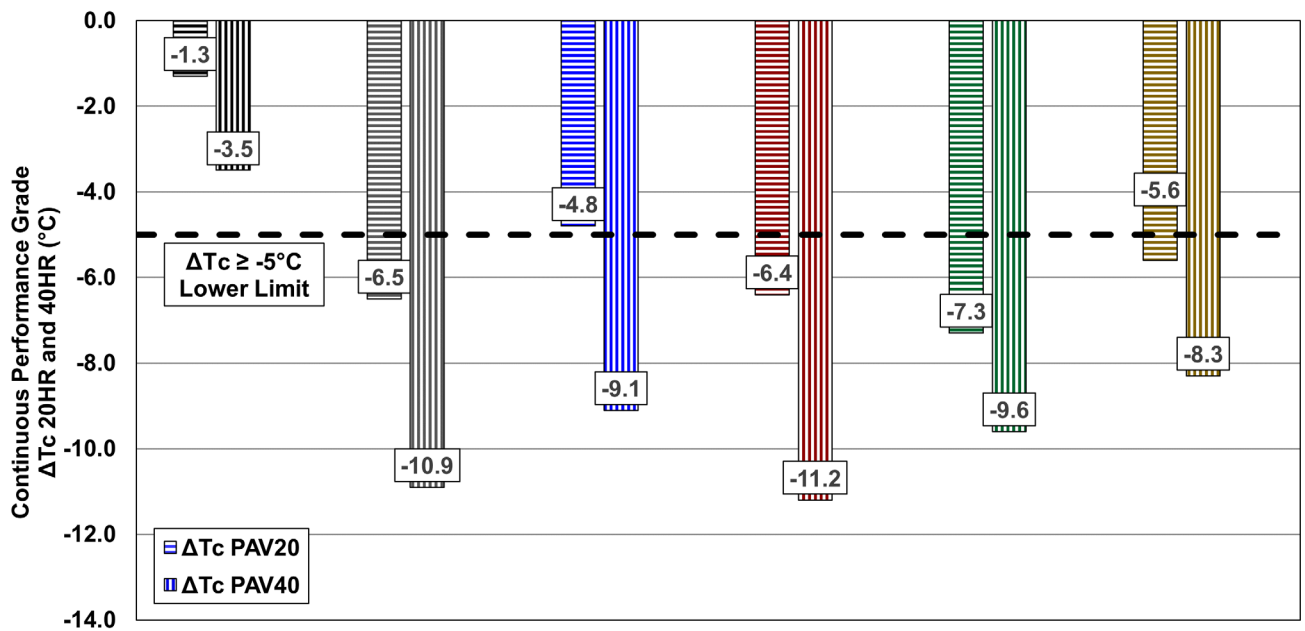
Note: Standard deviation error bars not included.

Figure 3.1: Continuous temperature binder grades for JMF verification sampled binders (20-hour PAV).



Note: Standard deviation error bars not included.

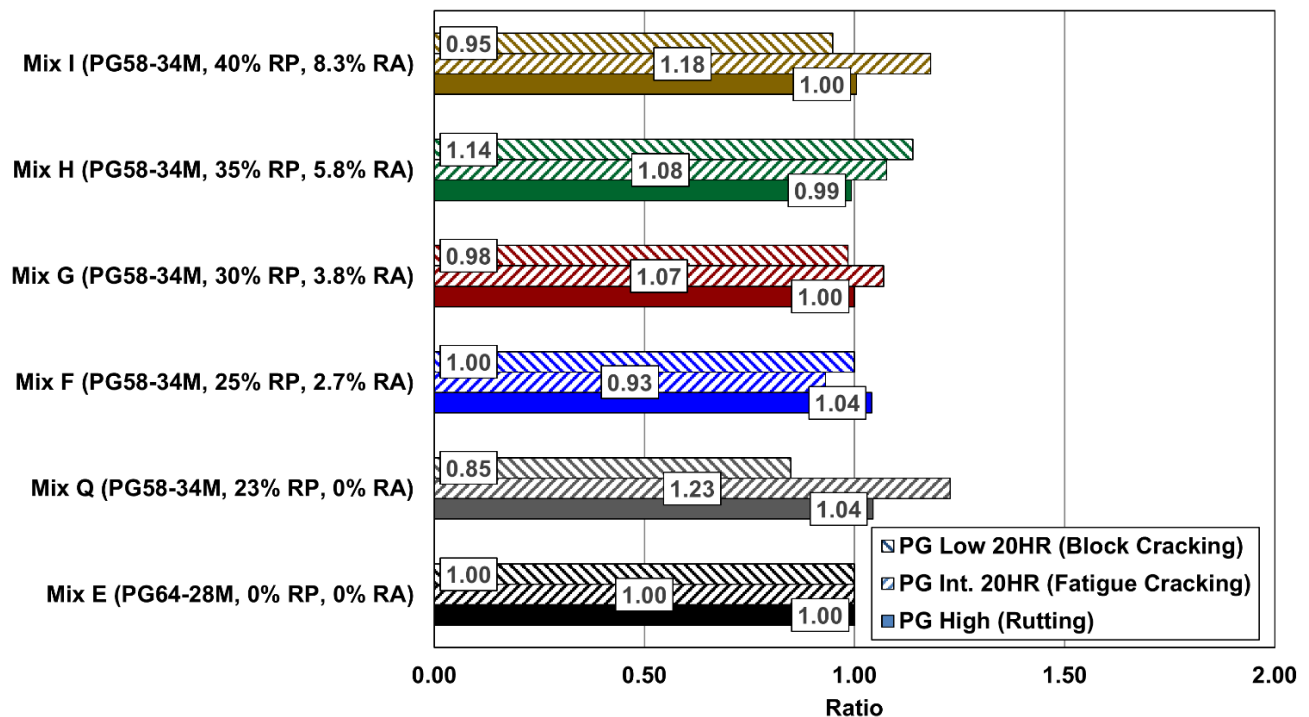
Figure 3.2: Continuous temperature binder grades for JMF verification sampled binders (40-hour PAV).



Mix E (PG64-28M, 0% RP, 0% RA) Mix Q (PG58-34M, 23% RP, 0% RA) Mix F (PG58-34M, 25% RP, 2.7% RA) Mix G (PG58-34M, 30% RP, 3.8% RA) Mix H (PG58-34M, 35% RP, 5.8% RA) Mix I (PG58-34M, 40% RP, 8.3% RA)

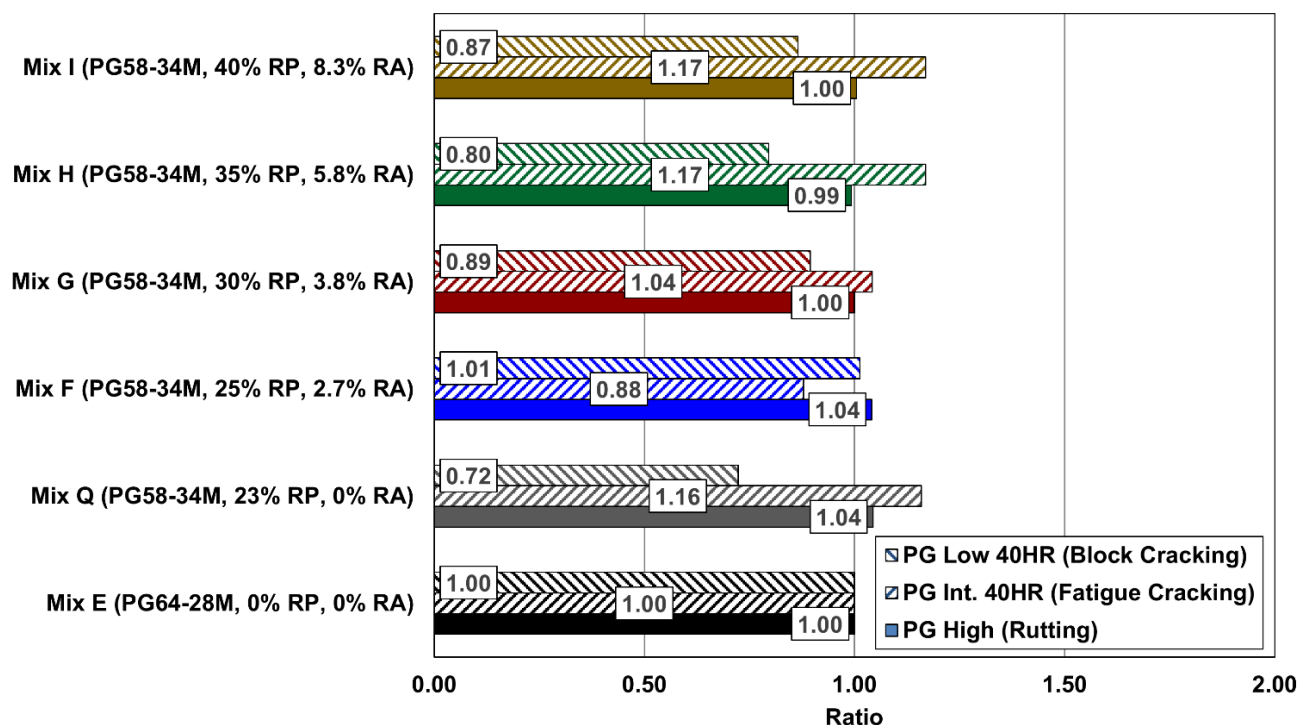
Note: Standard deviation error bars not included.

Figure 3.3: Delta Tc values for JMF samples (20-hour PAV specification value and for 40-hour PAV).



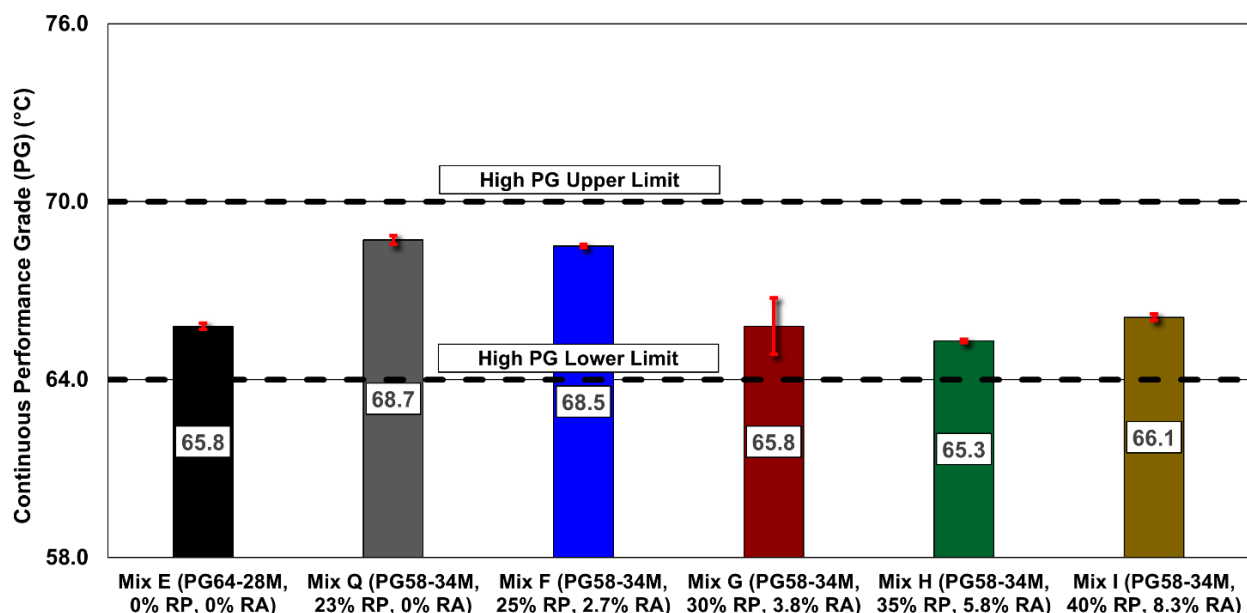
Note: PG high temperature greater than one grades higher (hotter) than the control, PG low temperature greater than one grades lower (colder) than control, and PG immediate temperature grades higher than the control. Benefits depend on structural design (higher intermediate PG, stiffer binder).

Figure 3.4: Binder grades for JMF verification sampled binders normalized to Mix E (0% RP, 0% RA) 20-hour PAV.



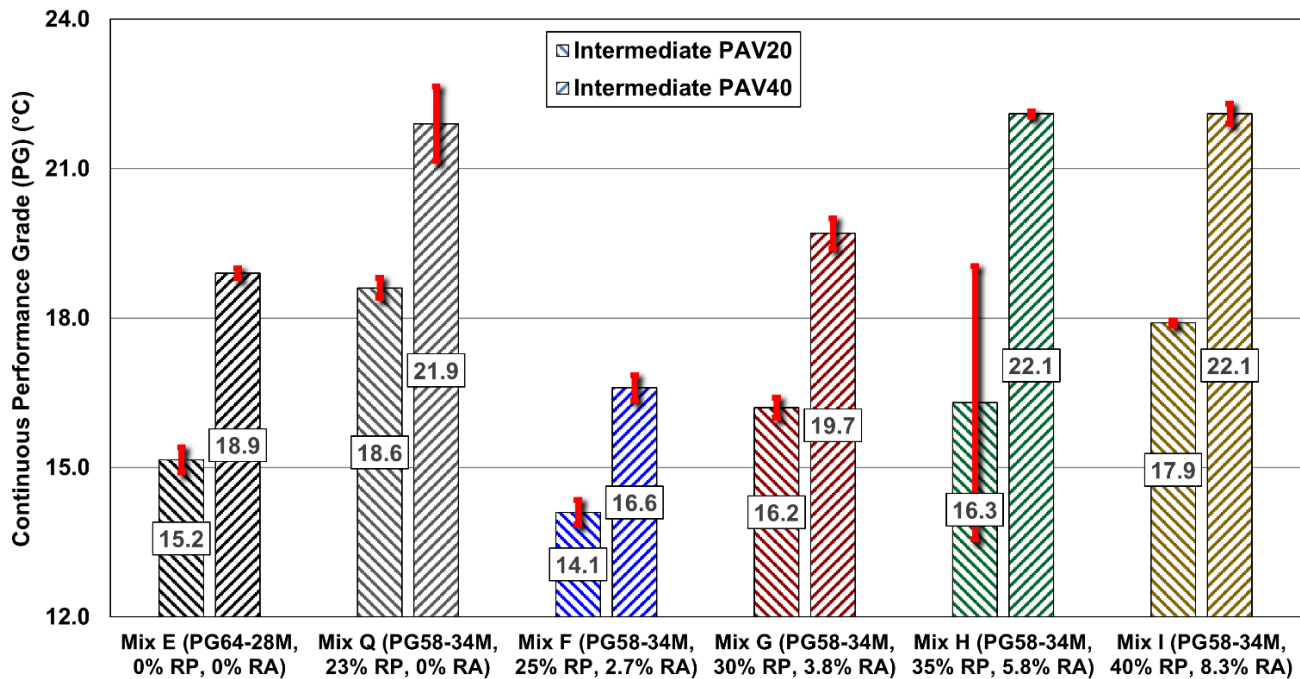
Note: PG high temperature greater than one grades higher (hotter) than the control, PG low temperature greater than one grades lower (colder) than control, and PG immediate temperature grades higher than the control. Benefits depend on structural design (higher intermediate PG, stiffer binder).

Figure 3.5: Binder grades for JMFC verification sampled binders normalized to Mix E (0% RP, 0% RA) 40-hour PAV.



Note: Specification limit shown as dashed line; error bars show one standard deviation of results.

Figure 3.6: Continuous high temperature binder grade for JMFC verification with sample variability.



Note: Error bars show one standard deviation of results.

Figure 3.7: Continuous intermediate temperature binder grade for JMF verification sampled binders 20-hour PAV and 40-hour PAV with sample variability.

3.2.2 Frequency Sweep

Frequency sweep testing was not performed on JMF verification sampled binders.

3.2.3 FTIR Testing

FTIR testing was not performed on JMF verification sampled binders.

3.3 Binder Testing Results from Quality Assurance Mix Samples

Binder testing results from the QA mix samples are summarized in this section, including calculation of PG grading, calculation of delta T_c , frequency sweep results, and FTIR results to identify carbonyl content as a measure of aging.

3.3.1 PG Grading and Delta T_c

The following are comments regarding the results shown in Table 3.1 and the figures that are called out below.

- Table 3.1 and Figure 3.9 show that the true grade temperatures were consistent between the two QA samples. Mix H and Mix I showed the highest variability between the high temperature true grades, and Mix I had the highest variability for the low temperature true grade. Note that the true grade for Mix E did not meet the minimum high temperature PG requirement, with high temperature true grades below 64°C, while the JMF submittal did meet the requirement. A

potential cause for this is that the PG 58-34M binder used in the test sections with RAP may have been used as the control binder rather than the intended PG 64-28M binder.

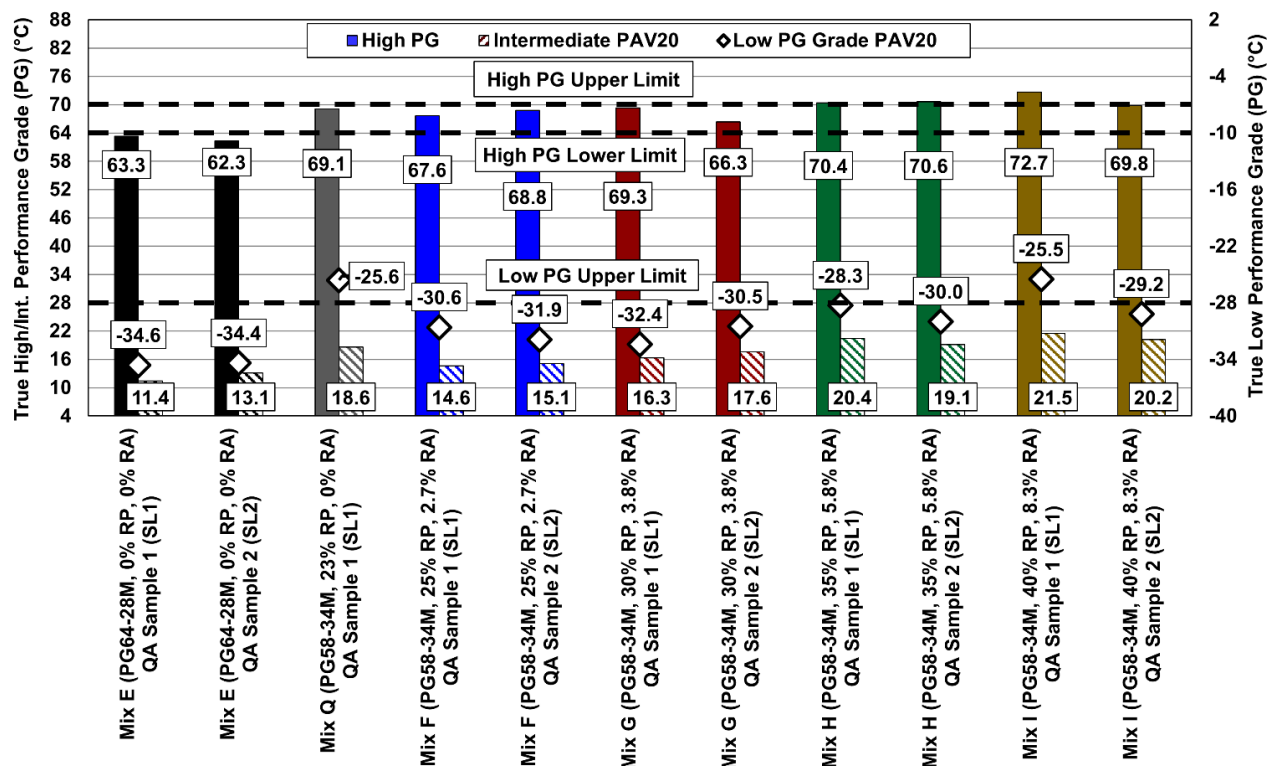
- Figure 3.10 shows results averaged for the two QA samples and shows that the control Mix E (0% RP, 0% RA) binder had the lowest average true grade high temperatures, followed by Mix G, Mix F, Mix Q, Mix H, and Mix I.
- Figure 3.8 and Figure 3.10 show Mix E missing the target QA PG of 64°C. The possible reason mentioned was incorrect inclusion of PG 58-34M binder as the control mix at the plant (instead of PG 64-28M). An alternative possible reason for the mix being softer than expected might be overdosing of LAS in the mix.
- The mixes with RAP had higher average high binder true grade temperatures, indicating better resistance to rutting than the control, Mix E, which had no RAP and most likely had the wrong binder. The difference in high temperature grade between Mix E and Mix I is large at 8.5°C. Mix H and Mix I meet requirements for PG 70 binder rather than PG 64 binder and, therefore, did not meet the specification for this pilot project, which requires the same high temperature true grade (PG 64) as the intended binder for the control Mix E. The intention of the specification was to limit the high binder true grade temperatures of the mixes with RAP to limit their stiffness at intermediate and low temperatures, though a higher high binder true grade temperature indicates better rutting performance at high temperatures.
- The control, Mix E, did not meet its own high temperature requirement to be a PG 64. It instead had an average true binder grade of 62.8°C and, therefore, an average performance grade of PG 58.
- For the intermediate binder true grade temperatures, Table 3.1 and Figure 3.10 show that the rank order from softest to stiffest (lowest temperature to highest temperature) is Mix E (probably PG 58-34M, no RAP), Mix F, Mix G, Mix Q (PG 58-34M, 23% RAP and no RA), Mix H, and Mix I. The difference in the intermediate temperature grade of the 20-hour PAV-aged binder between the averaged Mix E and Mix I is 8.6°C.
- A lower intermediate binder true grade temperature indicates that the mix will be softer at intermediate temperatures, which for thin overlays such as those on this pilot project, will often produce better fatigue and reflective cracking resistance. These results indicate that the Mixes F, G, H, I, and Q with RAP may have worse fatigue and reflective cracking resistance than the control Mix E when used in thin asphalt layers, though Mix E is softer than was specified and appears to have a greater risk of rutting.
- Figure 3.10 shows that the ranking for average 20-hour PAV low temperature from lowest true grade (softest) to highest (stiffest) is Mix E, Mix F, Mix G, Mix H, Mix I, and Mix Q. Mix E, Mix F, Mix G, and Mix H had low temperature true grades that met the required low temperature PG of -28°C, while Mix I and Mix Q failed to meet the criteria. The error bars on each figure, including Figure 3.10, indicate one standard deviation between the averaged

results of subplot 1 and 2. The variability between the sublots of Mix I suggests that some of the mix may meet the minimum low temperature PG criteria.

- Figure 3.11 shows the average intermediate and low temperature continuous grade results for 40-hour PAV aging. The results show similar rankings to those of the 20-hour PAV testing.
- Figure 3.12 compares the 20-hour and 40-hour PAV results for both sublots, and Figure 3.13 shows the same results averaged for the sublots. Comparison of the subplot data indicates generally consistent results, with the greatest differences between sublots occurring for Mix H and Mix I, which have the highest RAP contents and RA dosages. Comparison of the average 20-hour and 40-hour results indicates similar effects of aging across all mixes, with approximately a 3.5°C to 5.5°C change in the true low temperature grades with the additional aging.
- Since the Superpave asphalt binder performance-graded system provides a snapshot in time of the specific mix sample during pavement construction, future QA specifications may recommend performing an extracted binder PG check at periodic intervals of the construction project. Multiple snapshots may help provide a more comprehensive understanding of the actual as-built PG of the asphalt binder throughout the roadway. Periodic interval sampling and QA testing already occur with performance-based testing on HMA loose mix. More frequent sampling coupled with detailed specifications of allowable variability within the PG system may assist contractors in meeting design minimums or maximums.
- These results again indicate that controlling binder stiffness based on high temperature true grade may result in poorer expected rutting performance while not necessarily providing more resistance against low temperature cracking and fatigue and reflective cracking for thin overlays.
- A more negative delta T_c value (if none are positive, as is the case for these six mixes) indicates that there is more difference between the critical stiffness temperature controlling the binder true grade temperature and the critical creep compliance temperature. The more negative value indicates worse resistance to block cracking after long-term aging than does a more positive delta T_c value. The delta T_c results for 20-hour and 40-hour PAV-aged specimens are shown in Figure 3.14 for the two QA samples, and they are averaged in Figure 3.15. The results show that of the 10 QA subplot tests on the five mixes for which delta T_c was specified (all but the mainline mix, Mix Q), only three met the specification limit of having a value of -5°C or higher. One of the control mix QA subplot samples, Mix E (no RAP and no RA), just failed the specification and the other just passed it, indicating that this base binder, which is likely not the specified PG 64-28M for Mix E but instead the PG 58-34M used on all the other mixes, has difficulty passing this specification. Control Mix E had more positive delta T_c values with 20-hour aging than the mixes with RAP. The average order from most positive to most negative for the 20-hour PAV aging is Mix E, Mix F, Mix G, Mix H, Mix I, and Mix Q while for 40-hour PAV aging, the mixes from most positive (or least negative) to most negative (best expected age-related cracking performance to worst) are Mix F, Mix E, Mix G, Mix I, Mix H, and Mix Q. The variability between sublots, as

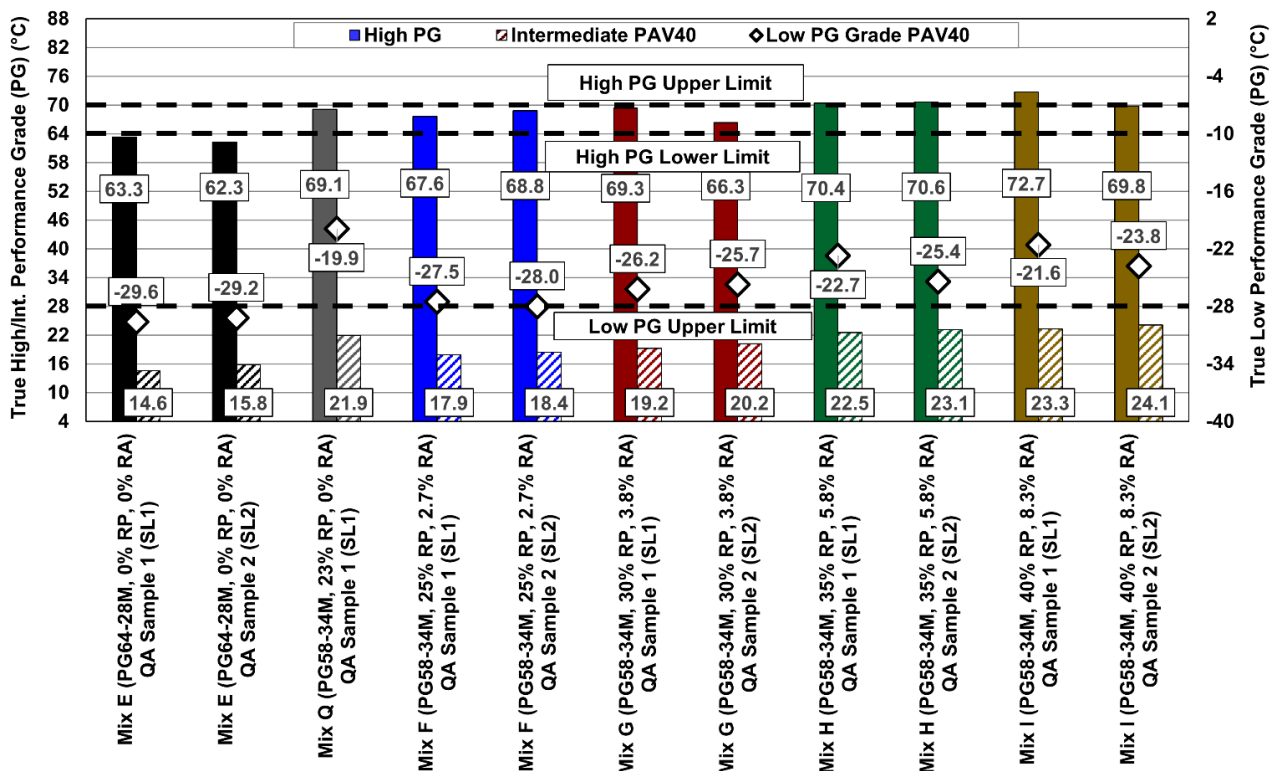
indicated by the error bars, suggests that some sublots may have had more varying RA dosages and RAP contents and/or RAP stiffnesses.

- For these mixes, the results indicate that the mixes with increasing percentages of RAP were more likely to have long-term block cracking than are those without lower percentages of RAP, though the differences are small. The difference between Mix E and Mix Q for the standard 20-hour PAV aging is 2.8°C. This difference increases between Mix F and Mix Q for the 40-hour PAV aging to -4.4°C, which is more severe.
- The binder test results from the average QA samples showed that the delta T_c values of Mixes E, F, and G were each above the minimum specified value of -5.0. The variability between sublots indicates that underdosing or overdosing of the RAs may have a strong effect on the final delta T_c value.
- Figure 3.16 and Figure 3.17 summarize the binder true grade temperatures normalized to Mix E for 20-hour and 40-hour PAV aging. The results for both levels of PAV aging indicate that the RAP mixes have higher high binder true grade temperatures, indicating better rutting performance; higher intermediate binder true grade temperatures, indicating worse fatigue and reflective cracking for thin overlays; and higher low binder true grade temperatures, indicating worse resistance to low temperature cracking. It should be noted that the control binder in Mix E may not have been the specified PG 64-28M and may have been the PG 58-34M used with the RAP mixes.
- These results indicate the drawbacks of attempting to limit intermediate and low temperature stiffness by limiting specified high temperature stiffness values, resulting in higher dosages of RA than are needed to meet specifications. This finding has also been seen in a recent UCPRC study (14).



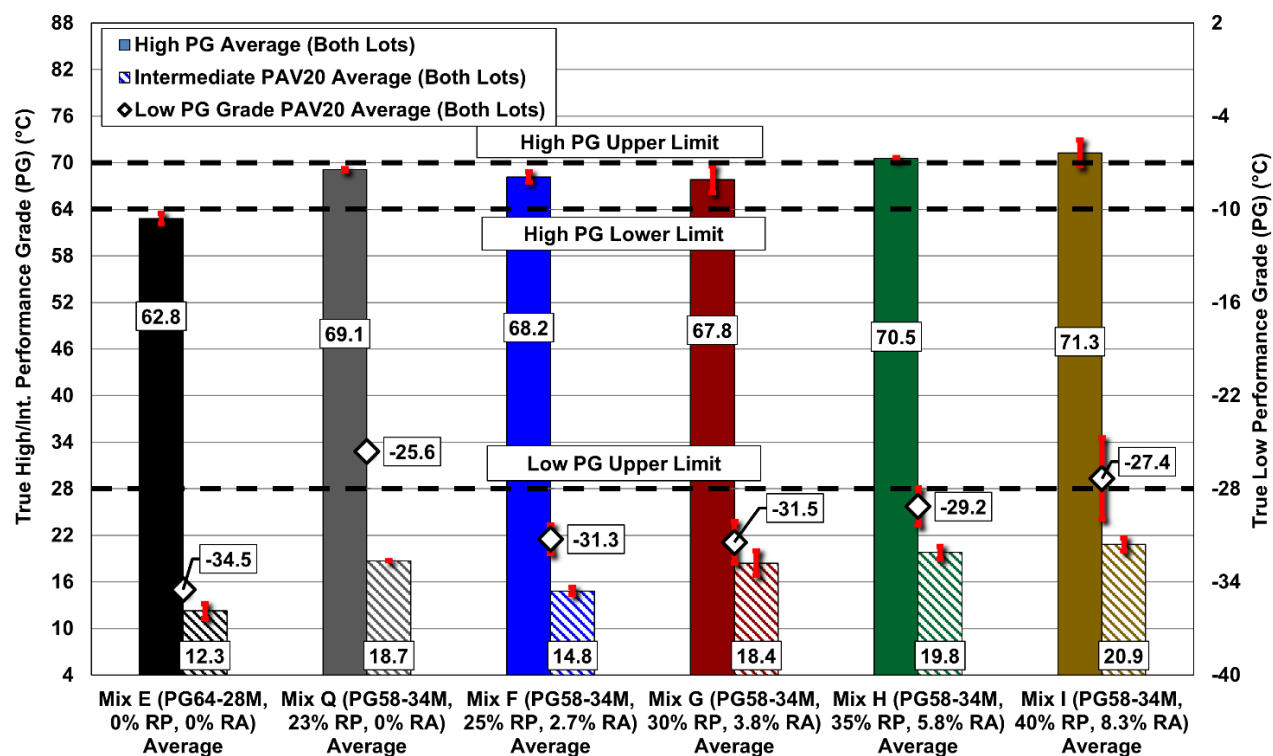
Note: Specification limit shown as dashed line; error bars indicate one standard deviation of results.

Figure 3.8: Continuous temperature binder grades for QA both sublots (20-hour PAV).



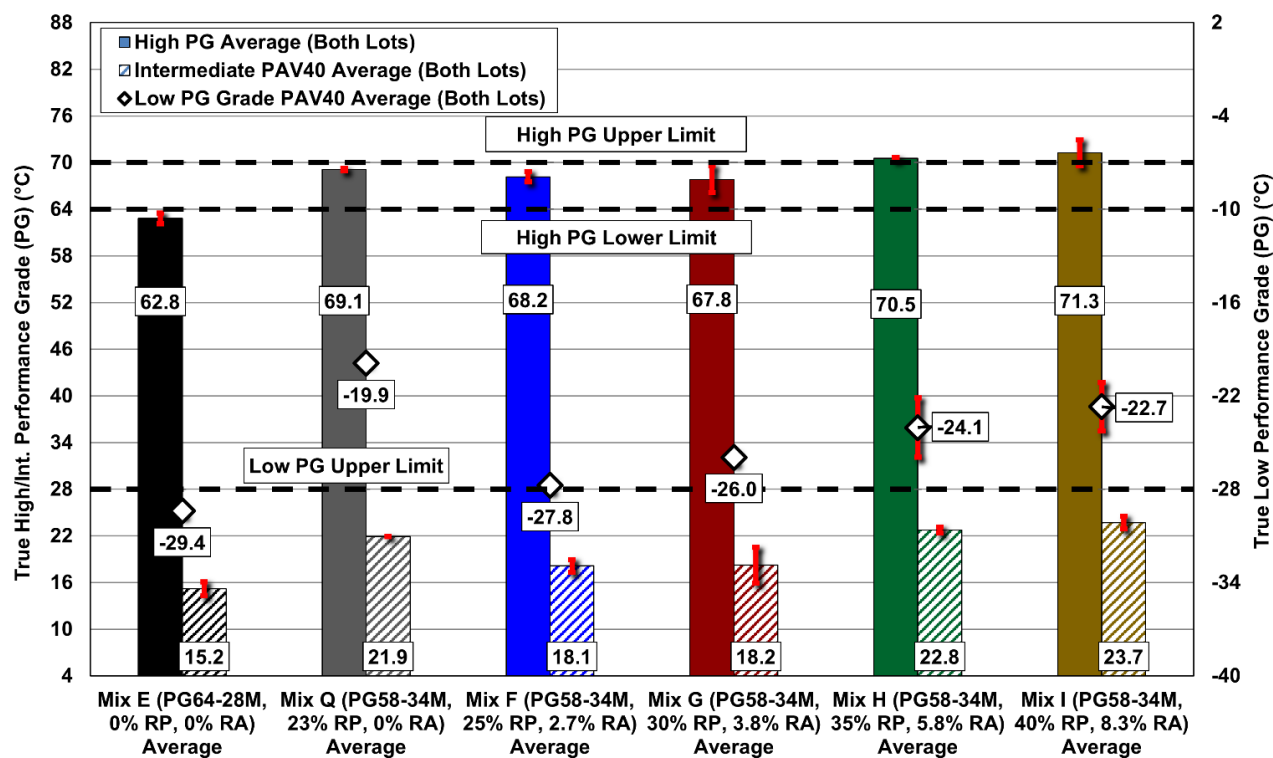
Notes: Specification limit shown as dashed line; error bars indicate one standard deviation of results.

Figure 3.9: Continuous temperature binder grades for QA both sublots (40-hour PAV).



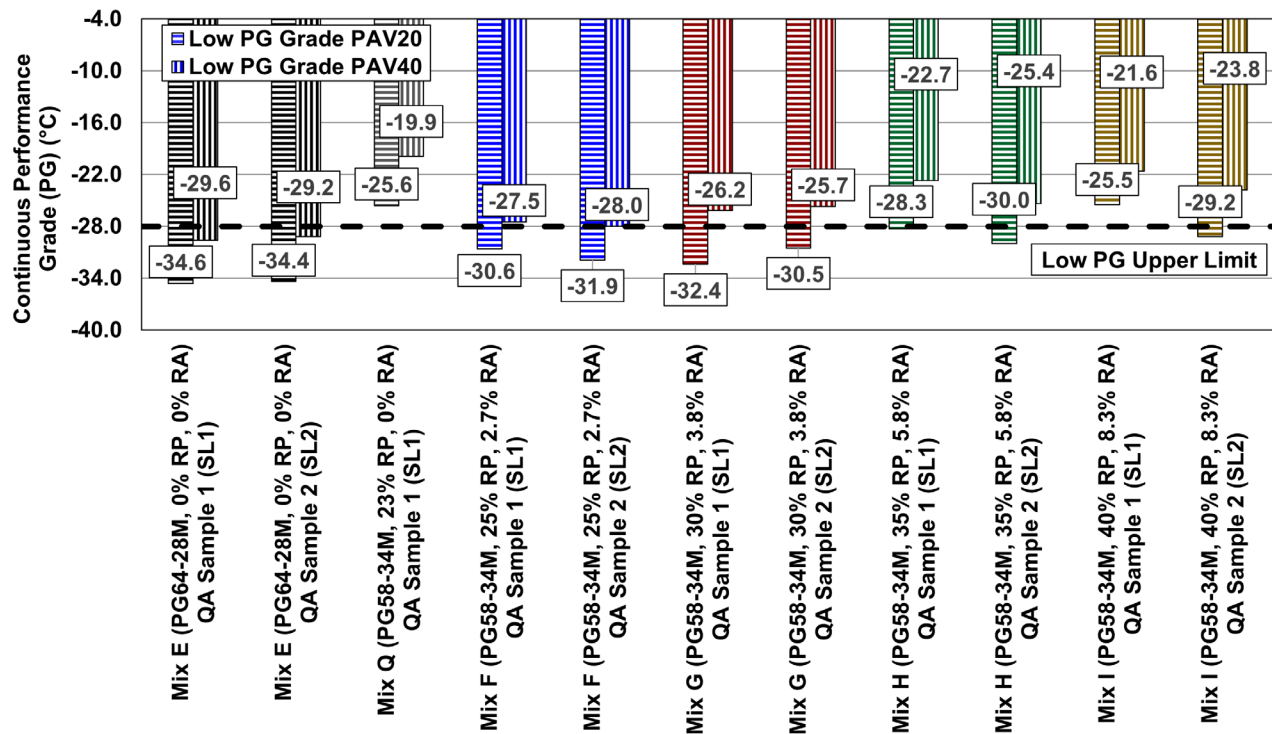
Note: Specification limit shown as dashed line; error bars indicate one standard deviation of results.

Figure 3.10: Continuous temperature binder grades for QA average of both sublots (20-hour PAV).



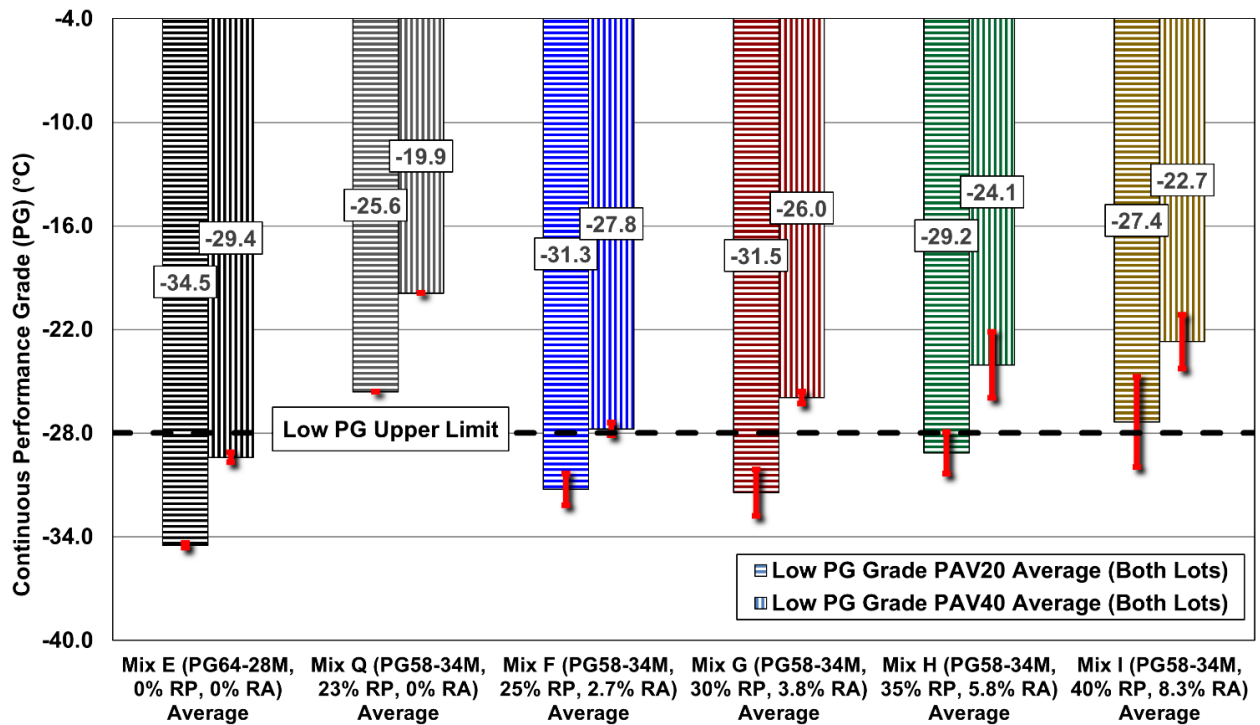
Note: Specification limit shown as dashed line; error bars indicate one standard deviation of results.

Figure 3.11: Continuous temperature binder grades for QA both sublots (40-hour PAV).



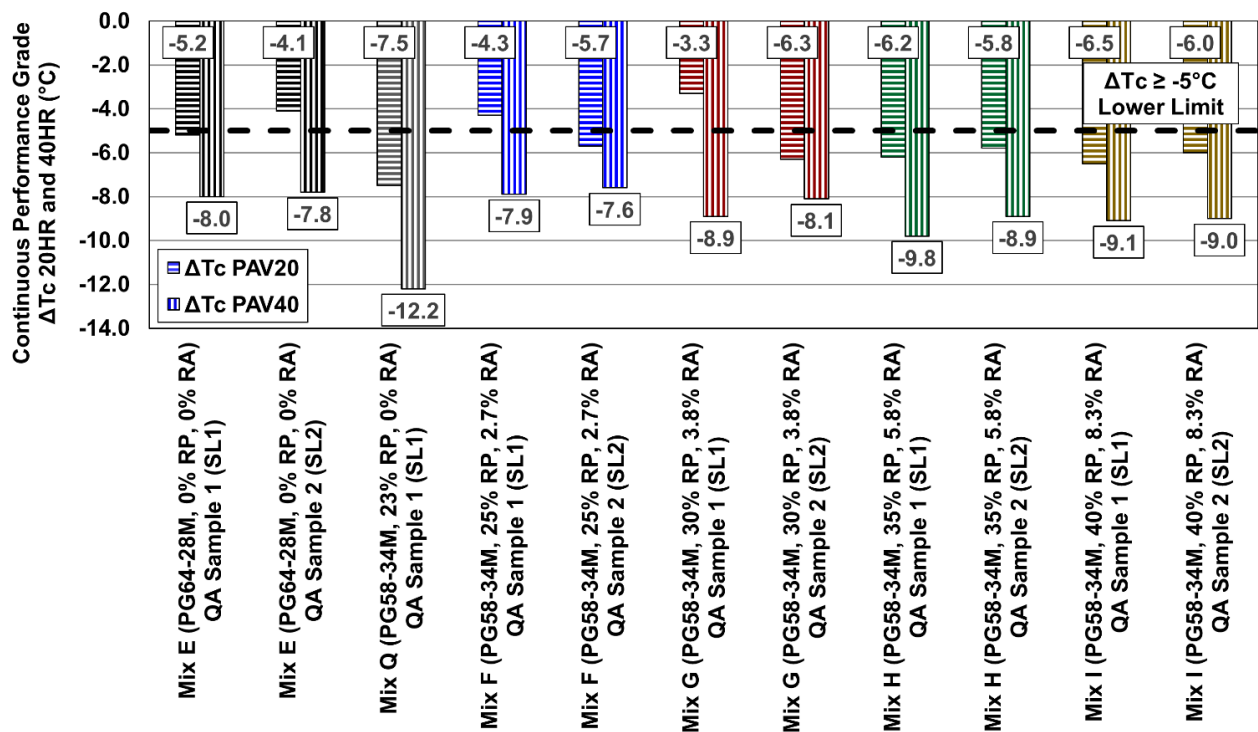
Note: Specification limit shown as dashed line.

Figure 3.12: Continuous low temperature binder grade for QA both sublots (20-hour and 40-hour PAV).



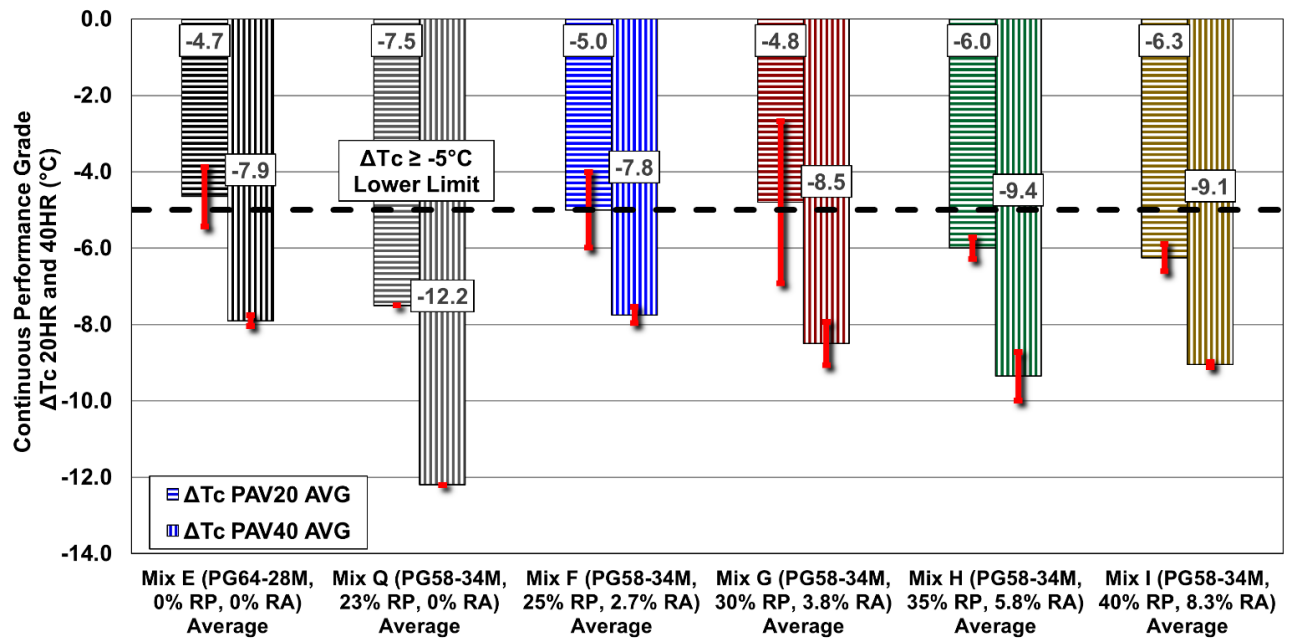
Note: Specification limit shown as dashed line; error bars indicate one standard deviation of results.

Figure 3.13: Continuous low temperature binder grades for QA average of both sublots (20-hour and 40-hour PAV).



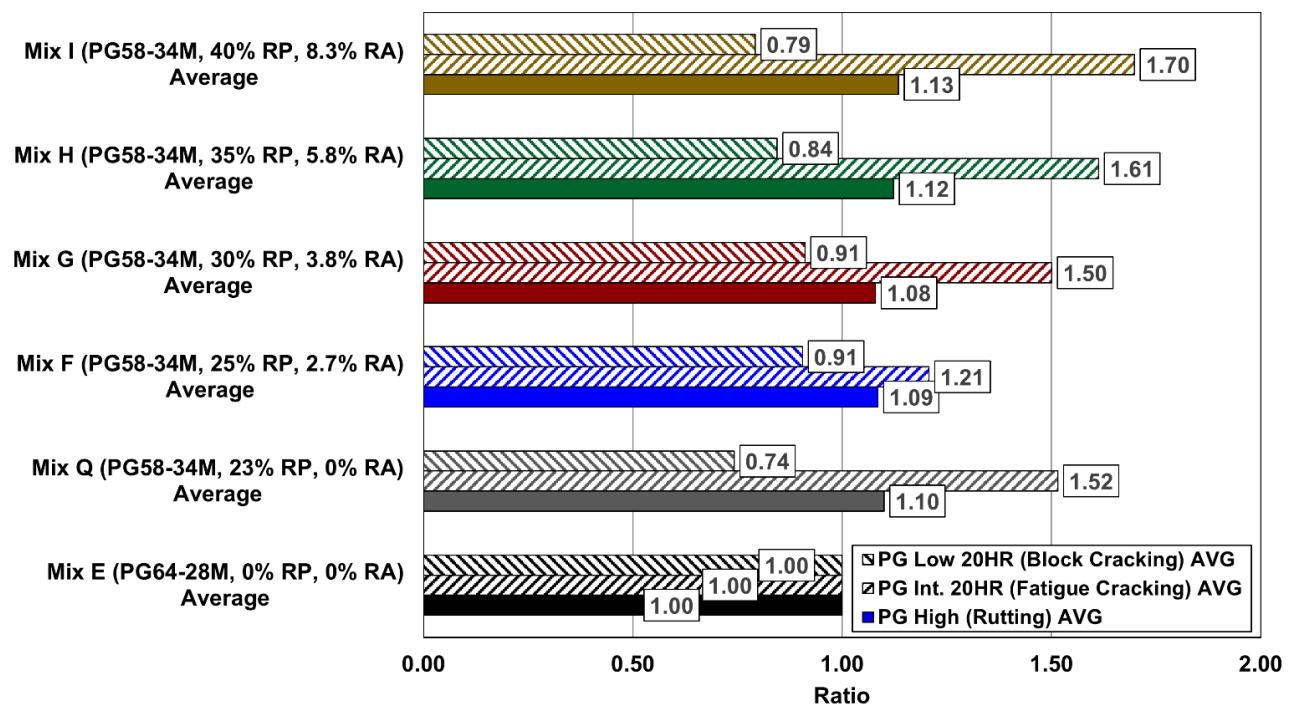
Note: Specification limit shown as dashed line.

Figure 3.14: Delta T_c values for QA of both sublots (20-hour and 40-hour PAV).



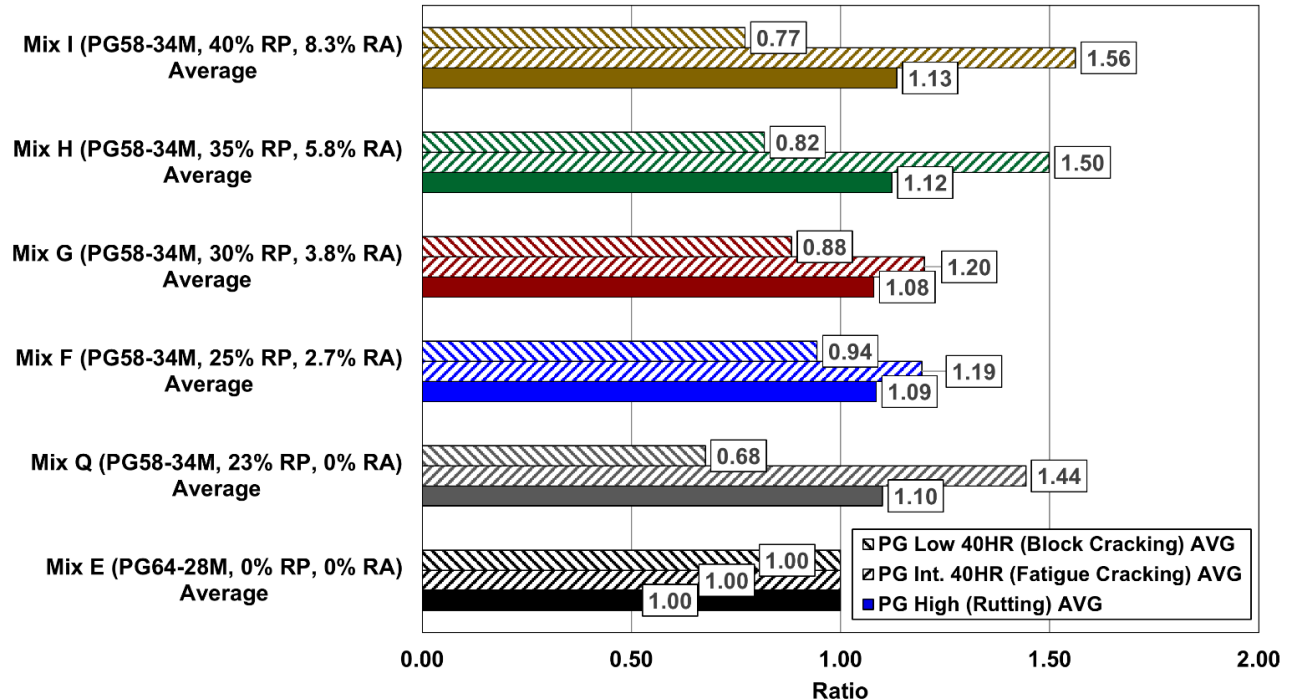
Note: Specification limit shown as dashed line, error bars indicate one standard deviation of results.

Figure 3.15 Delta T_c values for QA average of both sublots (20-hour and 40-hour PAV).



Note: PG high temperature greater than one grades higher (hotter) than the control, PG low temperature greater than one grades lower (colder) than control, and PG immediate temperature greater than one grades higher than the control. Benefits depend on structural design (higher intermediate PG, stiffer binder).

Figure 3.16 Binder grades for QA Average of both sublots normalized to Mix E (0% RP, 0% RA) (20-hour PAV).



Note: PG high temperature greater than one grades higher (hotter) than the control, PG low temperature greater than one grades lower (colder) than control, and PG immediate temperature greater than one grades higher than the control. Benefits depend on structural design (higher intermediate PG, stiffer binder).

Figure 3.17 Binder grades for QA Average of both sublots normalized to Mix E (0% RP, 0% RA) (40-hour PAV).

3.3.2 Frequency Sweep

The average binder dynamic stiffness master curves from the first subplot of the QA sampled materials are shown in Figure 3.18. The results are averages of four replicate tests. The results show that the extracted binders from four of the mixes, the mainline mix with 23% RAP (Mix Q) and the mixes with 25%, 30%, and 35% RAP (Mixes F, G, and H, respectively), had nearly identical master curves. The binder from the mix with 40% RAP was considerably stiffer (Mix I), while the binder from the control mix with no RAP (Mix E) was considerably softer. This is further evidence that the control mix with no RAP likely had the wrong binder, the PG 58-34M used in all the other mixes rather than the specified PG 64-28M.

Figure 3.19 shows the binder stiffnesses versus reduced frequency normalized to the binder from Mix E with no RAP from the first subplot verification sampled binder. The results show that the largest stiffness differences between the four mixes with similar master curves and the mixes with 40% RAP and no RAP were in the middle frequencies, corresponding to intermediate temperatures and traffic speeds. The low binder stiffnesses of the control mix with no binder (Mix E) at high temperatures and slow traffic speeds, corresponding to the lowest frequencies at the left of the plot, indicate that the binder stiffness presents a higher risk of rutting than all the other binders.

Figure 3.20 shows a Black Space diagram (stiffness versus phase angle) with stiffness for the binders extracted from each mix at a reduced temperature of 15°C and a reduced frequency of $8 (10^{-4})$ Hz for three aging conditions: (1) plant mixed, (2) 20-hour PAV-aged, and (3) 40-hour PAV-aged. Imposed on the plot are the Glover-Rowe thresholds that have been identified to correlate with an increased risk of long-term aging-related block cracking (14). The results show that the binder from the control mix has the least chance of block cracking because it is very soft, likely because it is the wrong binder grade. The mixes with the greatest risks of block cracking from high moduli and low phase angles after aging are the mainline mix with 23% RAP and no RA (Mix Q) followed by the mix with 35% RAP and 5.8% RA (Mix H). The mix (Mix I with 40% RAP and 8.3% RA) that showed the highest stiffnesses in the unaged binder master curves as well as in the unaged condition in Figure 3.20 had less change in block cracking risk (increased stiffness and decreased phase angle) from PAV aging for 20 hours than did most of the other mixes, but it is uncertain why. Mix I, therefore, had less risk of block cracking, according to the test results and Glover-Rowe criteria, than did other mixes with less RAP, which is a positive result for a mix used on the surface.

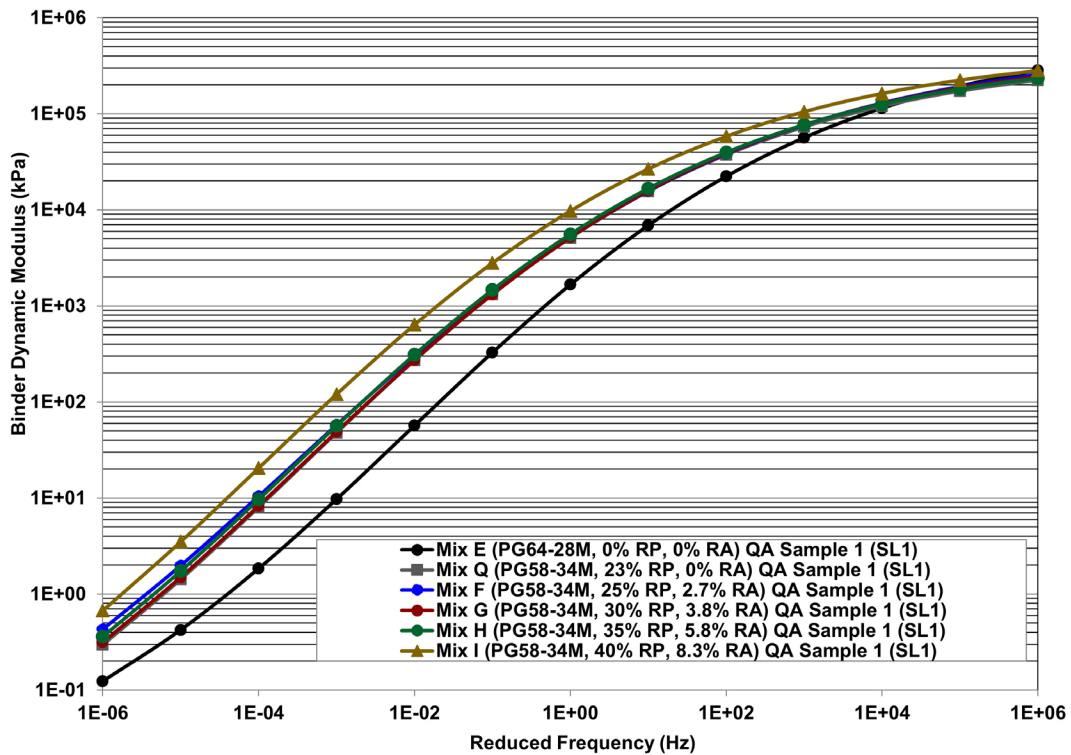


Figure 3.18: Frequency sweep master curves for plant extracted first subplot (SL1) of QA sampled binders.

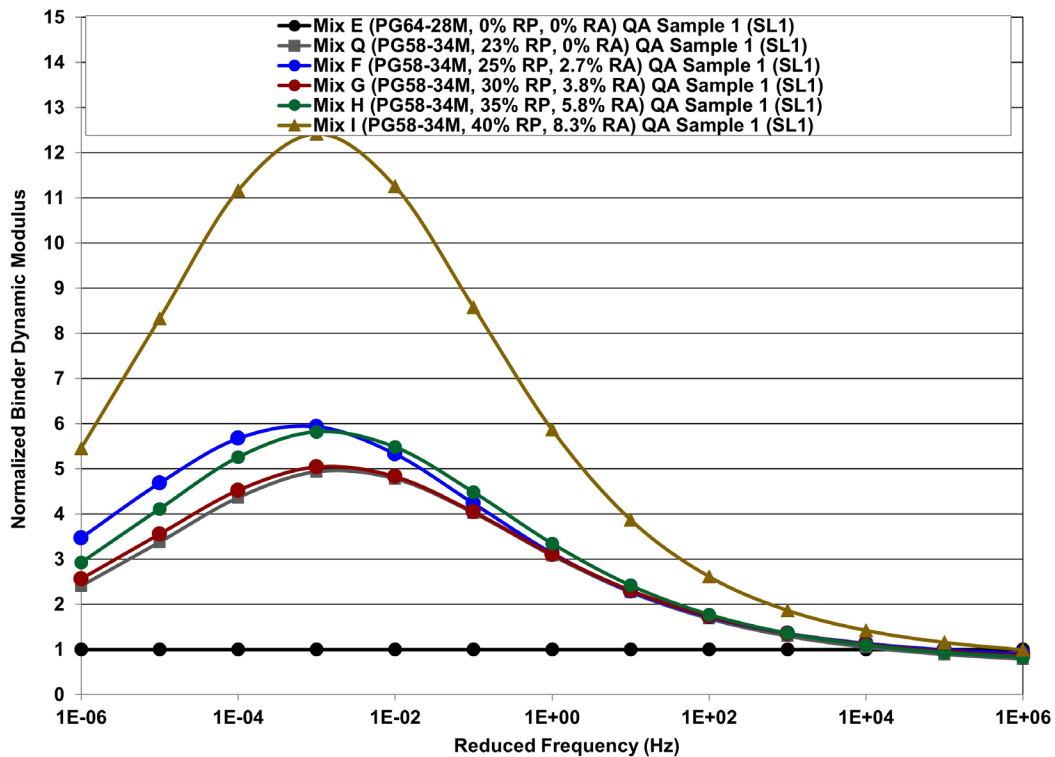
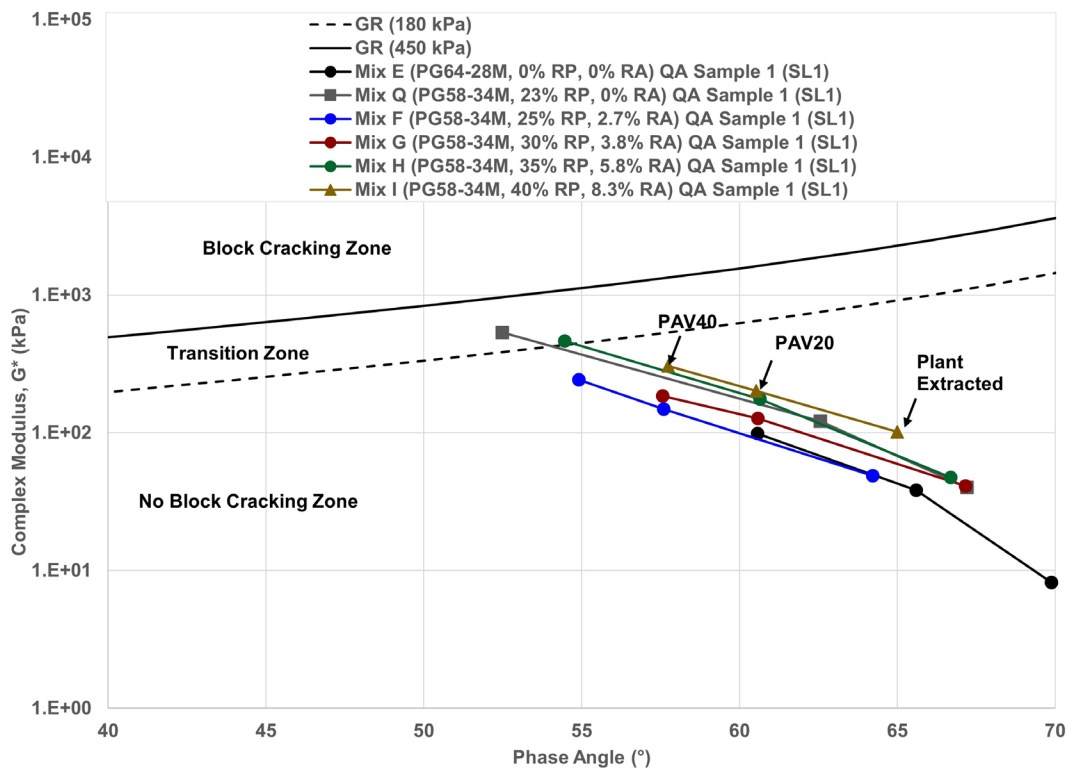


Figure 3.19: Frequency sweep master curves for plant extracted first subplot (SL1) of QA sampled binders normalized to Mix E (PG 64-28M, 0% RP, 0% RA) QA Sample 1 (SL1).



Note: Plant extracted: extracted and recovered binder from plant-produced mixes; PAV20: 20 hours of PAV aging of extracted and recovered binder from plant-produced mixes; PAV40: 40 hours of PAV aging of extracted and recovered binder from plant-produced mixes.

Figure 3.20: Black Space plot for first subplot (SL1) of QA sampled binders with Glover-Rowe criteria.

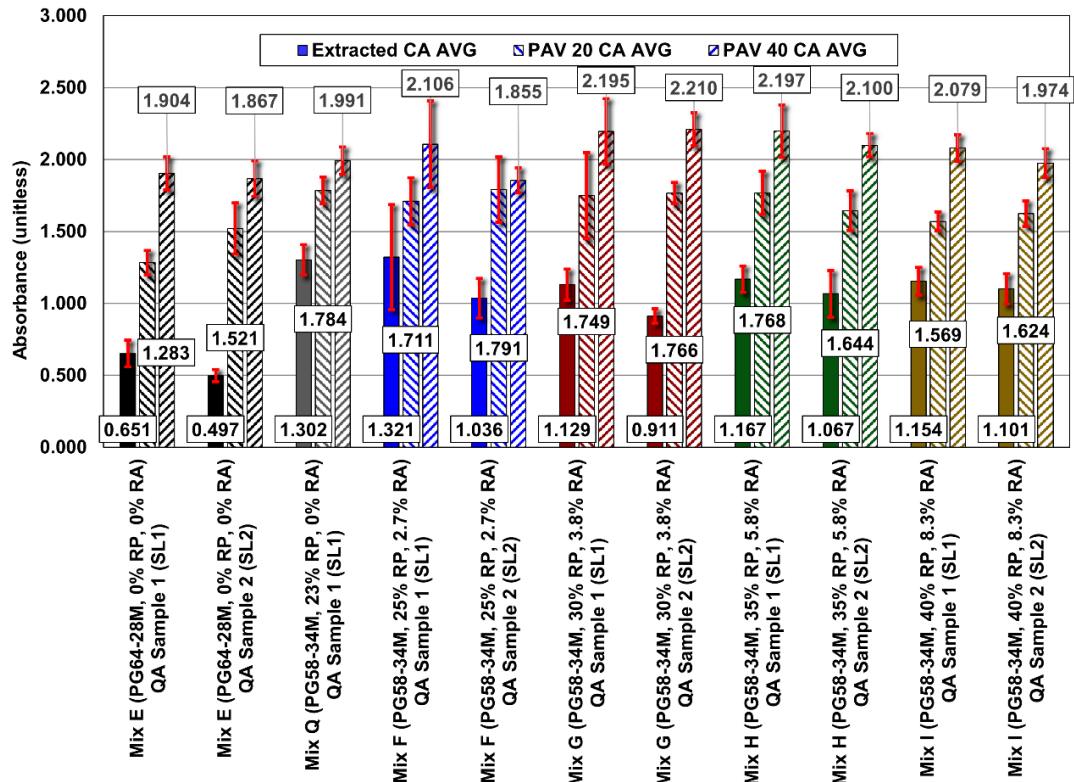
3.3.3 FTIR Testing

The extracted binders from the two sublots of QA sampled binders were tested with the FTIR after plant mixing and 20-hour and 40-hour PAV aging to evaluate the quantities of aging chemical products: carbonyl and sulfoxide. Figure 3.21 plots the carbonyl indices of the binders for these three conditions for both QA samples. The results show that the carbonyl contents before and after PAV aging were similar between the two sublots for each mix. Figure 3.22 shows the sulfoxide indices for each of the binders extracted from the two QA samples, which are also similar between the two sublots for each mix. Figure 3.23 shows the average carbonyl contents across the two sublots, and Figure 3.24 shows the same for the sulfoxide contents. The results show that the control mix with no RAP had a significantly lower carbonyl content after sampling, and that although it remained the lowest after 20 and 40 hours of PAV aging, the differences between it and the mixes with RAP were less as aging was increased. The results also show that the control mix binder also had the lowest sulfoxide content after sampling and after PAV aging. In addition, the results show that the sulfoxide contents essentially remained constant after 20 hours and 40 hours of PAV aging.

Figure 3.25 and Figure 3.26 show the carbonyl contents and the sulfoxide contents, respectively, of the binder from each mix normalized to those of the control mix with no RAP. The figures show that mixes with RAP had much greater differences in carbonyl compared with the control mix with no RAP after extraction, and that the differences decreased with increased aging. The mixes with RAP all had

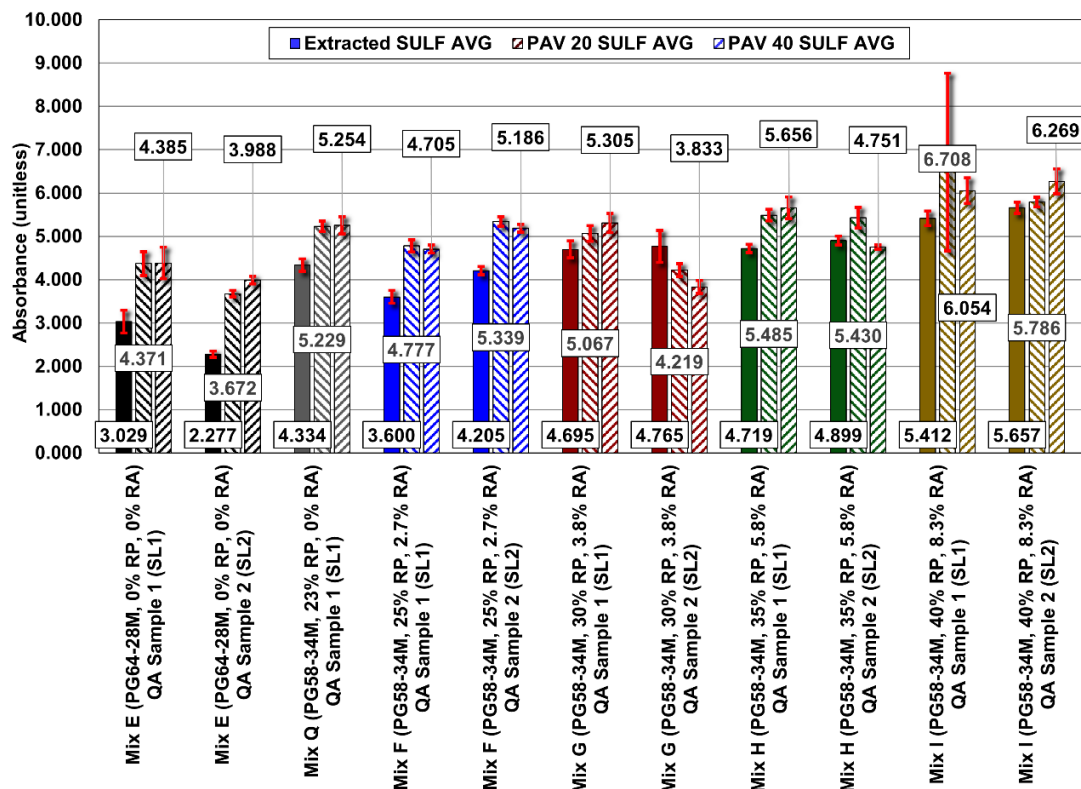
similar amounts of carbonyl despite differences in RAP content. The sulfoxide contents after extraction decreased as RAP contents decreased. The differences in sulfoxide between the control mix and the mixes with RAP decreased with increased aging.

Previous research by the UCPRC (4) and earlier research by other organizations (primarily Glover and others at Texas A&M University [16]) has shown that carbonyl content is a good indicator of the changes in binder performance indicators for rutting at high temperatures and for stiffness related to different types of cracking at lower temperatures. Similar strong correlations between carbonyl content and the binder performance indicators for rutting at high temperatures and stiffness at low temperatures can be seen for the six mixes included in this project that were QA sampled during paving (three replicates each of two samples on six mixes). The results show a strong correlation between the carbonyl area versus the Glover-Rowe criteria (Figure 3.27) related to block cracking, the stiffness at 64°C and 10 Hz (Figure 3.28) related to rutting, and the crossover modulus (Figure 3.29) related to low temperature cracking. The crossover modulus is the stiffness at which the phase angle is 45 degrees, with decreasing crossover modulus indicating less ability to relax stresses under thermal contraction. The results show how the risk of block cracking increases with aging, the risk of rutting decreases, and the risk of low temperature cracking increases.



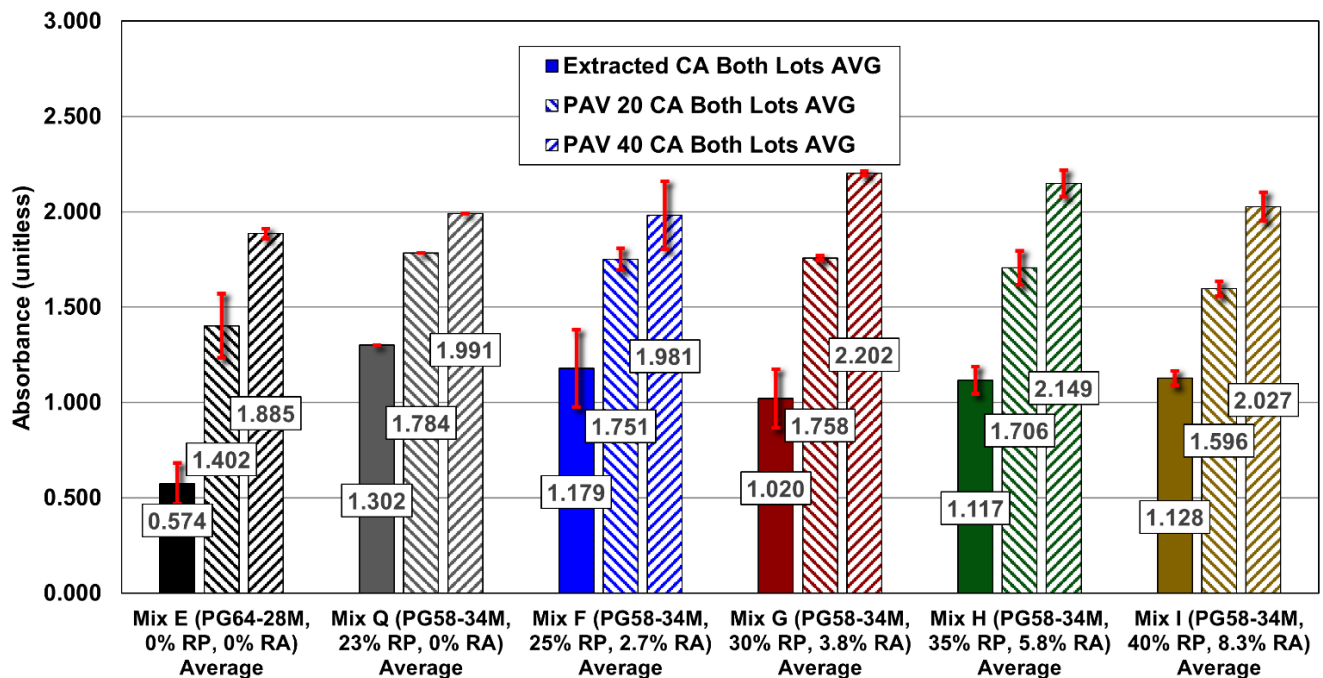
Notes: Error bars indicate one standard deviation of results.

Figure 3.21: Carbonyl area index changes after aging for QA sampled binders.



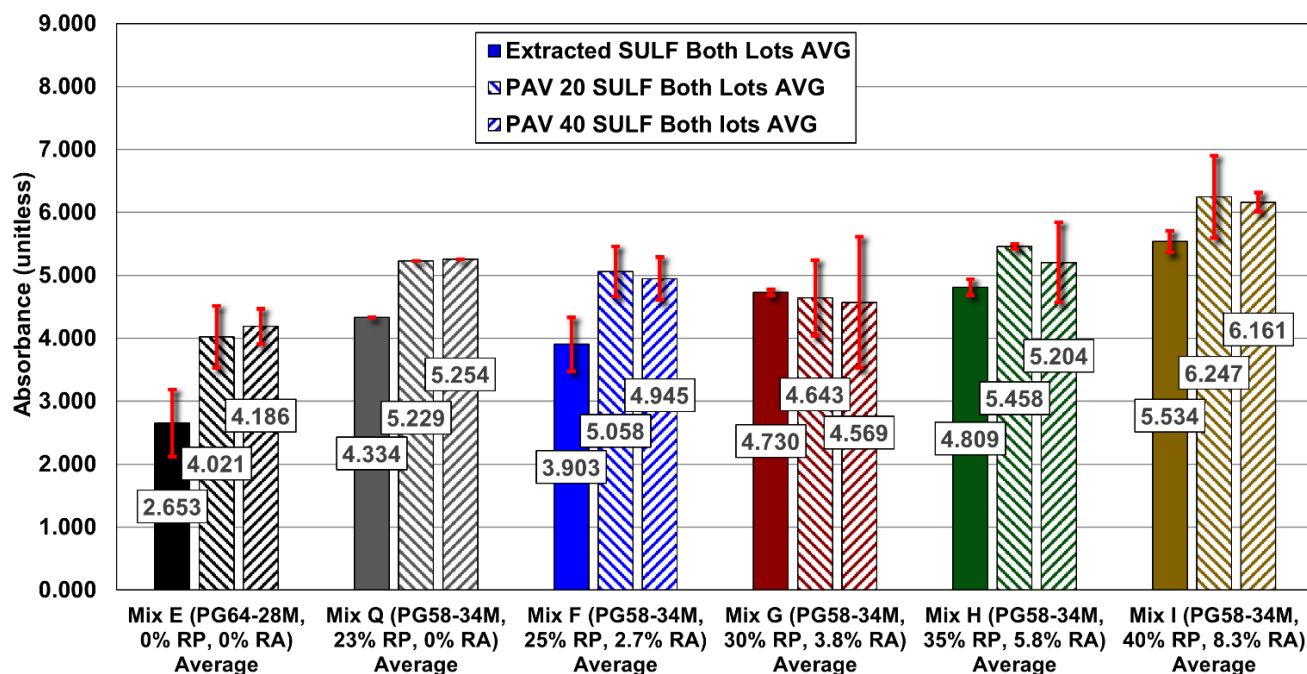
Note: Error bars indicate one standard deviation of results.

Figure 3.22: Sulfoxide area index changes after aging for QA sampled binders.



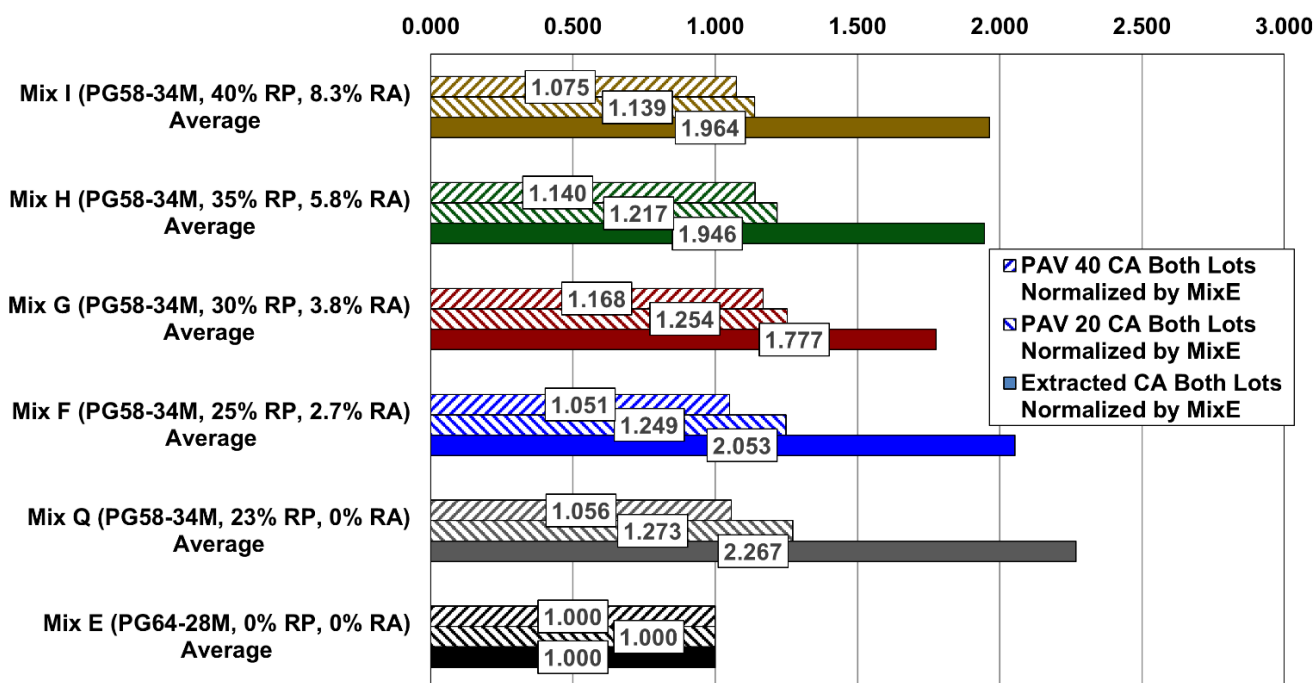
Note: Error bars indicate one standard deviation of results.

Figure 3.23 Binder carbonyl content for QA average of both sublots.



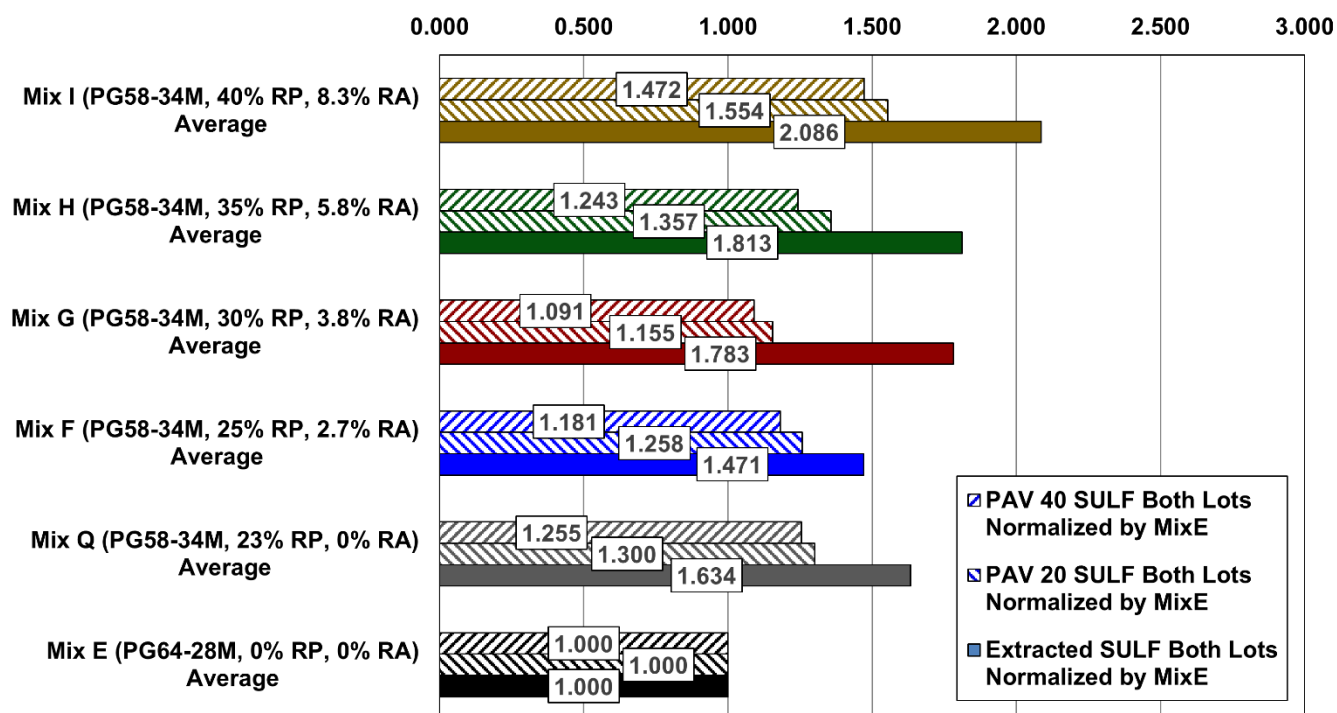
Note: Error bars indicate one standard deviation of results.

Figure 3.24 Binder sulfoxide content for QA average of both sublots.



Note: Normalized absorbance greater than one indicates higher concentration of carbonyl.

Figure 3.25 Binder carbonyl content for QA average of both sublots normalized to Mix E.



Note: Normalized absorbance greater than one indicates higher concentration of sulfoxide.

Figure 3.26 Binder sulfoxide content for QA average of both sublots normalized to Mix E.

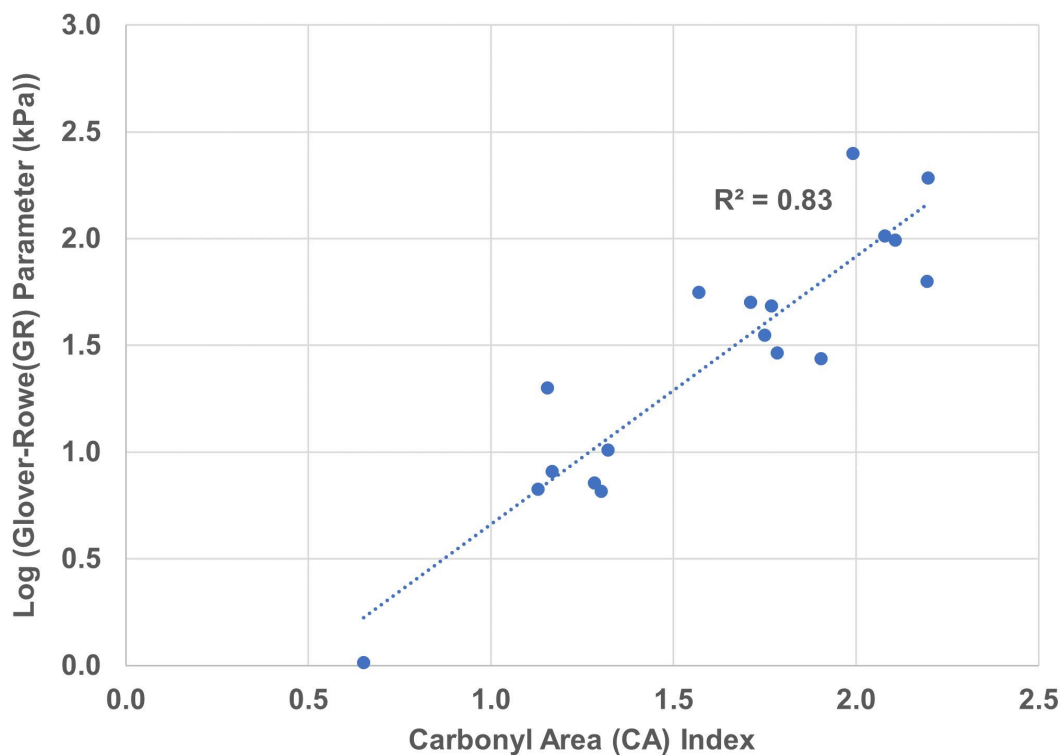


Figure 3.27: Carbonyl area versus Glover-Rowe parameter for first subplot (SL1) of QA sampled binders at all aging conditions.

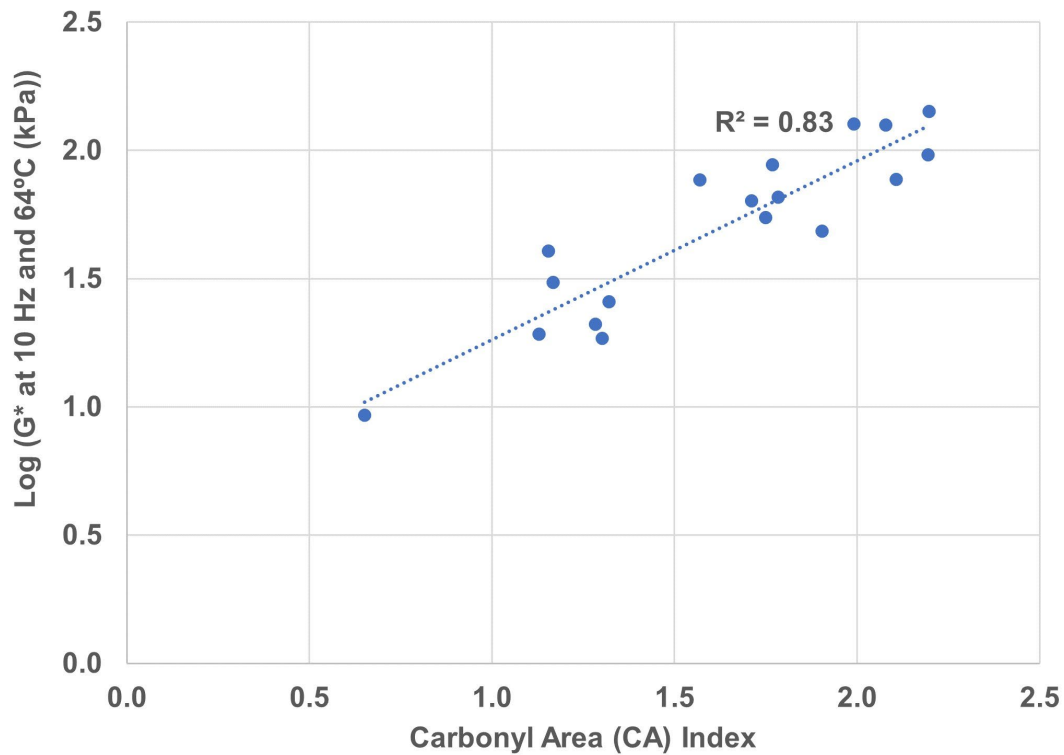


Figure 3.28: Carbonyl area versus G^* at 10 Hz and 64°C for first subplot (SL1) of QA sampled binders at all aging conditions.

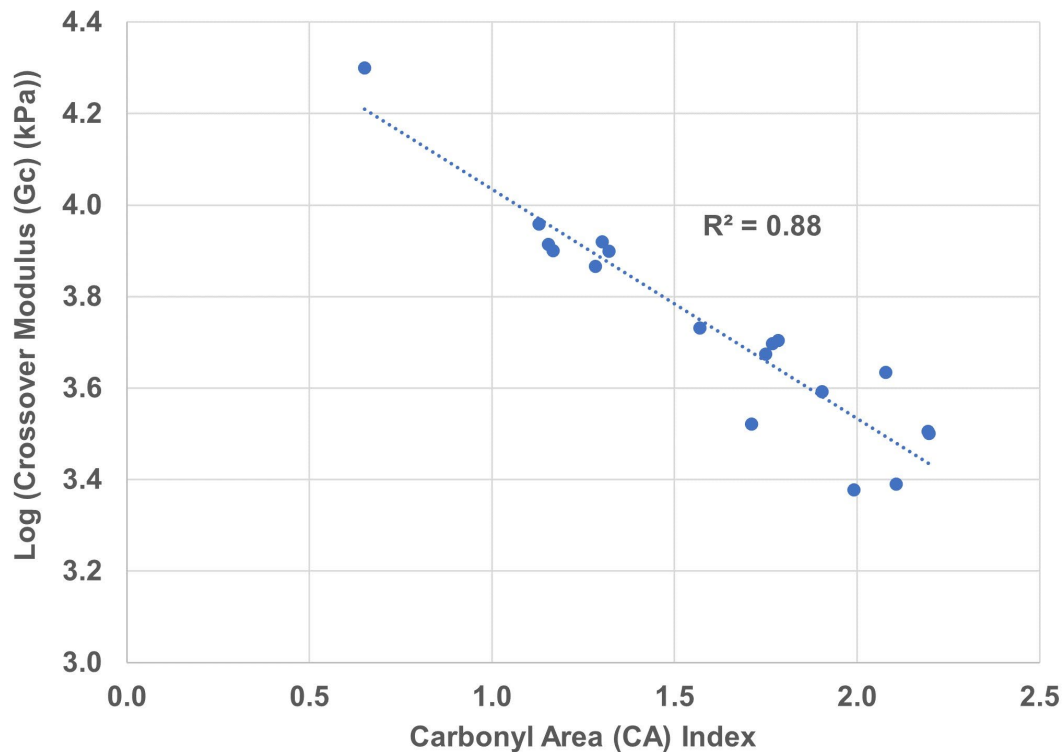


Figure 3.29: Carbonyl area versus crossover modulus for first subplot (SL1) of QA sampled binders at all aging conditions.

4 MIX TESTING RESULTS

4.1 Introduction

This chapter discusses mix testing results for the plant-produced mixes from JMF verification prior to construction and QA sampling during construction. Mix designs and test method details are discussed in Chapter 2 and are not repeated in this chapter.

4.2 Mix Test Variability

4.2.1 Overview

It is desirable that pavement materials tests are sensitive to material variables in the same way that the material performance in the field is sensitive to the same variables and that the repeatability of the test is high (in other words, the test variance is low). A few asphalt concrete mix distresses are related to monotonic loading conditions, particularly fracture from low temperature cracking or from long-term aging and contraction at intermediate temperatures resulting in block cracking, as tested by fracture. The variability of monotonic tests is generally consistent regardless of the test value once operator and equipment inconsistencies are controlled.

The distresses of rutting and fatigue are caused by phenomena related to repeated loading. Assessments of mix properties for rutting and fatigue are generally considered to require an RLT test to obtain the best mix characterization for permanent deformation leading to rutting at high temperatures and damage at intermediate temperatures leading to fatigue cracking (17,18). The variability of RLTs is high when considered in terms of the standard deviation of the test. However, the sensitivity of RLTs to mix variables—such as tensile strain (fatigue) or shear stress (rutting), binder stiffness and type, air-void content, and aggregate gradation—is very high. The sensitivity of RLT tests for permanent deformation and fatigue damage is sufficiently similar to mix sensitivity in the field to predict rutting and fatigue performance when used with a mechanistic-empirical simulation framework (19). In other words, RLTs can discern the differences in expected performance between different mixes (or compaction levels, loading times, or temperatures) because the sensitivity of the tests to these variables is greater than the variability for a given set of mix variables (20). It has also been found that the variability of RLTs is not constant but rather increases as the number of repetitions to failure increases, such that the coefficient of variation (COV) (standard deviation of repetitions to a given damage state or failure divided by mean repetitions) is approximately a constant.

The calculated variability of RLT test results can be reduced and changed to a relatively constant variability, as opposed to a constant COV, by changing the definition of the test result parameter from the number of repetitions to reach the failure state to instead be the stress or strain state that results in a given number of repetitions to the failure state. This change of definition of the test result parameter has been done in Caltrans performance-related specifications for the flexural fatigue test, where the specification parameter has been changed from the repetitions to failure at a given tensile strain, which requires an exponential scale to plot, to instead be the tensile strain that results in 1 million cycles to failure, which can be plotted on a linear scale. The test method is the same, except that the

strains are selected to produce approximately 1 million repetitions to failure at the lowest strain used for a given mix. Changing the parameter definition has also reduced the time necessary to complete testing for a mix.

Methods of minimizing the variability of test results for all types of asphalt concrete performance-related tests include consistent materials handling for uniform aging, consistent air-voids, consistent specimen dimensions, calibrated equipment, and certified testing staff. Once these sources of specimen preparation and testing variability are controlled, inherent test variability is typically influenced by considerations of representative volume element (RVE) for the composite material (ratio of largest particle size to least specimen dimension) and the sensitivity of the results to the location of the critical stress state relative to the random locations of larger aggregate particles in the specimen.

Variabilities of mix test results on this pilot project were generally consistent with those for the same tests on other projects. Within-sample variability values are shown for the following tests performed on this pilot project during both JMF approval (where applicable) and QA testing: mix stiffness at 20°C and 10 Hz (flexural and axial tests), RLT tests (confined and unconfined), four-point beam repetitions to failure at a given strain (lowest strain used), and IDEAL-CT parameter and strength. The I-FIT semicircular beam cracking test was not included in this project because it was found on previous projects to produce similar results to those from the IDEAL-CT test, but the I-FIT test requires more specimen preparation effort. The variability data shown for each test is within-sample, meaning that the JMF sample and the two QA samples are each treated as different samples. Test variability for all tests will be assessed across all the pilot projects once they are completed.

4.2.2 Variability of Test Results on This Pilot Project

The average within-sample variabilities of the flexural and triaxial dynamic moduli at 10 Hz and 20°C from the frequency sweep tests are shown in Table 4.1.

Table 4.1: Variability of Within-Sample Stiffness (MPa) and Coefficient of Variation for Dynamic Modulus at 20°C and 10 Hz

Test	Replicate Tests	Average Standard Deviation (MPa)	Minimum Coefficient of Variation ^a	Maximum Coefficient of Variation ^a	Average Coefficient of Variation ^a
Flexural dynamic modulus at 10 Hz, 20°C	3	188	0.005	0.09	0.05
Triaxial dynamic modulus at 10 Hz, 21°C	3	298	0.02	0.09	0.05

^a Standard deviation/mean.

The average within-sample variabilities of the unconfined and confined RLT test results are shown in Table 4.2 for the flow number parameter and in Table 4.3 for repetitions to 3% permanent deformation. The termination criteria for the test are 20,000 repetitions or 5% permanent deformation. Variability for the flexural fatigue test is shown in Table 4.4 and in Table 4.5 for the IDEAL-CT test.

Table 4.2: Variability of Within-Sample Repetitions to Flow Number and Coefficient of Variation for Repeated Load Triaxial Test

Test	Replicate Tests	Average Standard Deviation (repetitions)	Minimum Coefficient of Variation ^a	Maximum Coefficient of Variation ^a	Average Coefficient of Variation ^a
Unconfined Flow Number at 45°C	3	186	0.10	0.38	0.21
Confined Flow Number at 45°C	3	2078	0.02	0.28	0.12
Unconfined Flow Number at 55°C	3	52	0.16	0.42	0.25
Confined Flow Number at 55°C	3	2557	0.08	0.48	0.23
Unconfined Flow Number at 50°C	3-6	86	0.11	0.46	0.21

^a Standard deviation/mean.

Table 4.3 Variability of Within-Sample Repetitions to 3% Permanent Deformation and Coefficient of Variation for Repeated Load Triaxial Test

Test	Replicate Tests	Average Standard Deviation (repetitions)	Minimum Coefficient of Variation ^a	Maximum Coefficient of Variation ^a	Average Coefficient of Variation ^a
Unconfined Repetitions at 45°C	3	332	0.13	0.38	0.23
Confined Repetitions at 45°C	3	2010	0.00	0.59	0.11
Unconfined Repetitions at 55°C	3	123	0.18	0.50	0.30
Confined Repetitions at 55°C	3	1378	0.00	0.41	0.13
Unconfined Repetitions at 50°C	3-6	202	0.11	0.61	0.26

^a Standard deviation/mean.

The average within-sample variabilities of the flexural fatigue beam test results are shown in Table 4.4.

Table 4.4: Variability of Within-Sample Tensile Strain at 1 Million Repetitions to Failure and Coefficient of Variation for Flexural Fatigue Test

Test	Replicate Tests	Average Standard Deviation (repetitions to failure)	Minimum Coefficient of Variation ^a	Maximum Coefficient of Variation ^a	Average Coefficient of Variation ^a
Repetitions to failure at 400-500 $\mu\epsilon$	3-6 at each strain level	1,015,540	0.30	1.22	0.91

^a Standard deviation/mean.

The average within-sample variabilities of the indirect tension (IDEAL-CT) fracture test results are shown in Table 4.5.

Table 4.5: Variability of Within-Sample Fracture Test Parameter (Cracking Tolerance Index) and Strength (psi) and Coefficient of Variation

Test	Replicate Test	Average Standard Deviation (parameter or psi)	Minimum Coefficient of Variation ^a	Maximum Coefficient of Variation ^a	Average Coefficient of Variation ^a
Reheat CT Index (#)	5+	18.1	0.16	0.30	0.21
Reheat Strength (psi)	5+	7.8	0.03	0.12	0.07
MTOA CT Index (#)	5+	11.3	0.09	0.33	0.23
MTOA Strength (psi)	5+	9.2	0.02	0.09	0.07

^a Standard deviation/mean.

The within-sample test variabilities found in this project are within the ranges of those found in other projects, except for the flexural fatigue test variability where the COV was approximately 2.5 times larger for this project than for the El Dorado 49 (ELD 49) high RAP pilot project. As noted previously, the variability of each of these tests will continue to be assessed in future pilot projects and other test programs.

4.3 Testing of Job Mix Formula Mixes Prior to Construction for JMF Verification

Testing of the JMF sample from a hot drop prior to construction consisted only of the binder properties and the mix properties included in the Non-Standard Special Provisions for the project (nSSP). The only mix property specified was the IDEAL-CT number.

In the previous high RAP and RAS pilot project on ED 49, many other tests were also completed for the JMF review, including flexural stiffness and fatigue, RLT, and I-FIT semicircular beam cracking test. The I-FIT test was dropped from the testing program based on the conclusions from the ELD 49 project and other projects that showed a very high correlation with IDEAL-CT results. The other mix tests were performed for this project during QA but were not included in the JMF testing program because of time and cost.

4.3.1 Indirect Tensile Cracking Resistance: IDEAL-CT Test

Figure 4.1 shows the IDEAL-CT results in terms of the IDEAL-CT number and strength. It has been proposed that a larger IDEAL-CT number indicates better age-cracking resistance (21). Previous research by the UCPRC indicates that both the IDEAL-CT number and the IDEAL-CT strength have a strong correlation with flexural stiffness and a weak correlation with fatigue cracking resistance at a given strain (22). This research also found that the IDEAL-CT number and strength have been found to be highly inversely correlated with each other as well.

The results show that the control mix that was specified to be a PG 64-16 with no RAP (Mix E) had an IDEAL-CT number of 39.8. The specification required that the mix with RAP have IDEAL-CT numbers greater than or equal to the value from the control mix. As shown in Figure 4.1, all the mixes with RAP, from 25% to 40%, met the specification. In addition, the mix with 25% RAP significantly

exceeded the specification, likely due to an overdosing of the RA when the JMF sample was mixed at the plant. The strength values show the expected inverse correlation with the IDEAL-CT number.

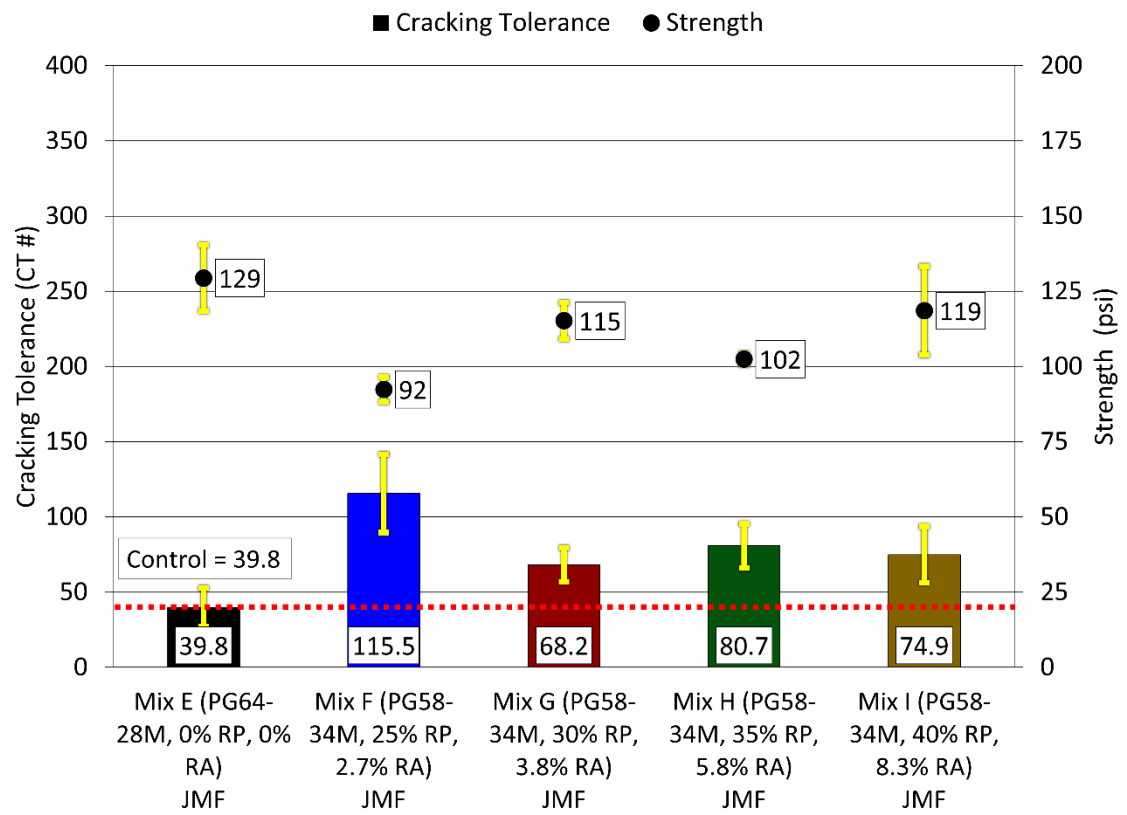


Figure 4.1: IDEAL-CT test results for JMF verification sampled mixes (cracking tolerance index and indirect tensile strength).

4.4 Testing of Mixes Sampled During Construction for Quality Assurance

The UCPRC sampled and tested two sublots of each high RAP nSSP mix and one subplot of the mainline conventional mix (Mix Q). The results of the testing are presented in the following discussion.

4.4.1 Mix Design Volumetric Properties: Air-Voids, N_{design} , and Asphalt Binder Content %

Unlike the previous high RAP and RAS pilot project on ELD 49 (23), volumetric properties are reported here to help understand the relationship between the performance-related test properties and the conventional mix design information. The standard volumetric tests were run, and the results are shown in Table 4.6 and Table 4.7. The results shown in Table 4.6 are from tests performed at the UCPRC’s UC Davis-ATIRC Laboratory. Results shown in Table 4.7 are from tests performed at Vulcan’s San Bernardino and Irwindale Regional Laboratories. All results in the tables are averages from the two QA samples. The results from the individual QA samples are shown in the figures that follow the tables.

The total binder contents determined from extraction by the UCPRC and the gyratory compaction air-void contents are shown in Figure 4.2. The results show that binder contents fall within specification (4.2% to 5.0%) except for the second QA sample for Mix I with 40% RAP, where the second sample had

a binder content of 5.3%. The binder contents were consistent between the two QA samples for each mix, with the largest difference, 0.3%, for Mix I. The air-void content results under laboratory gyratory compaction are all within specification. The greatest variability is for the control mix with no RAP and the mix with 25% RAP (Mix F). The contractor's QC results for total binder contents and gyratory compaction air-void contents are shown in Figure 4.3. The results show similar general trends to those from the UCPRC testing; however, some of the binder contents show larger differences between sublots for a given mix.

The contractor's binder content results determined by ignition oven are shown versus the UCPRC binder content results determined by extraction, along with the specification limits, in Figure 4.4. The results indicate that for some mixes, the differences between the binder contents tested by the two methods are up to 1% different, which is significant, while they are close for the other sublots. Based on the extraction results, all the binder contents are within specification, except for the second subplot of the mix with 40% RAP (Mix I). Based on the ignition oven results, one of the subplot binder contents is below the specified minimum limit (Mix E), and three are above the maximum specified limit (one subplot each for Mixes F, H, and I).

The air-void contents under gyratory compaction are compared for the UCPRC and contractor's results in Figure 4.5, along with the specification limits for the different mixes. Nearly all of the contractor's results are lower than the UCPRC results, by up to 1.5% air-voids. The UCPRC results show that all mixes are within the specification limits around the JMF value, while the contractor results show three results with air-void contents below the specified minimum value. Figure 4.6 shows the contractor's results for voids in the mineral aggregate, which are generally consistent between sublots of a given mix and show decreasing values as the RAP contents are increased, which is consistent with the lower design air-void contents as the RAP contents are increased.

Figure 4.7 through Figure 4.12 show the aggregate gradations from the contractor's ignition oven testing, with each plot showing the gradation from the two sublots for each mix. The gradations are consistent between sublots. All of the mixes with RAP are coarser than the control mix with no RAP (Mix E), and the mixes with 30%, 35%, and 40% RAP are at the lower limit of the Caltrans aggregate gradation specification limits. A comparison of all the gradations is shown in Figure 4.12.

Overall, the results of UCPRC testing of the aggregate gradations, binder contents, and air-voids under gyratory compaction indicate that the mixes mostly met specifications and were generally consistent between QA sublots. Differences observed between the binder contents from UCPRC extraction and from the contractor's laboratory ignition oven are concerning and indicate that the ignition oven method did not produce consistent results for some of these mixes. The contractor and UCPRC results for air-voids under gyratory compaction are also different, with the UCPRC results indicating that the mixes are generally within specification while the contractor's data show lower air-voids for three high RAP mixes.

Table 4.6: Volumetric Data (Averages of Both Sublots) from the UCPRC in Production

Parameter		3/4" NMAS											
		Control		High RAP Blend		High RAP Blend		High RAP Blend		High RAP Blend		Mainline Blend	
		0% RAP, 0% RAS		25% RAP, 0% RAS		30% RAP, 0% RAS		35% RAP, 0% RAS		40% RAP, 0% RAS		23% RAP, 0% RAS	
		Value	Limits	Value	Limits	Value	Limits	Value	Limits	Value	Limits	Value	Limits
Grading (% passing sieve)	1"	—	100	—	100	—	100	—	100	—	100	—	100
	3/4"	—	93-100	—	93-100	—	93-100	—	93-100	—	93-100	—	93-100
	1/2"	—	76-88	—	76-88	—	76-88	—	76-88	—	76-88	—	76-88
	3/8"	—	—	—	—	—	—	—	—	—	—	—	—
	#4	—	50-60	—	50-60	—	50-60	—	50-60	—	50-60	—	50-60
	#8	—	36-46	—	36-46	—	36-46	—	36-46	—	36-46	—	36-46
	#200	—	2-6	—	2-6	—	2-6	—	2-6	—	2-6	—	2-6
RAS content (% by weight of aggregate)		0	—	0	—	0	—	0	—	0	—	0	—
RAP content (% by weight of aggregate)		0	—	25	—	30	—	35	—	40	—	23	—
Base asphalt binder performance grade		64-28M ^a	—	58-34M	—	58-34M	—	58-34M	—	58-34M	—	58-34M	—
RA/LAS type		Morlife (LAS)	—	tall oil	—	tall oil	—	tall oil	—	tall oil	—	Morlife (LAS)	—
RA/LAS dosage (% by weight of binder)		0.5	—	2.7	—	3.8	—	5.8	—	8.3	—	0.5	—
Total binder content (% by weight of mix)		4.6	4.2-5.0	4.8	4.2-5.0	4.9	4.2-5.0	4.9	4.2-5.0	5.1	4.2-5.0	4.5	4.2-5.0
Recycled binder content (% binder in mix)		0	—	1.12	—	1.34	—	1.57	—	1.79	—	1.04	—
Estimated binder replacement excluding RA/LAS (% of total binder)		0	—	23.4	—	27.4	—	32.0	—	35.1	—	23.0	—
Estimated binder replacement including RA/LAS (% of total binder)		0.5	—	26.1	—	31.2	—	37.8	—	43.4	—	23.5	—
Number of gyrations (N _{design})		85	85	85	85	85	85	85	85	85	85	85	85

Parameter	3/4" NMAS											
	Control		High RAP Blend		High RAP Blend		High RAP Blend		High RAP Blend		Mainline Blend	
	0% RAP, 0% RAS		25% RAP, 0% RAS		30% RAP, 0% RAS		35% RAP, 0% RAS		40% RAP, 0% RAS		23% RAP, 0% RAS	
	Value	Limits	Value	Limits	Value	Limits	Value	Limits	Value	Limits	Value	Limits
Air-void content (%)	4.7	2.5-5.5	3.2	2.5-5.5	2.4	0.5-3.5	1.8	0.5-3.5	1.4	0.6-3.6	4.5	2.5-5.5
Voids in mineral aggregate (%)	—	12.5-15.5	—	12.5-15.5	—	12.5-15.5	—	12.5-15.5	—	12.5-15.5	—	12.5-15.5
Dust proportion	—	0.6-1.3	—	0.6-1.3	—	0.6-1.3	—	0.6-1.3	—	0.6-1.3	—	0.6-1.3
Hamburg (rut depth [in.] at # passes)	0.250	0.5	0.095	0.5	0.101	0.5	0.083	0.5	0.096	0.5	0.056	0.5
Moisture susceptibility, dry strength (psi)	—	—	—	—	—	—	—	—	—	—	—	—
Moisture susceptibility, wet strength (psi)	—	—	—	—	—	—	—	—	—	—	—	—

^a Control mix binder was specified as PG 64-28M but may have actually been PG 58-24M.

Notes: LAS: liquid antistrip; RA: recycling agent.

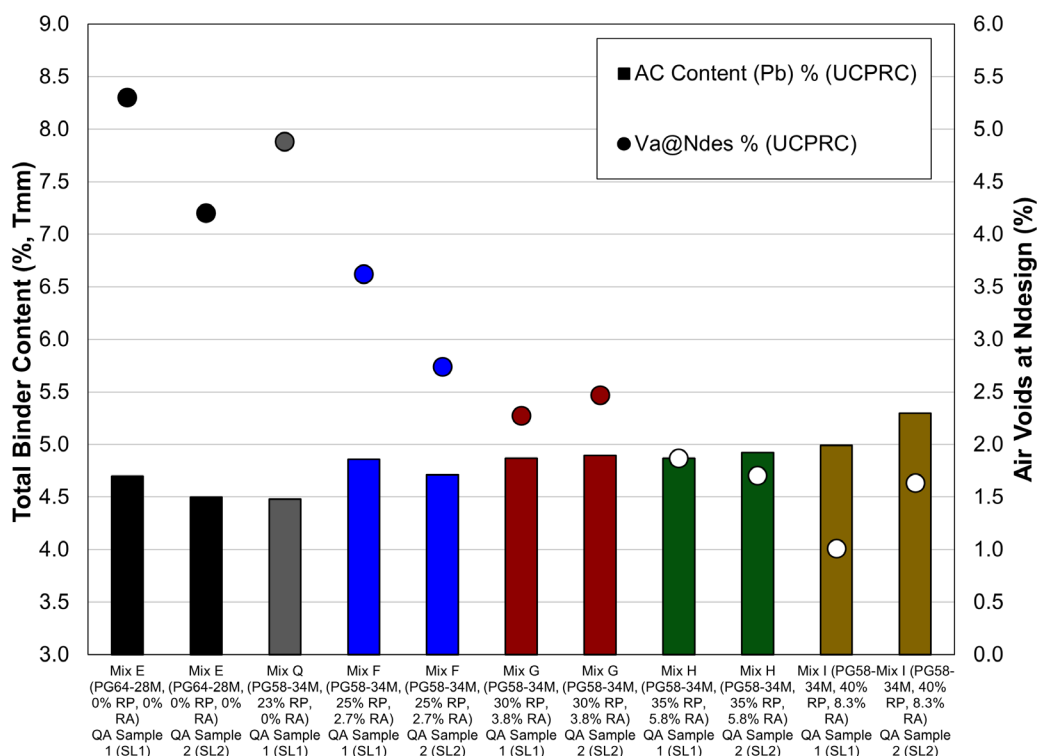
Table 4.7: Volumetric Data (Averages of Both Sublots) from Contractor in Production

Parameter		3/4" NMA											
		Control		High RAP Blend		High RAP Blend		High RAP Blend		High RAP Blend		Mainline	
		0% RAP, 0% RAS		25% RAP, 0% RAS		30% RAP, 0% RAS		35% RAP, 0% RAS		40% RAP, 0% RAS		23% RAP, 0% RAS	
		Value	Limits	Value	Limits	Value	Limits	Value	Limits	Value	Limits	Value	Limits
Grading (% passing sieve)	1"	100	100	100	100	100	100	100	100	100	100	—	—
	3/4"	99	93-100	99	93-100	98	93-100	98	93-100	99	93-100	—	—
	1/2"	83	76-88	84	76-88	81	76-88	80	76-88	82	76-88	—	—
	3/8"	74	—	74	—	71	—	70	—	71	—	—	—
	#4	56	50-60	55	50-60	51	50-60	43	50-60	44	50-60	—	—
	#8	41	36-46	35	36-46	31	36-46	29	36-46	31	36-46	—	—
	#200	4.8	2-6	4.1	2-6	4.3	2-6	4.4	2-6	5.0	2-6	—	—
Maximum specific gravity of mixture		2.517	—	2.495	—	2.480	—	2.472	—	2.479	—	—	—
RAP content (% by weight of aggregate)		64-28M ^a	—	25	—	30	—	35	—	40	—	—	—
Base asphalt binder performance grade		—	—	58-34M	—	58-34M	—	58-34M	—	58-34M	—	58-34M	—
RA type		0	—	tall oil	—	tall oil	—	tall oil	—	tall oil	—	—	—
RA dosage (% by weight of binder)		4.3	0	2.7	—	3.8	—	5.8	—	8.3	—	—	—
Binder content (% by weight of mix)		0	4.2-5.0	4.7	4.2-5.0	5.0	4.2-5.0	4.8	4.2-5.0	4.7	4.2-5.0	—	—
Recycled binder content (% binder in mix)		0	—	1.13	—	1.35	—	1.58	—	1.8	—	—	—
Estimated binder replacement excluding RA (% of total binder)		0	—	24.5	—	29.3	—	34.2	—	38.3	—	—	—
Estimated binder replacement including RA (% of total binder)		85	—	24.6	—	29.5	—	34.5	—	38.7	—	—	—
Number of gyrations (N _{design})		4.4	85	85	85	85	85	85	85	85	85	—	—
Air-void content (%)		13.4	2.5-5.5	3.1	2.5-5.5	1.3	0.5-3.5	0.6	0.5-3.5	0.6	0.6-3.6	—	—
Voids in mineral aggregate (%)		1.2	12.5-15.5	13.6	12.5-15.5	13.0	12.5-15.5	12.7	12.5-15.5	12.7	12.5-15.5	—	—

Parameter	3/4" NMA											
	Control		High RAP Blend		High RAP Blend		High RAP Blend		High RAP Blend		Mainline	
	0% RAP, 0% RAS		25% RAP, 0% RAS		30% RAP, 0% RAS		35% RAP, 0% RAS		40% RAP, 0% RAS		23% RAP, 0% RAS	
	Value	Limits	Value	Limits	Value	Limits	Value	Limits	Value	Limits	Value	Limits
Dust proportion	—	0.6-1.3	0.9	0.6-1.3	0.9	0.6-1.3	0.9	0.6-1.3	0.9	0.6-1.3	—	—
Hamburg (rut depth [in.] at # passes)	—	—	—	—	—	—	—	—	—	—	—	—
Moisture susceptibility, dry strength (psi)	—	—	—	—	—	—	—	—	—	—	—	—
Moisture susceptibility, wet strength (psi)	—	—	—	—	—	—	—	—	—	—	—	—

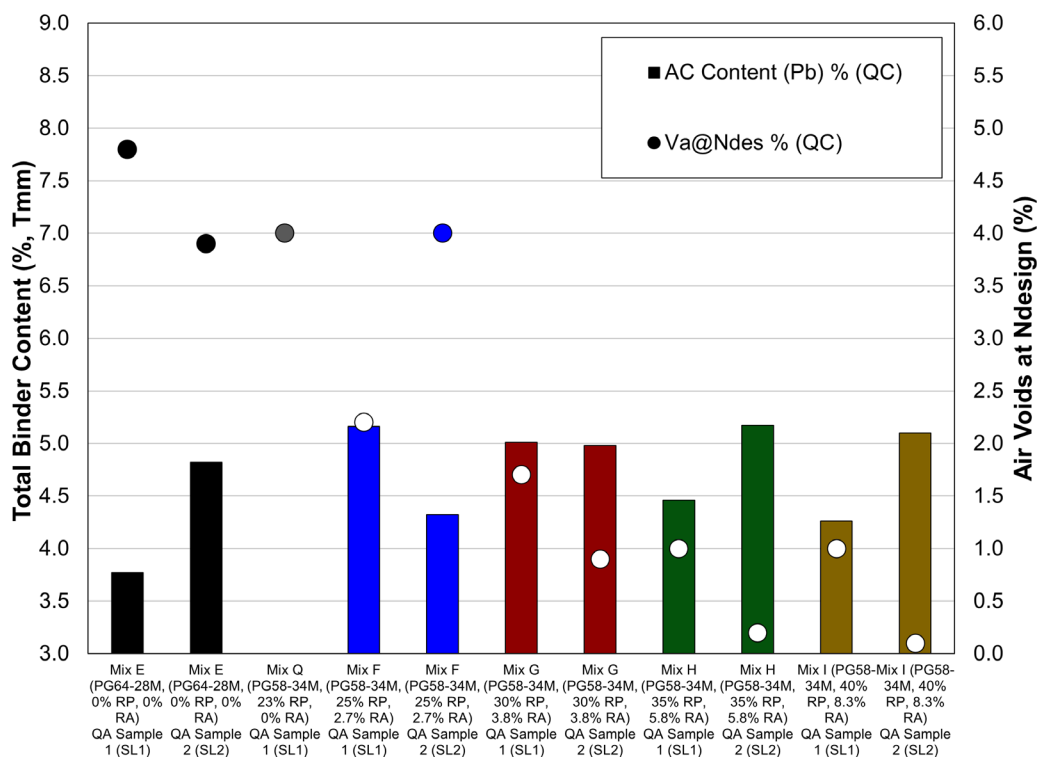
^a Control mix binder was specified as PG 64-28M but may have actually been PG 58-24M.

Note: RA: recycling agent.



Note: UCPRC results are for mix samples that were cooled, transported, and reheated for compaction. Contractor results are for mix samples that were not cooled and then reheated.

Figure 4.2: UCPRC volumetric test results for QA samples 1 and 2 (binder content and air-voids at 85 gyrations).



Note: UCPRC results are for mix samples that were cooled, transported, and reheated for compaction. Contractor results are for mix samples that were not cooled and then reheated.

Figure 4.3: Contractor volumetric test results for QA samples 1 and 2 (binder content and air-voids at 85 gyrations).

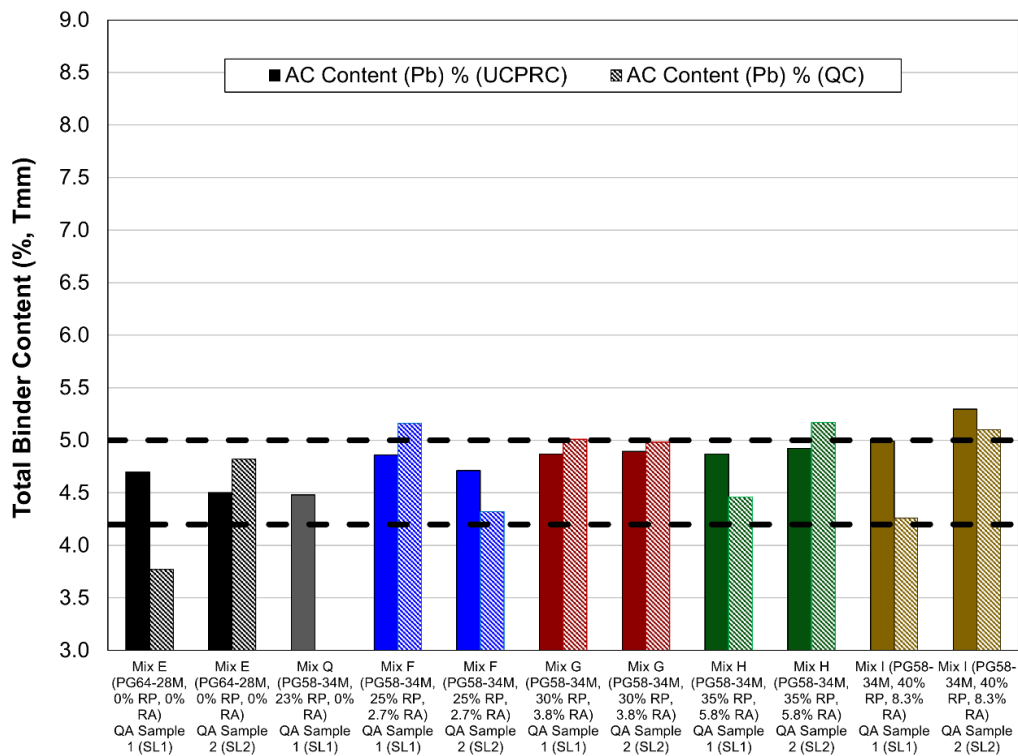


Figure 4.4: Comparison of UCPRC and contractor binder content results for QA samples 1 and 2.

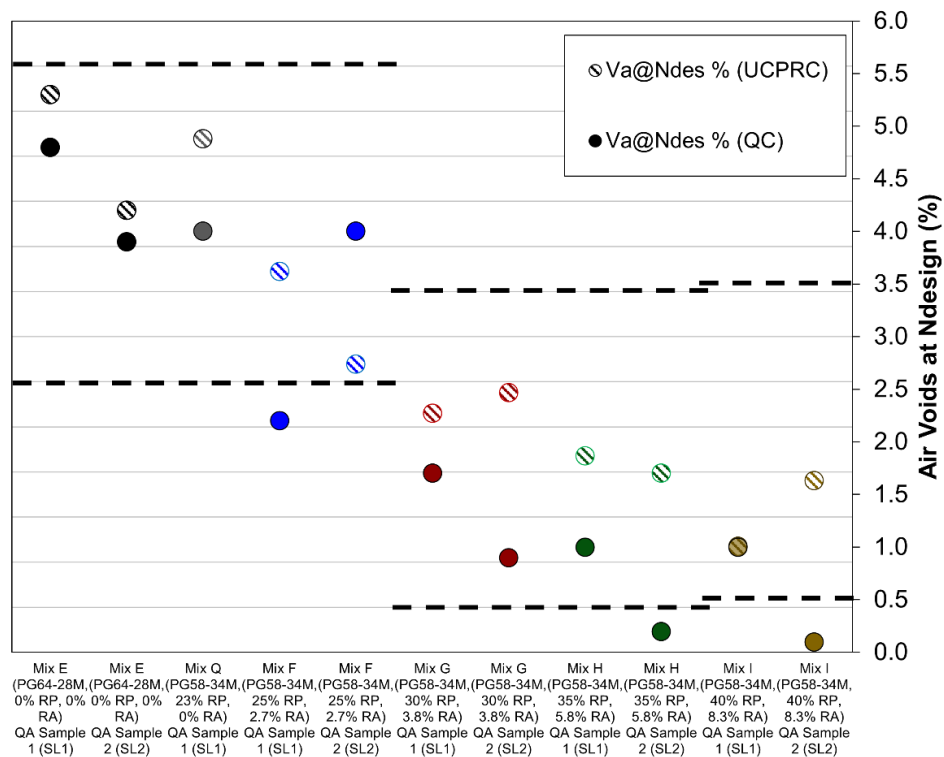


Figure 4.5: Comparison of UCPRC and contractor Ndes results for QA sample 1 and 2 (air-voids at 85 gyrations).

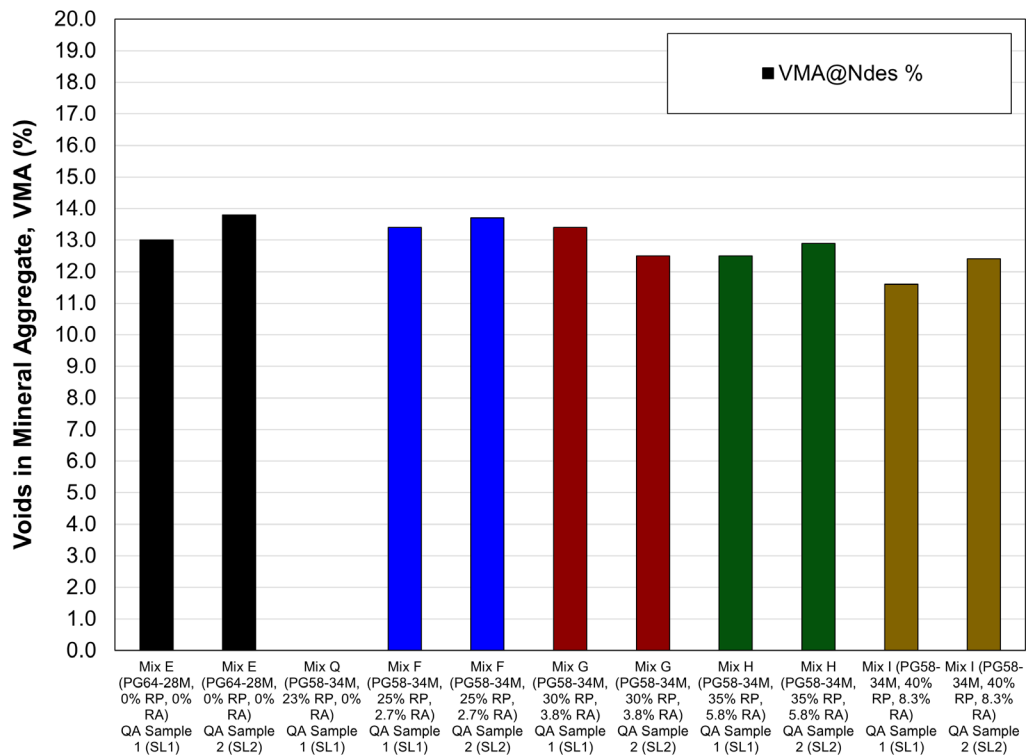


Figure 4.6: Contractor volumetric test results for QA samples 1 and 2 (voids in mineral aggregate at 85 gyrations).

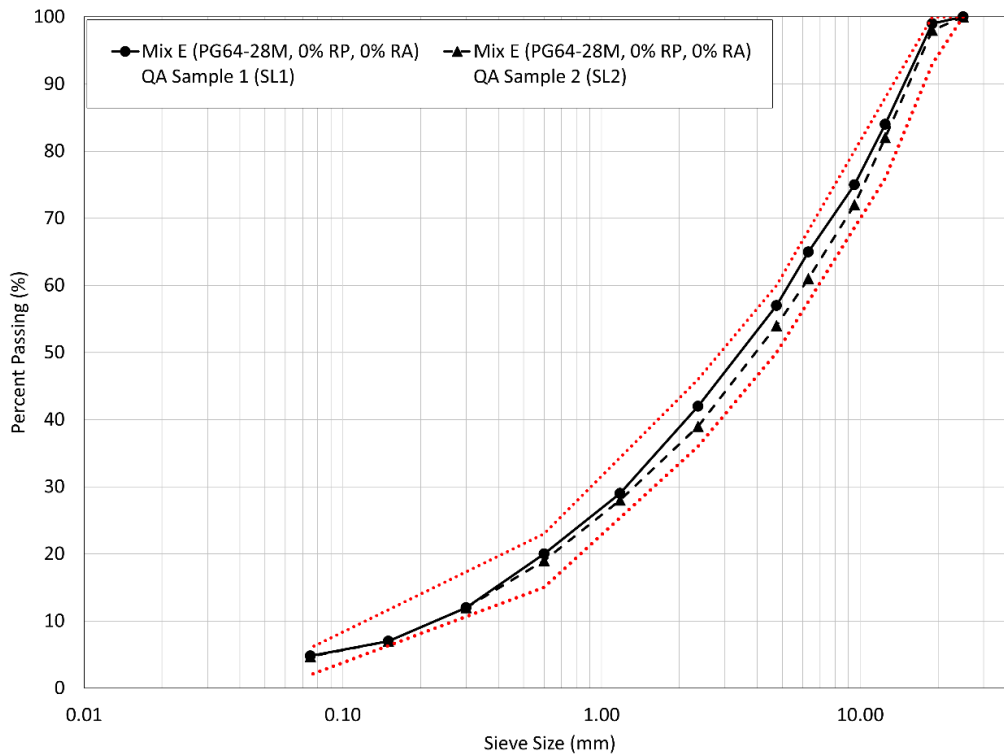


Figure 4.7: Contractor sieve analysis test QA samples 1 and 2 (percent passing for Mix E).

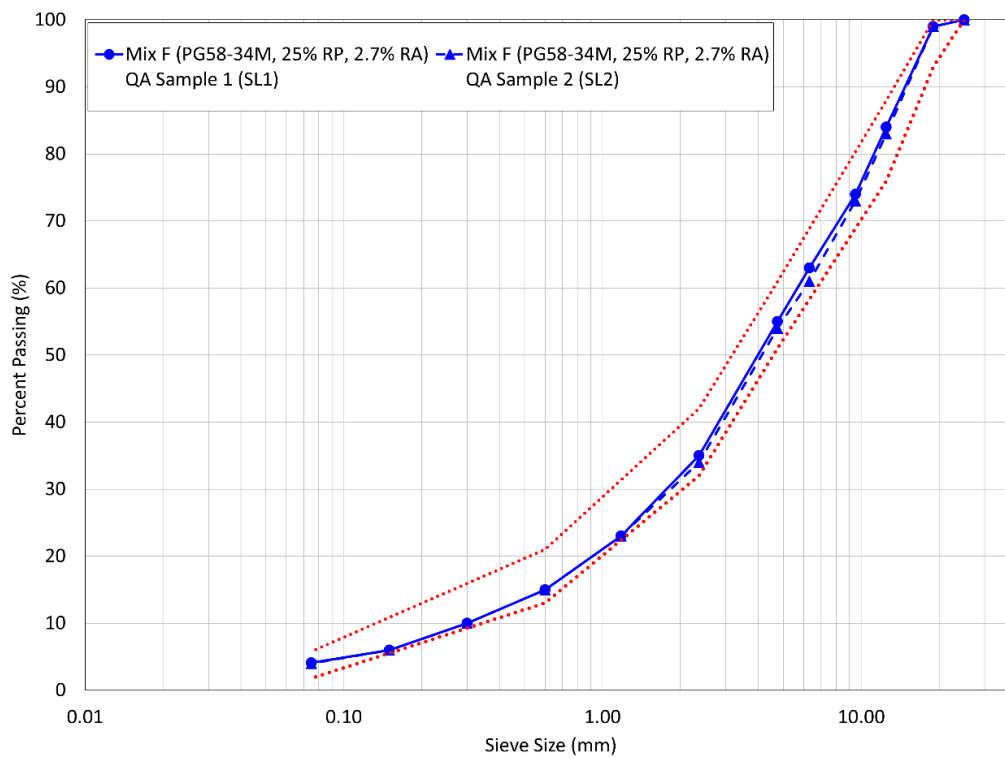


Figure 4.8: Contractor sieve analysis test QA samples 1 and 2 (percent passing for Mix F).

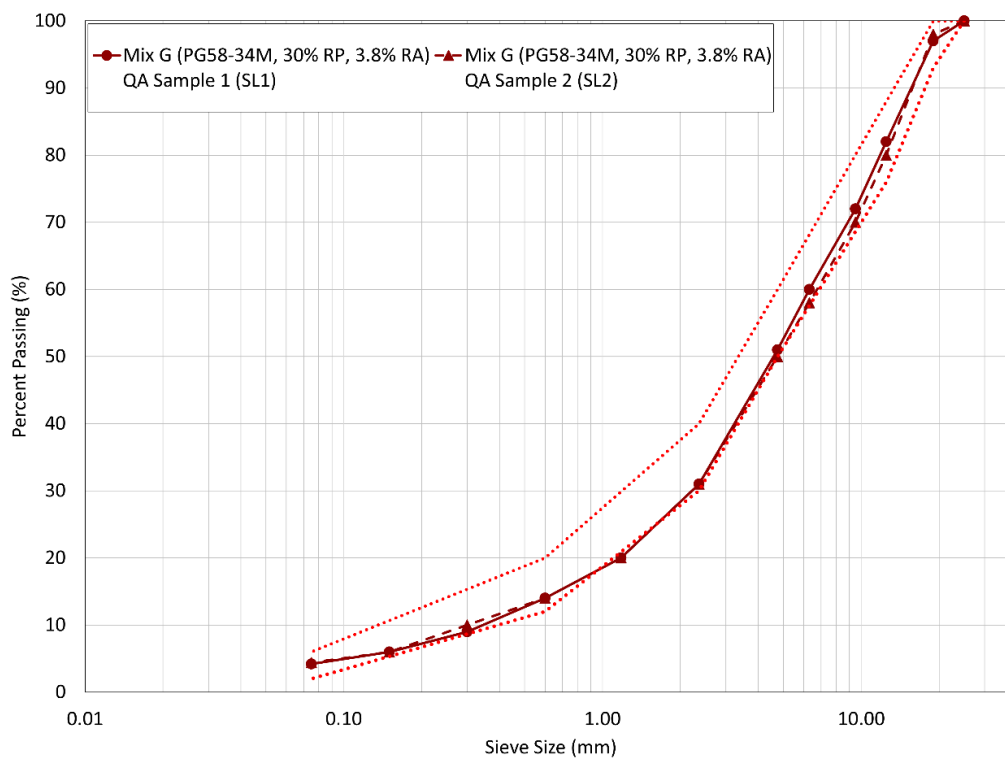


Figure 4.9: Contractor sieve analysis test QA samples 1 and 2 (percent passing for Mix G).

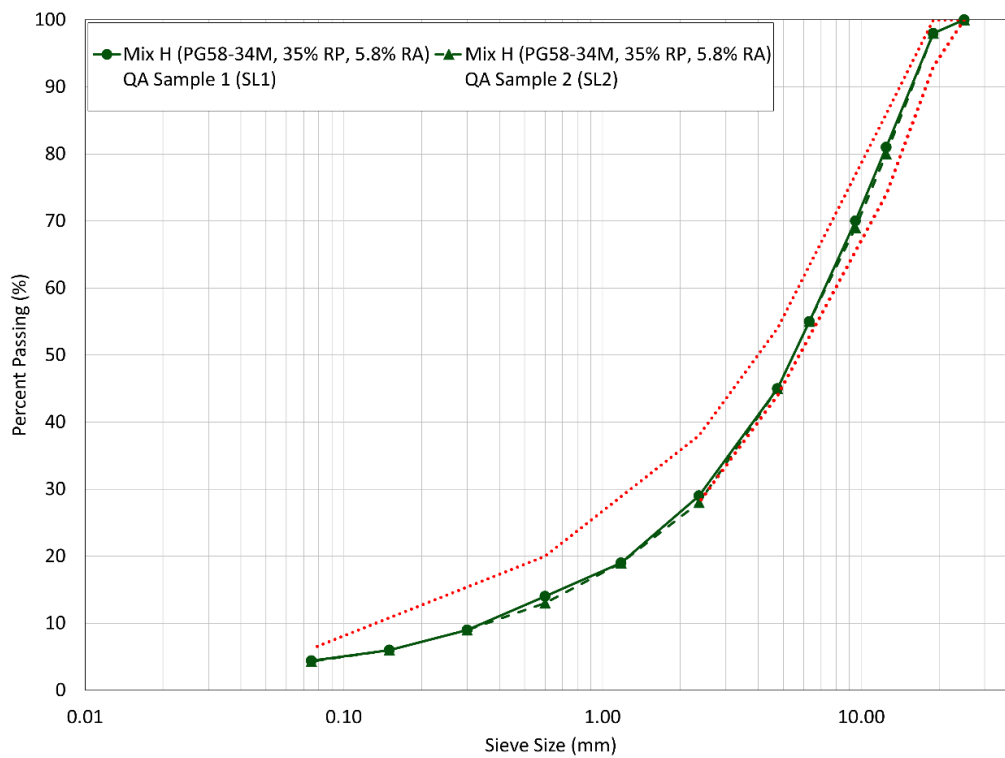


Figure 4.10: Contractor sieve analysis test QA samples 1 and 2 (percent passing for Mix H).

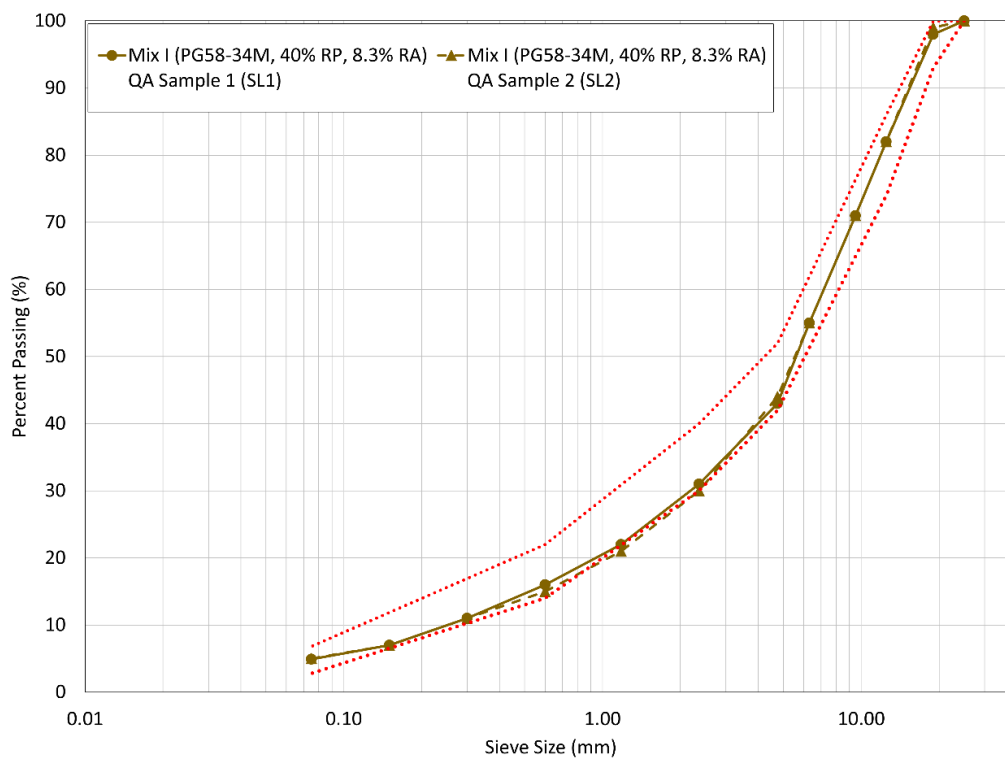


Figure 4.11: Contractor sieve analysis test QA samples 1 and 2 (percent passing for Mix I).

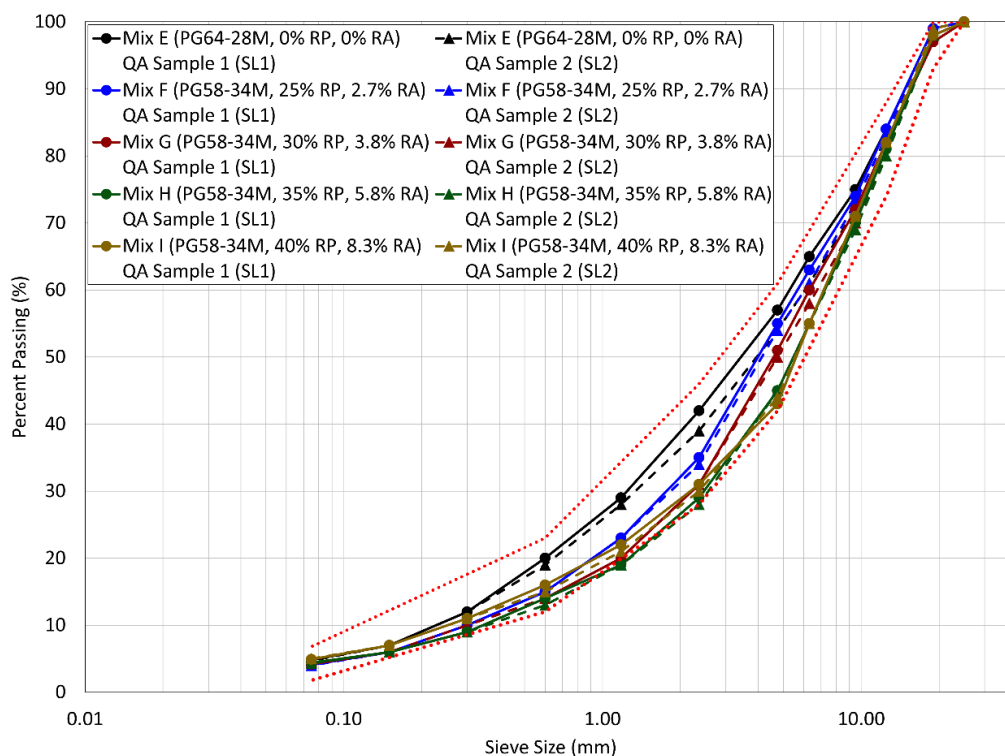
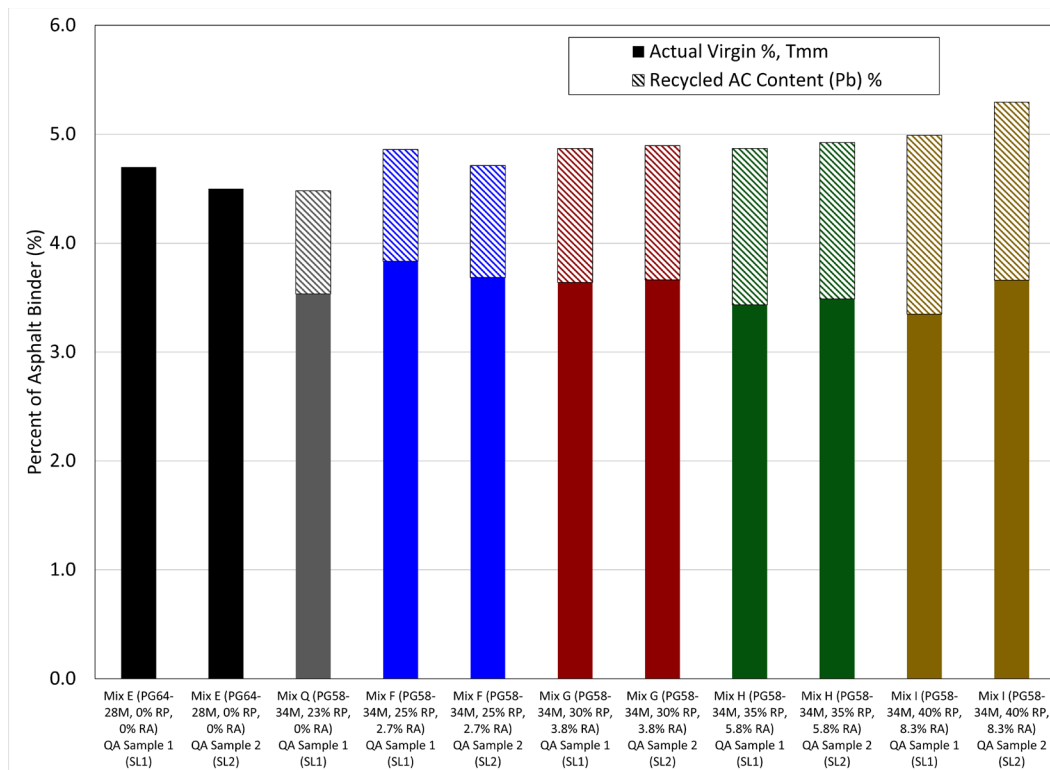


Figure 4.12: Contractor sieve analysis test QA samples 1 and 2 (percent passing for All Mixes).

4.4.2 Reclaimed Asphalt Pavement Recycled Binder Ratio

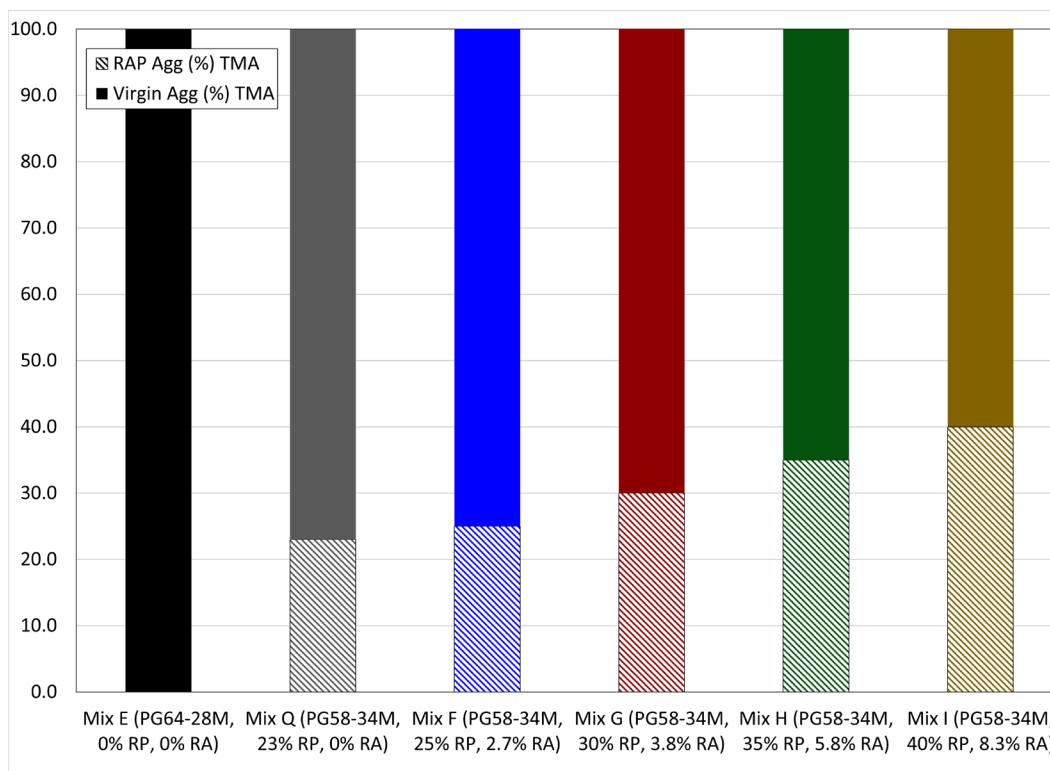
As described in Chapter 2, the RAP recycled binder ratio (RBR) is the percentage of the RAP binder content over total binder content. The total binder content consists of the RAP binder, the virgin binder, and the RA. The LAS additive is typically metered into the asphalt binder at the plant, but the nSSP for these pilot projects excludes it from consideration as part of the virgin binder and does not explicitly call for it to be included with the RA when calculating RBR. The RBR, as well as the percentage of RAP aggregates in the total mix, were shown in Table 2.4 for the JMF mix design calculated per the nSSP. The graphical representation of the percentages of virgin and RAP binder in the total binder for each QA subplot and the virgin and RAP aggregate in the total aggregate can be seen in Figure 4.13 and Figure 4.14, respectively. Figure 4.13 also shows the total binder content between the sublots from UCPRC binder extractions.

An alternative way to look at the binder is to consider the RA and LAS as part of the non-virgin binder portion of the total mix binder content and only the virgin binder as part of the virgin binder portion of the RBR, shown in Table 4.8. This way of looking at the total binder components is shown graphically in Figure 4.15. The table and figure show that an increasingly substantial part of the binder is RA as the RAP content increases. The RA dosage is determined based on meeting blended binder properties. The RA dosage will also depend on the stiffness of the RAP binder and some other chemical properties as well (also true when RAS are included in the mix). In addition to, or instead of, using RA to meet binder and mix properties, different PG grades of asphalt and/or different asphalt sources can also be used for the same purpose. The most effective solution can be engineered by the mix producer.



Note: Recycling agent (RA) is assumed to be part of virgin binder, and liquid antistrip is not counted.

Figure 4.13: Virgin and RAP asphalt binder percentages in the total binder of the mix designs following nSSP calculation.



Note: TMA: total mass of aggregate.

Figure 4.14: Virgin and RAP aggregate percentages in the total aggregate of the mix designs.

Table 4.8: Virgin and RAP Components of Mix Comparing nSSP Calculation of Recycled Binder Ratio with Alternative Calculation

Samples	Virgin Agg (% TMA)	RAP Agg. (% TMA)	AC Content (Pb, % TMM) (UCPRC result)	JMF Target AC Content (% TMM)	JMF Target Recycled AC Content (Pb, % TMM)	JMF Target RBR (% of binder) ^a	Actual RBR (% of binder per specification) ^a	LAS, RA (% of binder)	Actual RBR (% of binder alternative calculation) ^b
Mix E (PG 64-28M, 0% RP, 0% RA)/QA Sample 1 (SL1)	100.0	0	4.70	4.60	0.00	0%	0	0.5, 0.0	0.5
Mix E (PG 64-28M, 0% RP, 0% RA)/QA Sample 2 (SL2)	100.0	0	4.50	4.60	0.00	0%	0	0.5, 0.0	0.5
Mix Q (PG 58-34M, 23% RP, 0% RA)/QA Sample 1 (SL1)	77.0	23.0	4.48	4.60	0.95	20.7	21.2	0.5, 0.0	21.7
Mix F (PG 58-34M, 25% RP, 2.7% RA)/QA Sample 1 (SL1)	75.0	25.0	4.86	4.60	1.03	22.4	21.1	0.0, 2.7	23.8
Mix F (PG 58-34M, 25% RP, 2.7% RA)/QA Sample 2 (SL2)	75.0	25.0	4.71	4.60	1.03	22.4	21.8	0.0, 2.7	24.5
Mix G (PG 58-34M, 30% RP, 3.8% RA)/QA Sample 1 (SL1)	70.0	30.0	4.87	4.60	1.24	27.0	25.3	0.0, 3.8	29.1
Mix G (PG 58-34M, 30% RP, 3.8% RA)/QA Sample 2 (SL2)	70.0	30.0	4.89	4.60	1.24	27.0	25.2	0.0, 3.8	29.0
Mix H (PG 58-34M, 35% RP, 5.8% RA)/QA Sample 1 (SL1)	65.0	35.0	4.87	4.60	1.44	31.3	29.5	0.0, 5.8	35.3
Mix H (PG 58-34M, 35% RP, 5.8% RA)/QA Sample 2 (SL2)	65.0	35.0	4.92	4.60	1.44	31.3	29.2	0.0, 5.8	35.0
Mix I (PG 58-34M, 40% RP, 8.3% RA)/QA Sample 1 (SL1)	60.0	40.0	4.99	4.70	1.65	35.1	32.9	0.0, 8.3	41.2
Mix I (PG 58-34M, 40% RP, 8.3% RA)/QA Sample 2 (SL2)	60.0	40.0	5.30	4.70	1.65	35.1	30.9	0.0, 8.3	39.2

^a RA counted as part of virgin binder, and LAS not considered part of binder per nSSP.

^b RA and LAS counted as non-virgin part of total binder.

Notes: LAS: liquid antistrip; RA: recycling agent

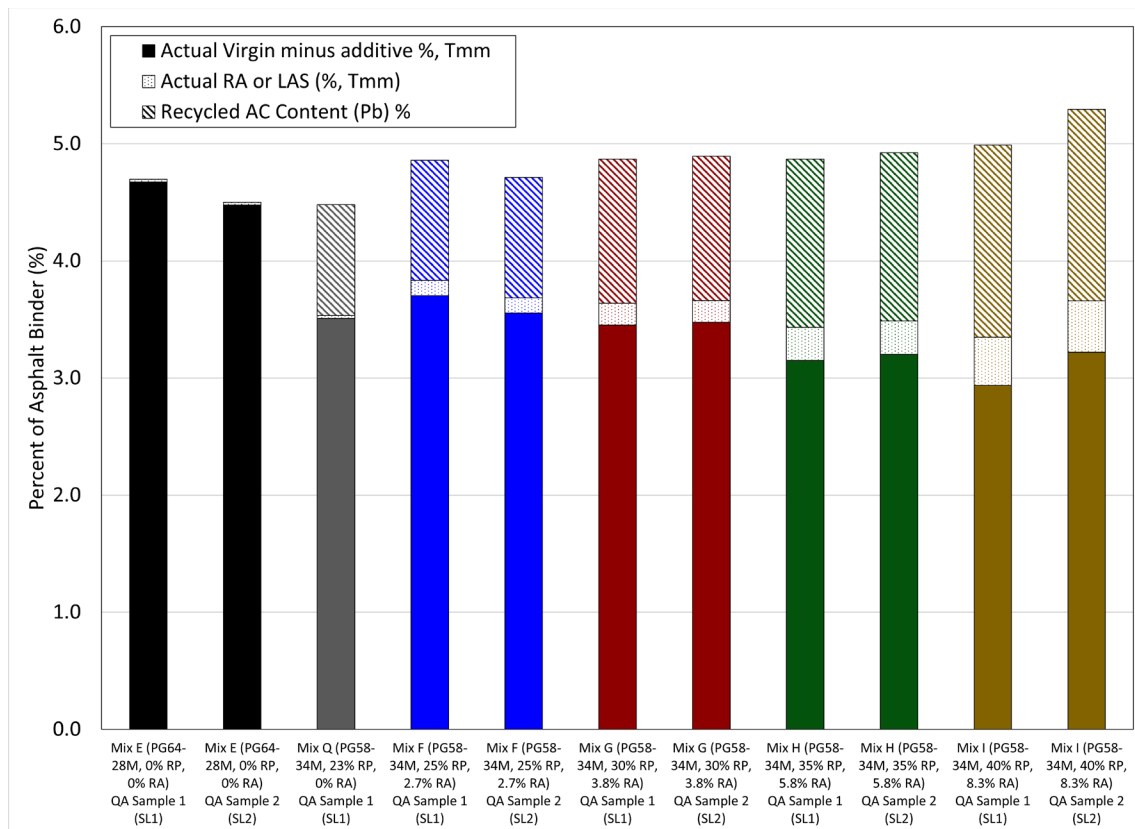


Figure 4.15: Virgin and RAP asphalt binder percentages in the total binder of the mix designs considering RA and LAS.

4.4.3 Mix Stiffness: Triaxial and Flexural Dynamic Modulus

Dynamic modulus (mix stiffness) testing was only performed on the samples from subplot 1 of the two QA samples.

Flexural Dynamic Modulus Frequency Sweep Results

The flexural dynamic modulus master curves from the QA sample testing for all the mixes in the pilot test sections and the mainline mix are shown in Figure 4.16. The results show that the stiffnesses of mixes containing different percentages of RAP between 25% and 40% and RA, along with the mainline mix with 23% RAP and no RA, group together, while the stiffness of the control mix (Mix E) with no RAP is considerably softer. The results match those of the extracted binder stiffness master curves, shown in Figure 3.18, except that the binder stiffness of Mix I with 40% RAP was stiffer than the other mixes with RAP including the mainline mix, while the mix stiffness is similar to the other mixes.

The relative stiffnesses are shown normalized to the first QA sample for the control mix with no RAP (Mix E) in Figure 4.17 and normalized to the mainline mix (Mix Q) with 23% RAP and no RA in Figure 4.18. The results normalized to the control mix show that all the mixes were 2 to 3.5 times stiffer than the control mix at intermediate frequencies. Intermediate frequencies correspond to intermediate temperatures as well. The low stiffnesses of the control mix relative to all the other mixes seen in the QA samples taken during construction is again an indication that what was supposed

to have been a PG64-28M binder may have been mistakenly replaced with the PG58-34M binder used in all the other mixes. The results shown in Figure 4.18 that are normalized to the mainline mix show that all the RAP mixes with RA are about 20% softer than the mainline mix. The mixes with 30%, 35%, and 40% RAP are closest to the mainline mix, while the mix with 25% RAP with 2.7% RA is up to 40% softer than the mainline mix, which has almost the same RAP content (23%) but no RA. Figure 4.19 shows the Black Space diagram for the QA samples for all of the mixes. There is considerable overlap for all the mixes, except for the control mix (Mix E), which has higher phase angles.

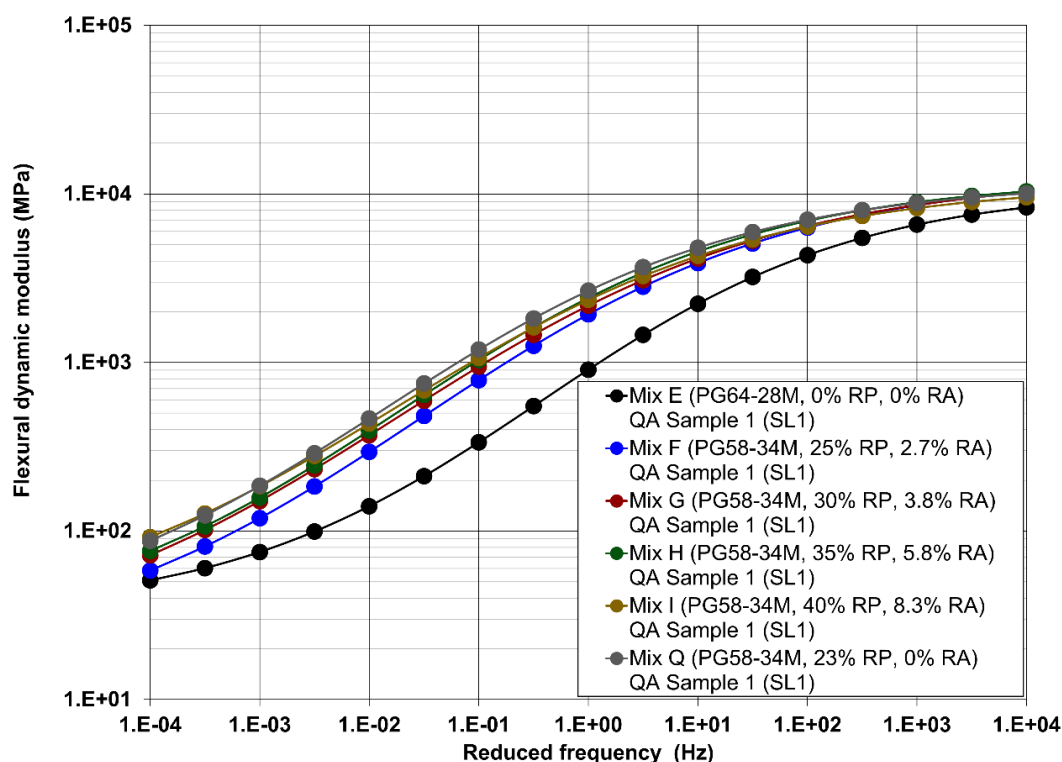


Figure 4.16: Flexural dynamic modulus master curves for QA sampled mixes.

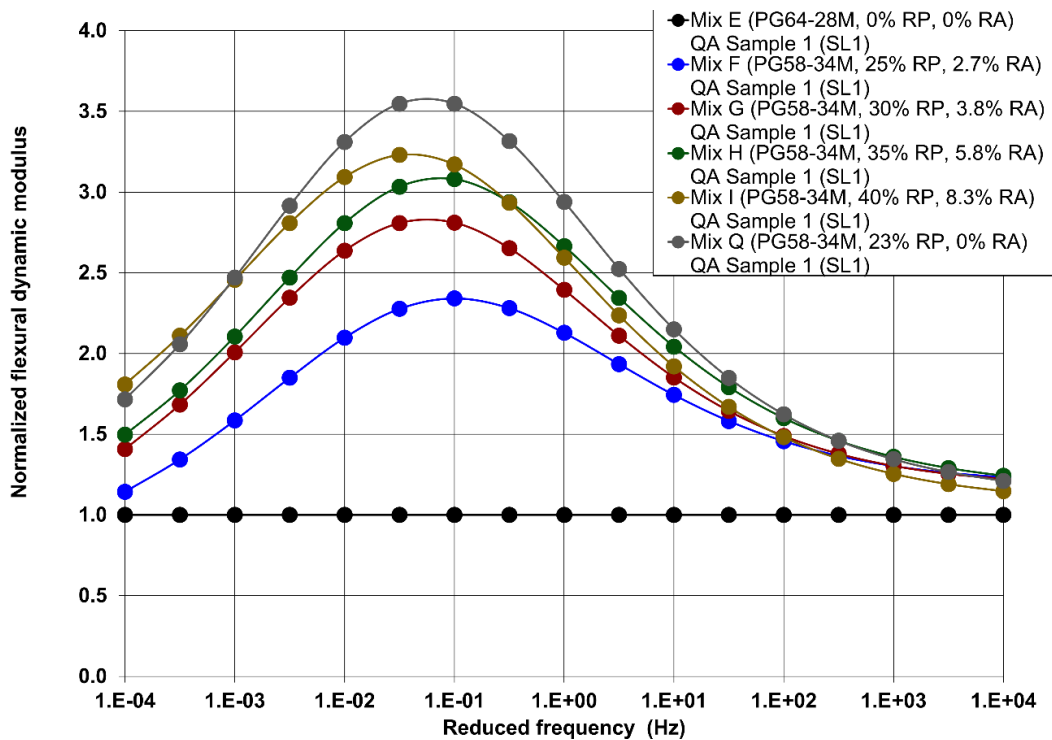


Figure 4.17: Flexural dynamic modulus master curves for QA sampled mixes normalized to the control mix with 0% RAP (Mix E).

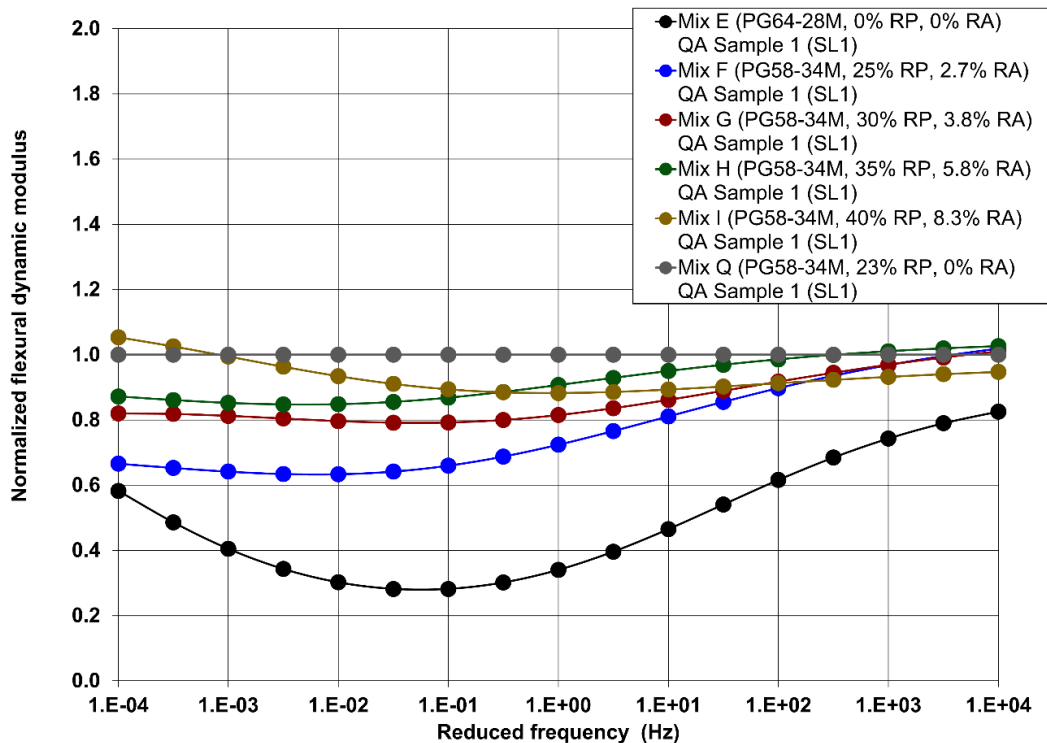


Figure 4.18: Flexural dynamic modulus master curves for QA sampled mixes normalized to the mainline mix with 23% RAP (Mix Q).

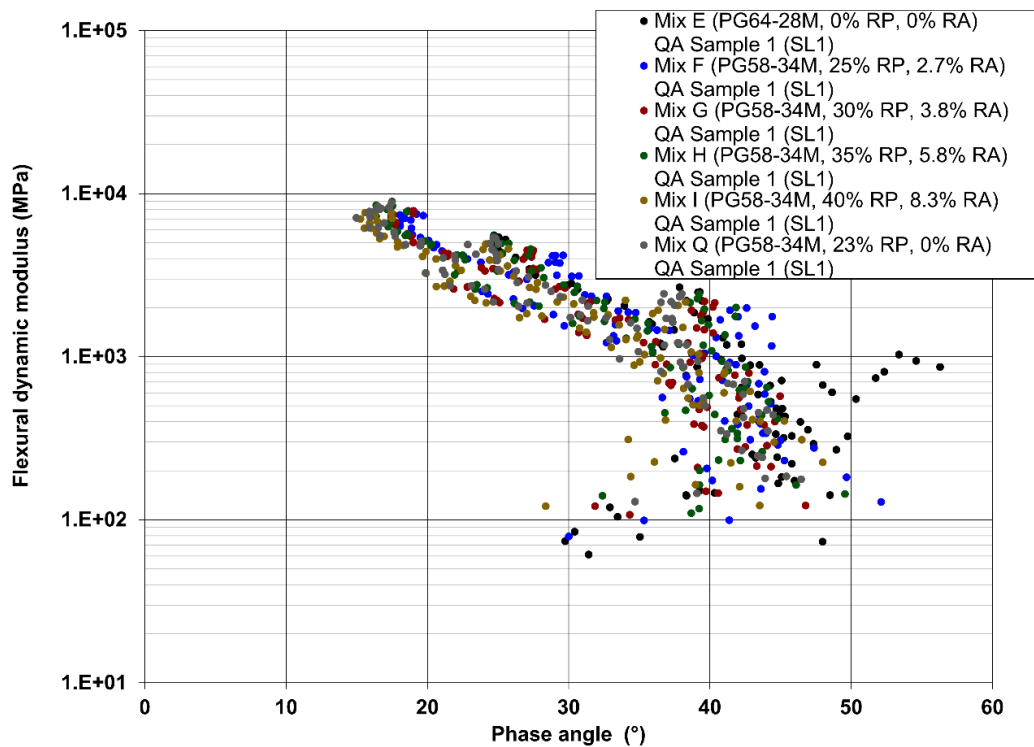


Figure 4.19: Black Space diagram for flexural dynamic modulus master curves for QA sampled mixes.

Triaxial Dynamic Modulus Frequency Sweep Results

Figure 4.20 shows the triaxial master mix stiffness curves for the QA samples for all mixes. The master curves are nearly identical, except for the control mix (Mix E), which likely had a wrong binder grade. This can also be seen in Figure 4.21 when the stiffnesses are normalized to the control mix and in Figure 4.22 when they are normalized to the mainline mix (Mix Q) with 23% RAP and no RA. The Black Space diagram for the mixes is shown in Figure 4.23. The results are generally consistent with those from the flexural frequency sweeps, as expected, except that the control mix does not exhibit phase angles that are much different from the other mixes, although the stiffnesses are lower.

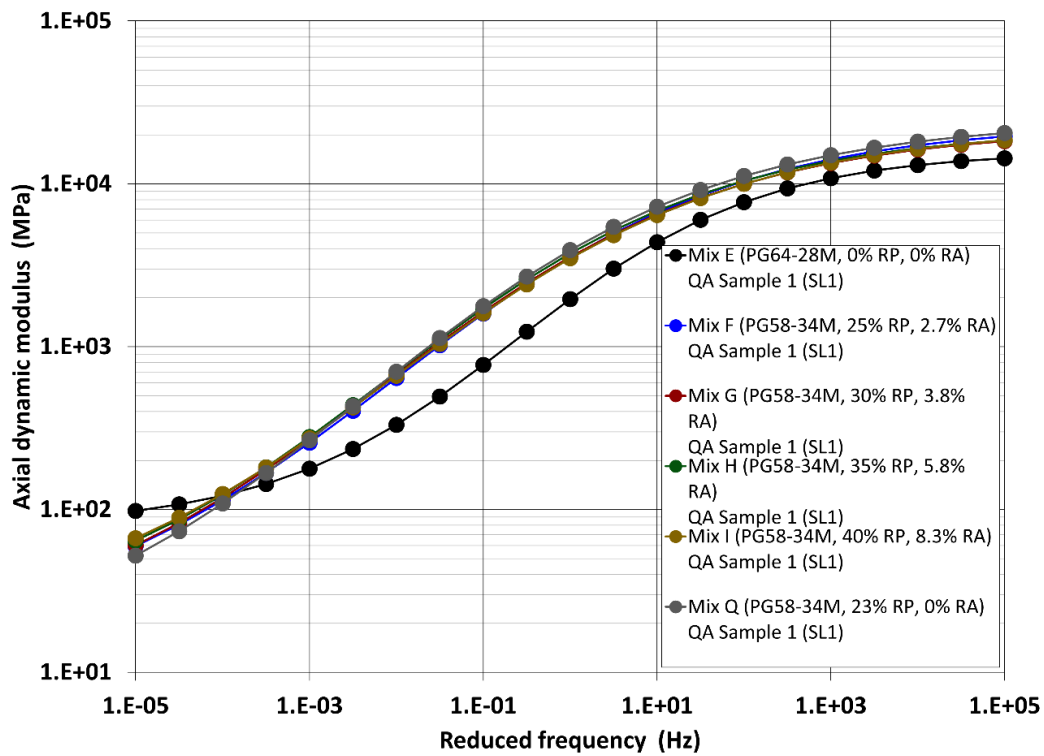


Figure 4.20: Axial dynamic modulus master curves for QA sampled mixes.

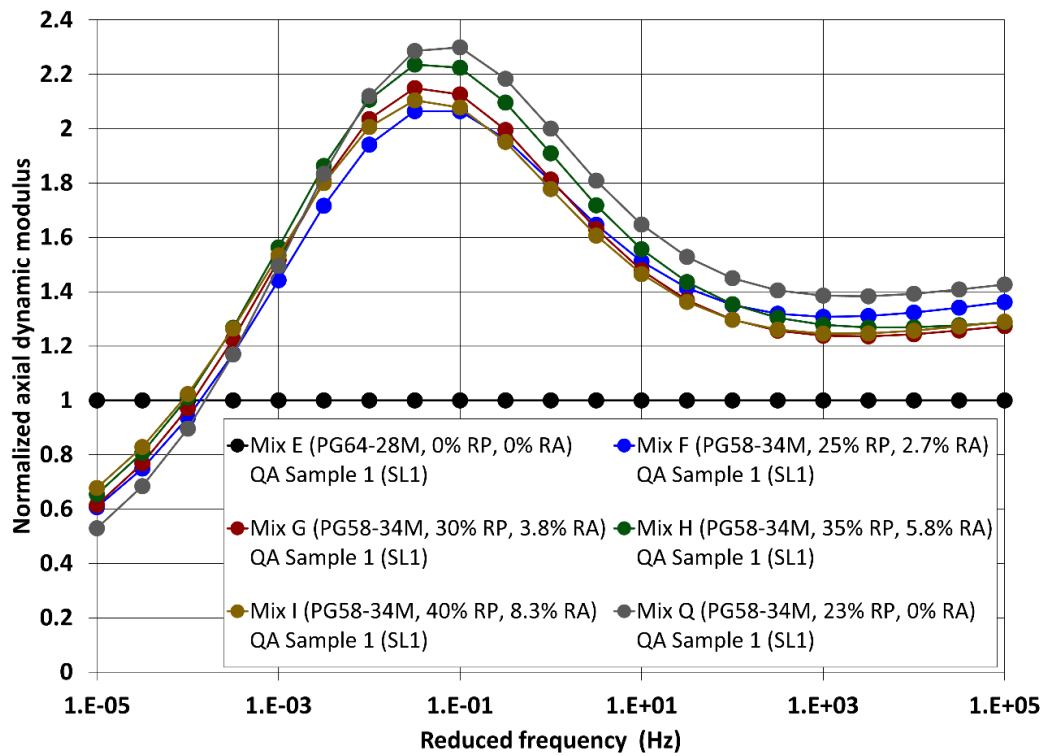


Figure 4.21: Axial dynamic modulus master curves for QA sampled mixes normalized to Mix E (0% RAP).

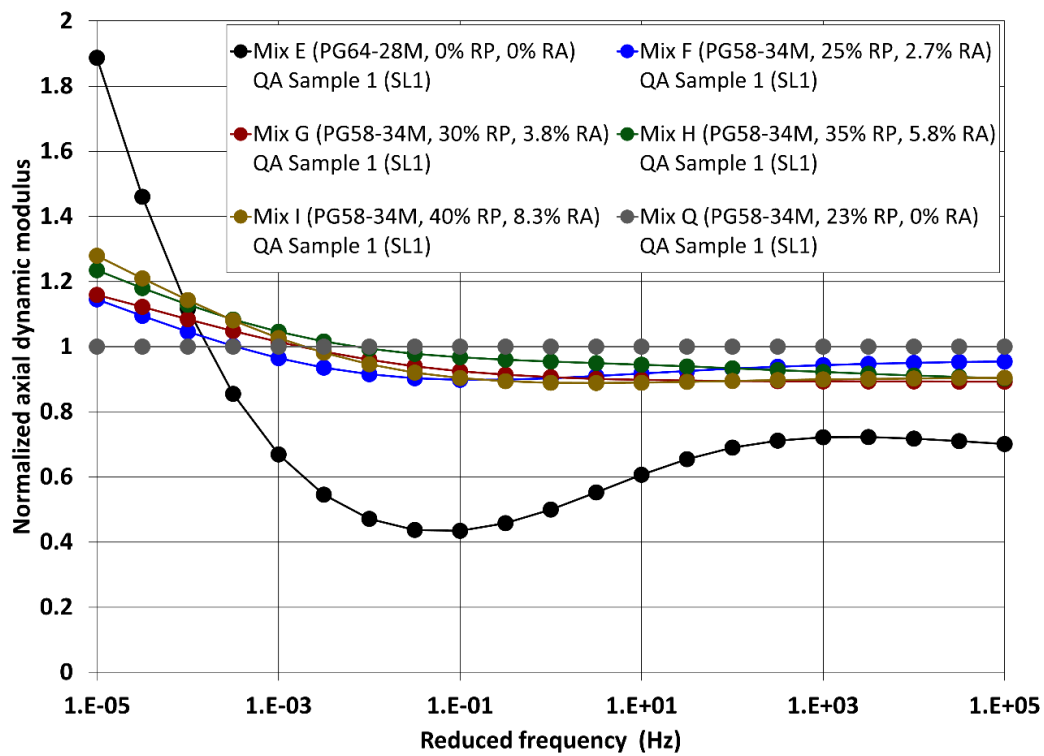


Figure 4.22: Triaxial dynamic modulus master curves for QA sampled mixes normalized to Mix Q (23% RAP).

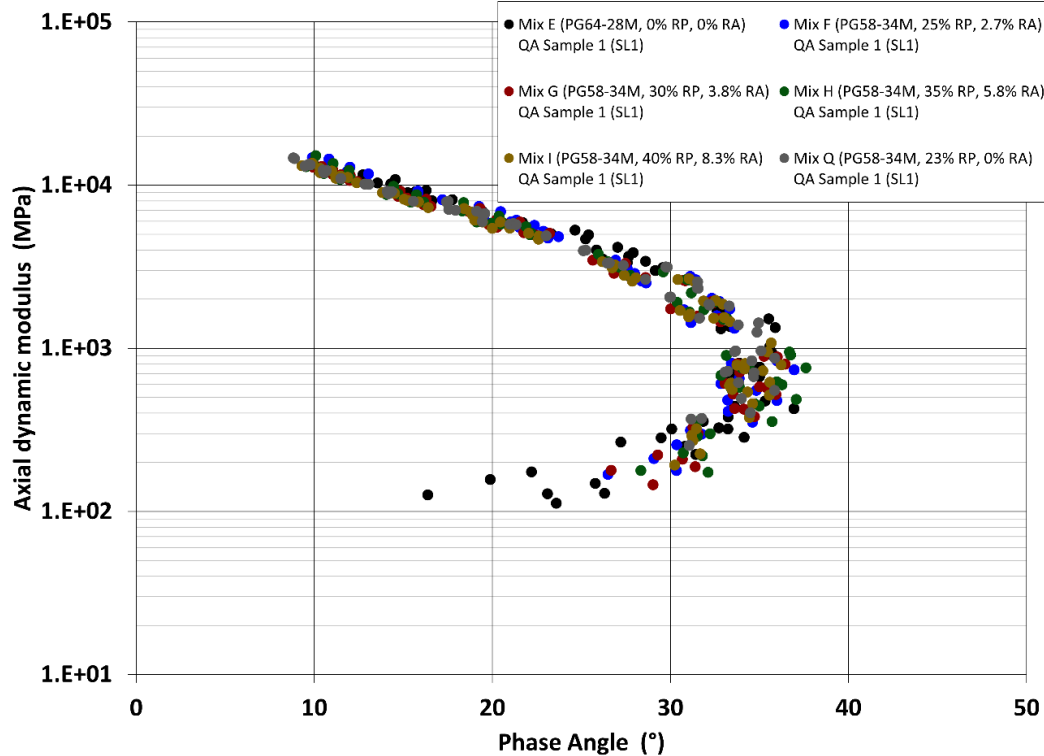


Figure 4.23: Black Space diagram for triaxial dynamic modulus master curves for QA sampled mixes.

4.4.4 Qualitative Assessment of Binder Blending from Comparison Binder and Mix Stiffness Rankings

As noted in the problem statements, the amount of blending of the virgin binder, the RAP and/or RAS binder, and the RA is an important question. The amount of blending is expected to increase as a function of time at elevated temperatures during mixing and silo storage. If there is insufficient blending, the use of RAs and softer virgin binders may result in a mix that is prone to rutting and has insufficient binder content for fatigue and fracture resistance. Binder extraction and testing results in complete blending of the three binder components. Mix testing produces results that reflect the actual amount of blending that has occurred after mixing, sampling, reheating, and also laboratory aging, if it is included in the specimen preparation. Mix testing results are also subject to the variable influences of aggregates at different temperatures and frequencies of loading, with less aggregate influence at low temperatures and high frequencies.

A qualitative assessment of the degree of binder blending can be made through comparison of binder stiffness testing rankings with mix stiffness testing rankings. If the rankings are similar, it is an indication that there are no major differences in binder blending. Comparisons of the rankings of binder and mix stiffness results at three frequencies at the reference temperature (20°C) are shown in Table 4.9. The rankings are based on the data in Figure 3.18, Figure 4.16, and Figure 4.22. The effects of aggregate on stiffness are generally least at low temperatures and high frequencies. However, because of the different temperature susceptibilities of virgin and blended binders, assessment of blending only at those conditions may not give a complete picture. The differences in mix stiffness were greatest at intermediate and high frequencies and smaller at low frequencies.

Table 4.9: Ranking of Extracted Binder and Mix Stiffnesses from Quality Assurance Testing

QA Binder Testing (continuous grade temperature ranking [stiffest to softest])	Mix Testing Reduced (frequency [Hz] at 20°C)	QA Mix Testing Flexural Stiffness Ranking (stiffest to softest)	QA Mix Testing Triaxial Stiffness Ranking (stiffest to softest)
Low temperature: I (stiffest) F, G, H, Q (similar) E (softest)	10^4 Mix stiffness differences small	Low temperature: F, G, H, Q (stiffest) I E (softest)	Low temperature: Q (stiffest) F H I, G (similar) E (softest)
Intermediate temperature: I (stiffest) F, G, H, Q (similar) E (softest)	10	Intermediate temperature Q (stiffest) H I G F E (softest)	Intermediate temperature Q (stiffest) H, F, G, I (similar) E (softest)
High temperature: I (stiffest) F, H (similar) G, Q (similar) E (softest)	10^{-2} Mix stiffness differences large	High temperature Q (stiffest) I H G F E (softest)	High temperature Q, H (stiffest) G, I (similar) F E (softest)

Notes: Mix E (0% RAP, 0% RAS), Mix F (25% RAP, 0% RAS), Mix G (30% RAP, 0% RAS), Mix H (35% RAP, 0% RAS), Mix I (40% RAP, 0% RAS, Mix Q (23% RAP,)% RAS). The two QA samples for Mix A tested for flexural dynamic modulus had different results.

All the results show the control (Mix E) as the softest. The binder results at low temperatures (high frequencies) show the mix with 40% RAP (Mix I) to be the stiffest, while the mix results show Mixes Q, F, and H to generally be stiffer than Mix I. This suggests that the RAP binder did not completely blend in Mix I as it did in the extracted binder. The binder results at intermediate temperatures show Mix I to be the stiffest again, while the mainline mix (Mix Q) is stiffer in the mix tests, again indicating less than complete blending of the 40% RAP in the mix. The same difference in rankings occurs at high temperatures (low frequency), leading to the same conclusion.

4.4.5 Rutting Resistance: Repeated Load Triaxial Test (Unconfined and Confined)

RLT test results in terms of flow number (load cycles at which third-stage permanent deformation occurs) and the permanent deformation at the flow number are shown at 45°C (113°F) for the unconfined condition in Figure 4.24 and for the confined condition in Figure 4.25. The unconfined results show “flow” occurring at fewer load cycles and smaller permanent deformations, as expected. The rankings of the mixes for the unconfined and confined conditions are similar, with the control mix that was supposed to have had a PG 64-28M binder but likely mistakenly had the PG 58-34M binder, showing the worst performance, particularly for the unconfined condition. The rest of the mixes had an approximately similar flow number performance. The

mix with 25% RAP and RA (Mix F) and the mainline mix with 25% RAP and no RA (Mix Q) had flow occur at low permanent strains, indicating loss of internal cohesion after less deformation.

The RLT flow number and permanent deformation at flow number are shown at 55°C (131°F) for the unconfined and confined conditions in Figure 4.26 and Figure 4.27, respectively. The rankings for flow number and permanent deformation at the flow number for the unconfined condition at 55°C are similar to those at 45°C. For the confined condition, which is more representative of field rutting behavior than the unconfined condition, the mixes with 35% and 40% RAP and RA (Mix H and Mix I) had the poorest performance, while the other four mixes were more similar and had better performance. It is not known why those two mixes had poorer performance since all the mixes had the same aggregate source and gradation, and at lower frequencies and higher temperatures, all the mixes with RAP had similar triaxial stiffnesses, shown in Figure 4.20 and Figure 4.21. The fully blended binder tests also indicated that Mix I, in particular, and Mix H were stiffer than most of the other binders, shown in Figure 3.18 and Figure 3.19. A possible clue as to why these mixes had poorer flow number performance may be seen in Table 4.9, where the assessment was that the RAP and RA may not have been fully blended with the virgin binder in Mix I and to a lesser degree in Mix H, which might result in these mixes being softer at high temperatures and slower frequencies.

Unconfined RLT flow number and permanent deformation at flow number results at 50°C (122°F) are shown in Figure 4.28 for the first subplot QA samples and in Figure 4.29 for the second subplot QA samples, which did not include the mainline mix with 25% RAP and no RA (Mix Q). The results at 50°C show rankings between those at 45°C and 55°C, as expected, and show very similar results between the two sublots, indicating consistency of the material across each test section.

RLT tests were run up to 20,000 cycles and were stopped either at that number of cycles or when permanent deformation had reached 5% permanent strain. Figure 4.30 through Figure 4.32 are for the first QA sample materials. Figure 4.30 and Figure 4.31 show the 45°C unconfined and confined repetitions, respectively, to 3% permanent axial strain or the permanent axial strain at 20,000 load cycles if 3% permanent strain was not reached. Figure 4.32 and Figure 4.33 show the same results at 55°C. Figure 4.34 and Figure 4.35 show the same results for the unconfined condition at 50°C for the first and second QA sublots, respectively. The cycles to 3% permanent strain at 45°C indicate that the control mix (Mix E), which likely had a softer binder than specified, had the worst unconfined performance. The mix with 40% RAP and RA (Mix I), which may not have had complete RAP binder blending, had the worst confined performance for permanent strain at the flow number, although the cycles to the flow number were similar for all of the mixes. The cycles to 3% permanent strain at 55°C indicate that the control mix (Mix E) had the worst unconfined performance, while the mix with 35% RAP and RA (Mix H) and Mix I had the worst confined performance. The unconfined results at 50°C for the two QA sublots have generally similar results, indicating uniformity of the mix within each test section.

Figure 4.36 through Figure 4.41 show permanent axial strain versus load cycles for the same sequence of unconfined and confined results at 45°C and 55°C for the first QA subplot, followed by the unconfined results at 50°C from both QA sublots. Rutting in the field generally shows a pattern of high initial rutting followed by a transition to a slower rate of permanent strain. The results show that unconfined RLT results do not show the same shape as field rutting, while the confined RLT results do have this pattern.

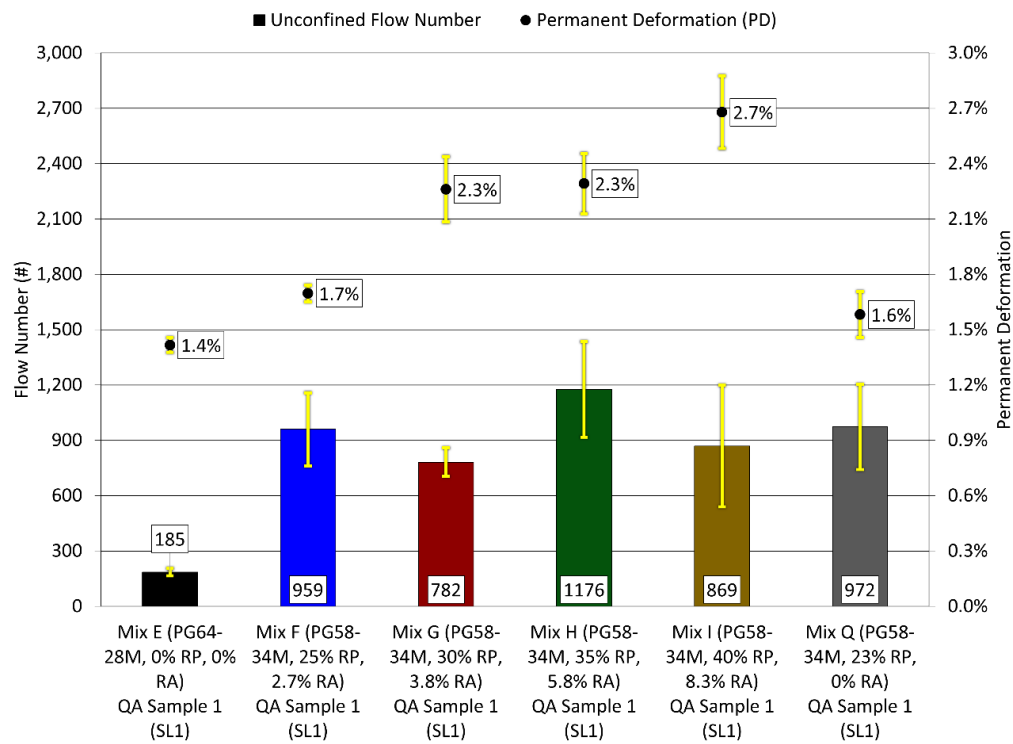


Figure 4.24: Unconfined repeated load triaxial results for QA subplot 1 sampled mixes at 45°C (load cycles and permanent deformation at flow number).

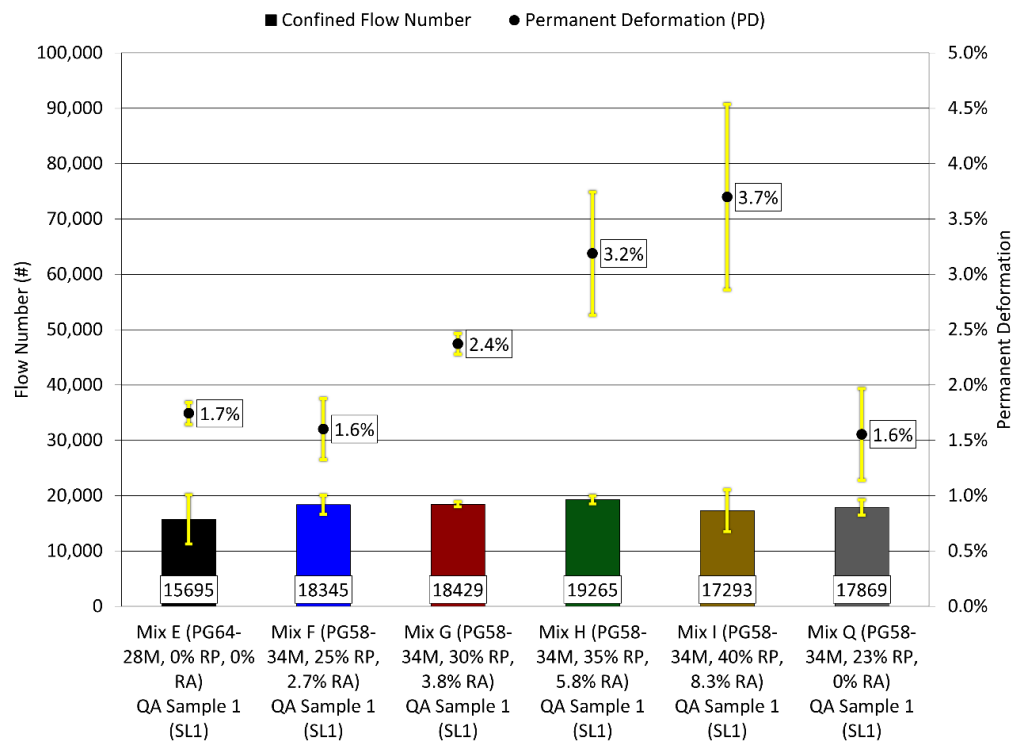


Figure 4.25: Confined repeated load triaxial results for QA subplot 1 sampled mixes at 45°C (load cycles and permanent deformation at flow number).

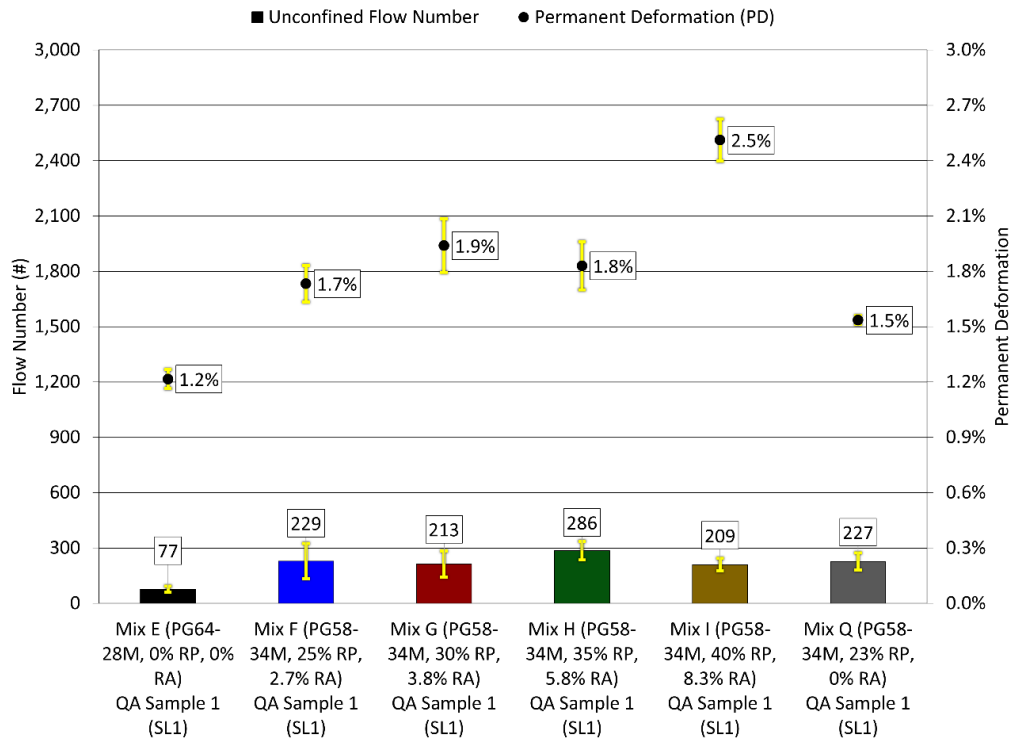


Figure 4.26: Unconfined repeated load triaxial results for QA subplot 1 sampled mixes at 55°C (load cycles and permanent deformation at flow number).

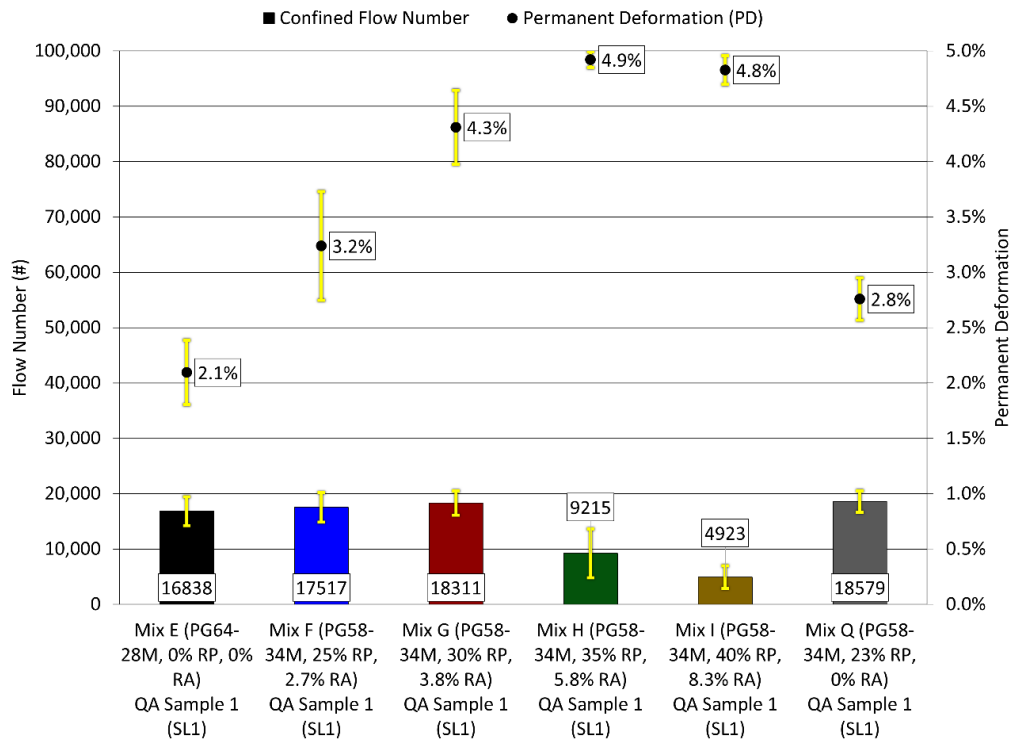


Figure 4.27: Confined repeated load triaxial results for QA subplot 1 sampled mixes at 55°C (load cycles and permanent deformation at flow number).

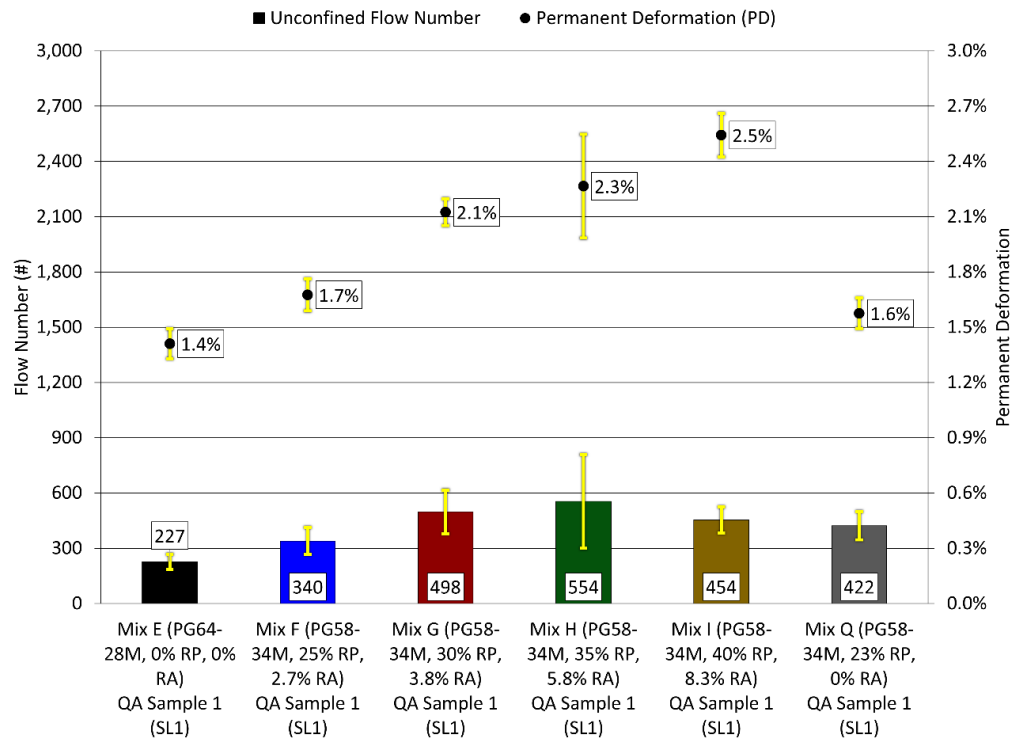


Figure 4.28: Unconfined repeated load triaxial results for QA subplot 1 sampled mixes at 50°C (load cycles and permanent deformation at flow number).

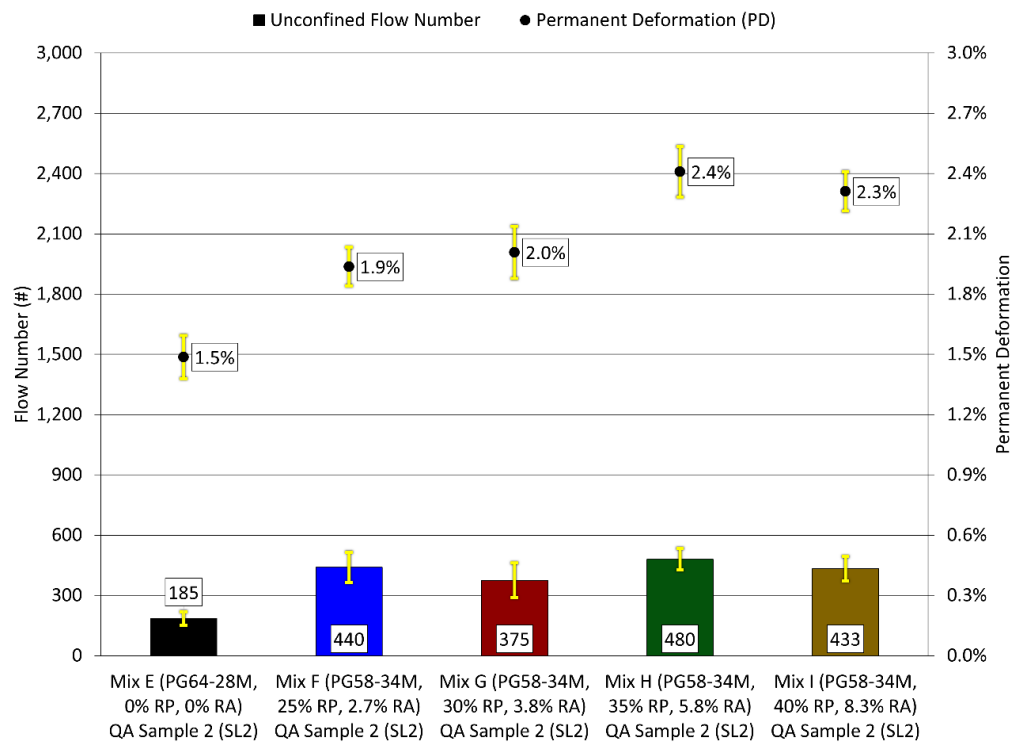
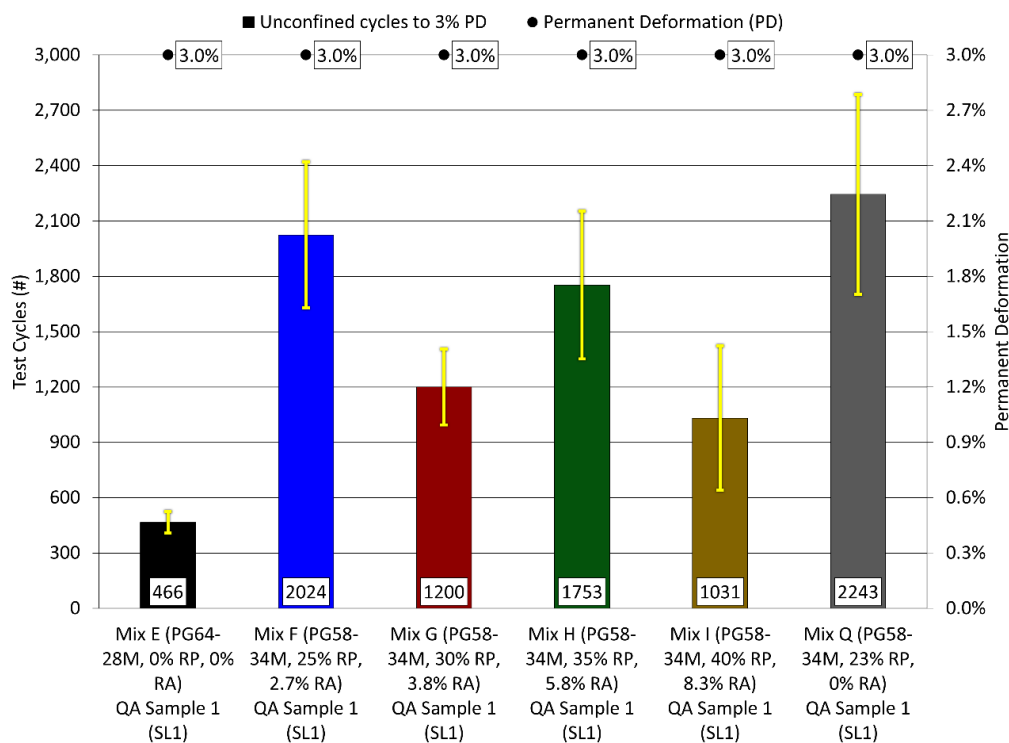
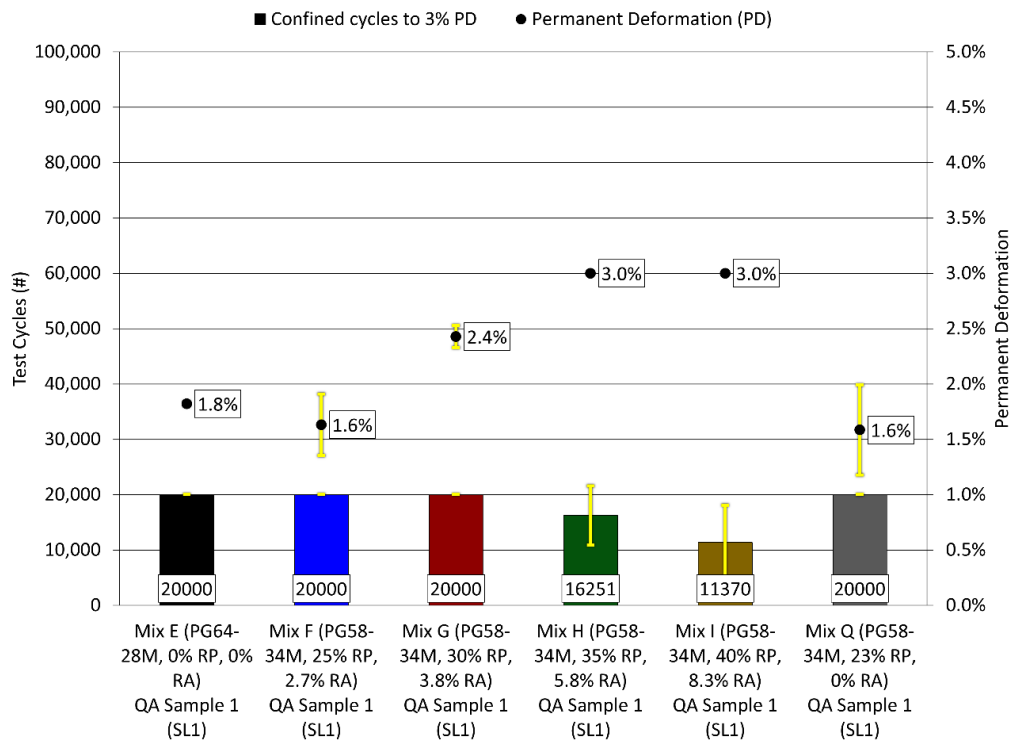


Figure 4.29: Unconfined repeated load triaxial results for QA subplot 2 sampled mixes at 50°C (load cycles and permanent deformation at flow number).



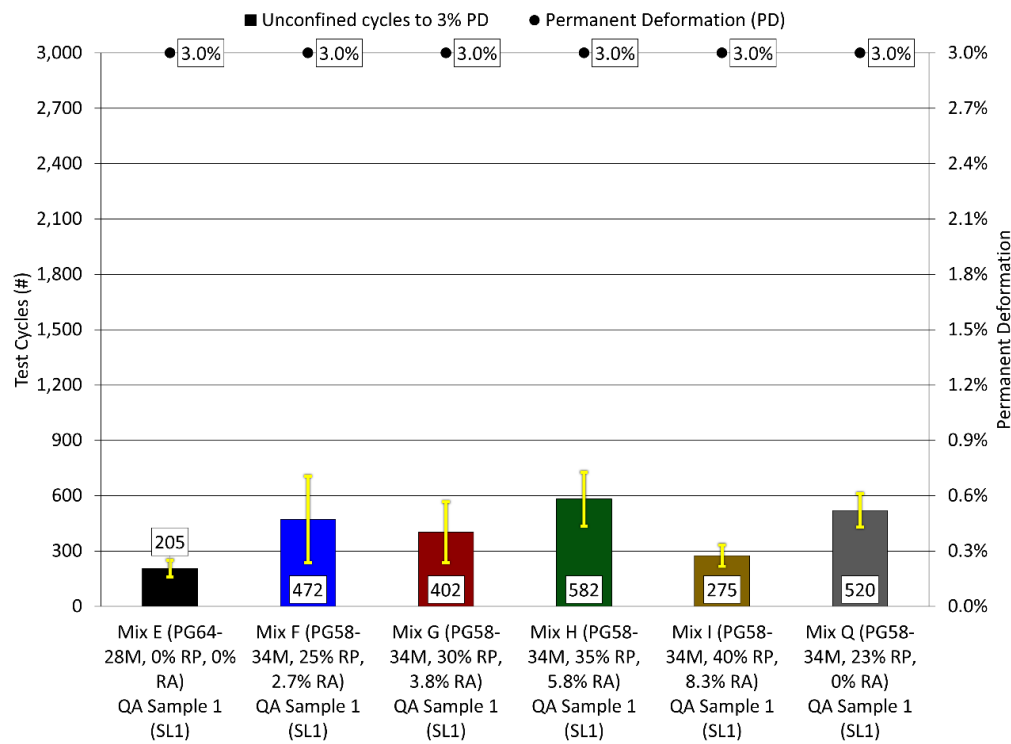
Note: A permanent strain less than 3% indicates that 3% was not reached before stopping at 20,000 cycles.

Figure 4.30: Unconfined repeated load triaxial results for QA subplot 1 sampled mixes at 45°C (load cycles to 3% permanent deformation or permanent deformation at 20,000 cycles).



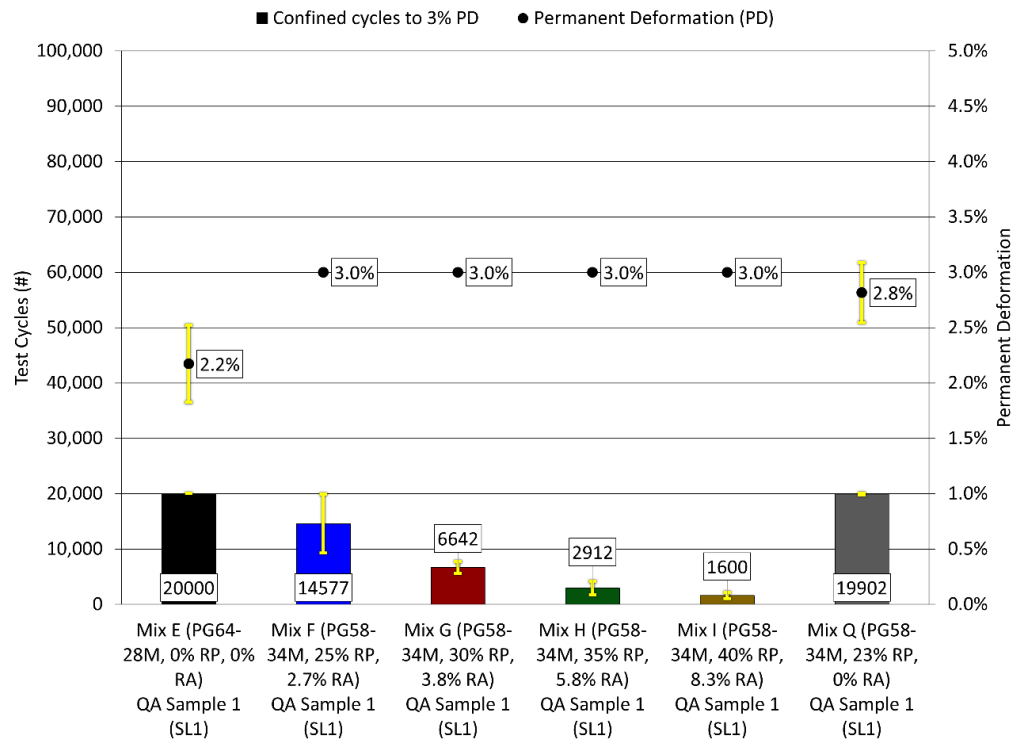
Note: A permanent strain less than 3% indicates that 3% was not reached before stopping at 20,000 cycles.

Figure 4.31: Confined repeated load triaxial results for QA subplot 1 sampled mixes at 45°C (load cycles to 3% permanent deformation or permanent deformation at 20,000 cycles).



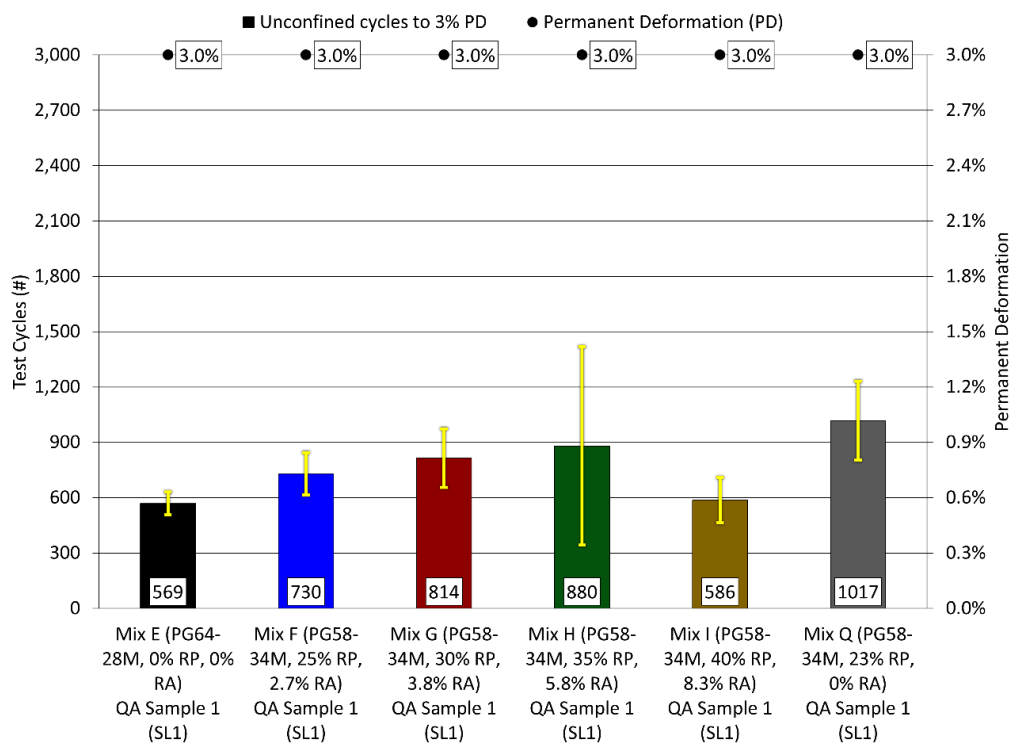
Note: A permanent strain less than 3% indicates that 3% was not reached before stopping at 20,000 cycles.

Figure 4.32: Unconfined repeated load triaxial results for QA subplot 1 sampled mixes at 55°C (load cycles to 3% permanent deformation or permanent deformation at 20,000 cycles).



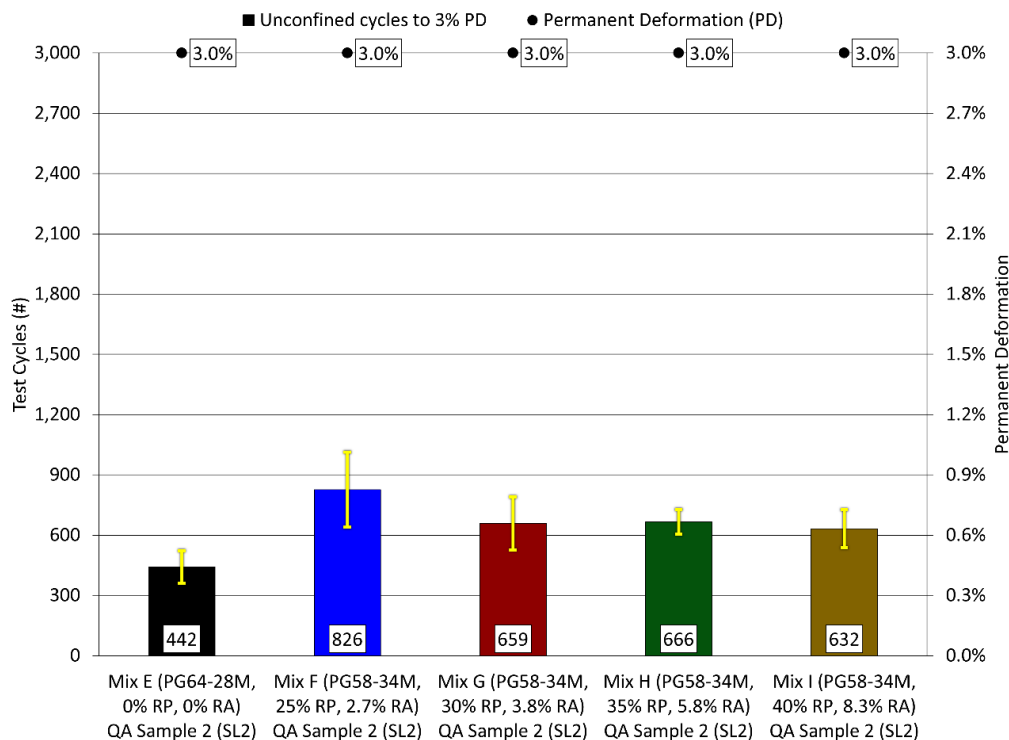
Note: A permanent strain less than 3% indicates that 3% was not reached before stopping at 20,000 cycles.

Figure 4.33: Confined repeated load triaxial results for QA subplot 1 sampled mixes at 55°C (load cycles to 3% permanent deformation or permanent deformation at 20,000 cycles).



Note: A permanent strain less than 3% indicates that 3% was not reached before stopping at 20,000 cycles.

Figure 4.34: Unconfined repeated load triaxial results for QA subplot 1 sampled mixes at 50°C (load cycles to 3% permanent deformation or permanent deformation at 20,000 cycles).



Note: A permanent strain less than 3% indicates that 3% was not reached before stopping at 20,000 cycles.

Figure 4.35: Unconfined repeated load triaxial results for QA subplot 2 sampled mixes at 50°C (load cycles to 3% permanent deformation or permanent deformation at 20,000 cycles).

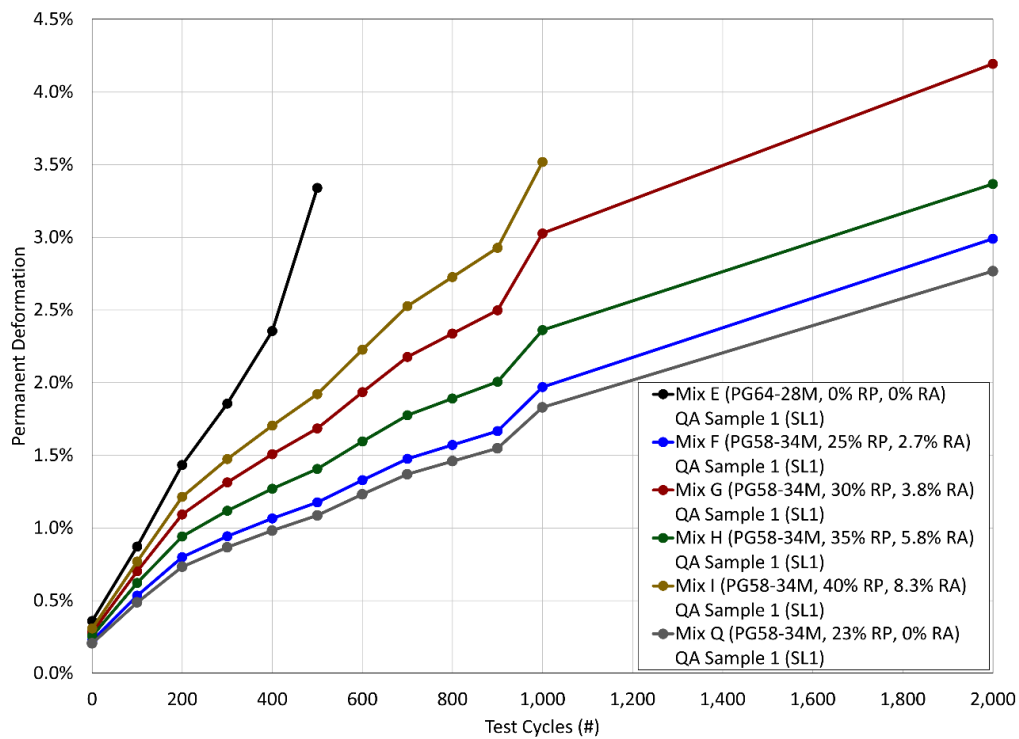


Figure 4.36: Unconfined repeated load triaxial results for QA subplot 1 sampled mixes at 45°C (load cycles and permanent deformation).

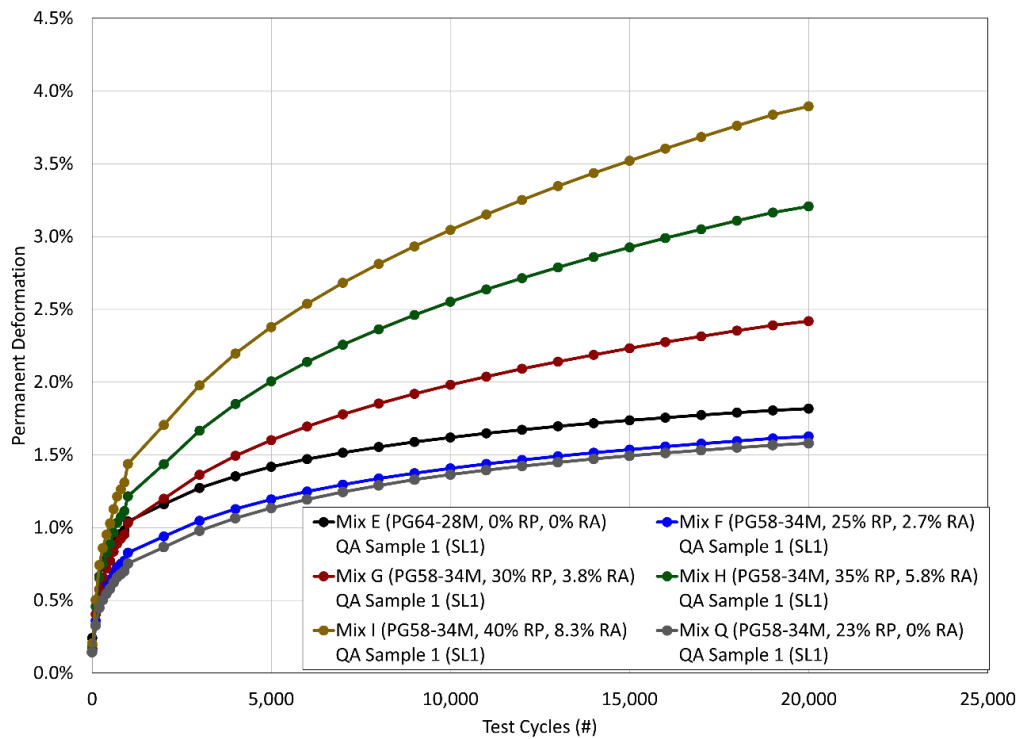


Figure 4.37: Confined repeated load triaxial results for QA subplot 1 sampled mixes at 45°C (load cycles and permanent deformation).

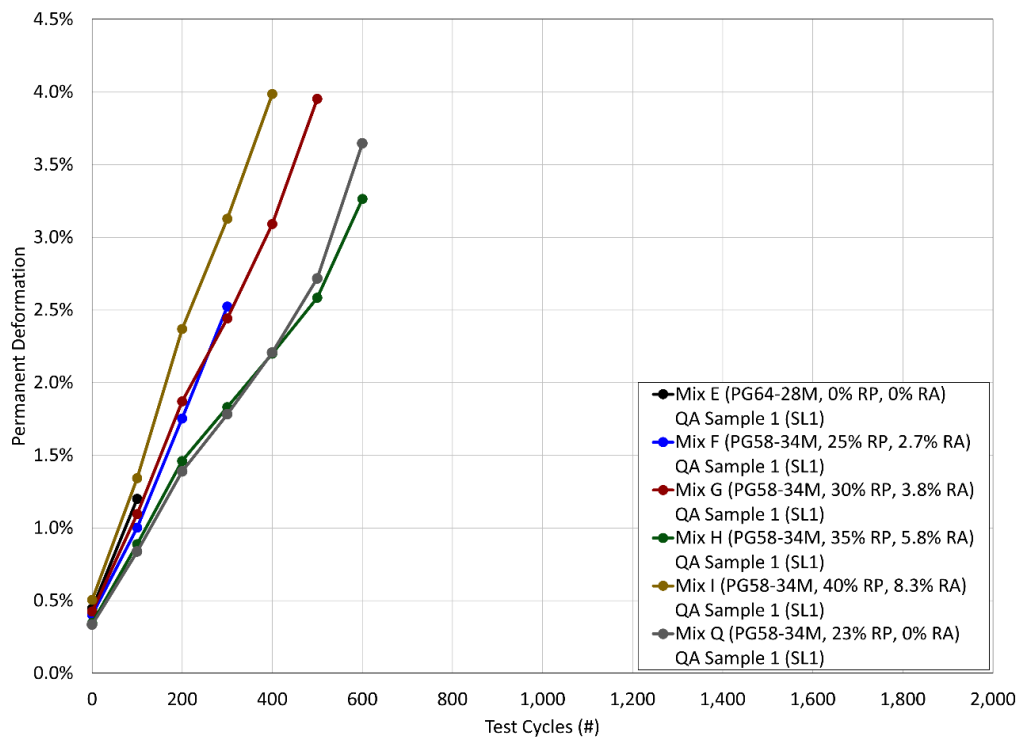


Figure 4.38: Unconfined repeated load triaxial results for QA subplot 1 sampled mixes at 55°C (load cycles and permanent deformation).

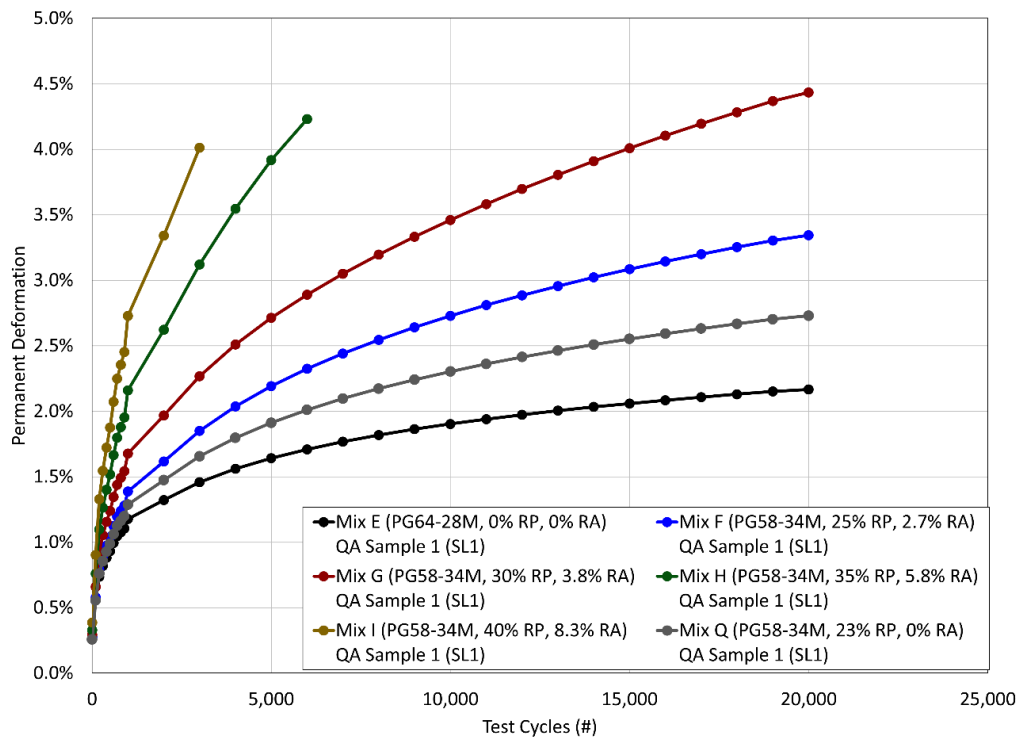


Figure 4.39: Confined repeated load triaxial results for QA subplot 1 sampled mixes at 55°C (load cycles and permanent deformation).

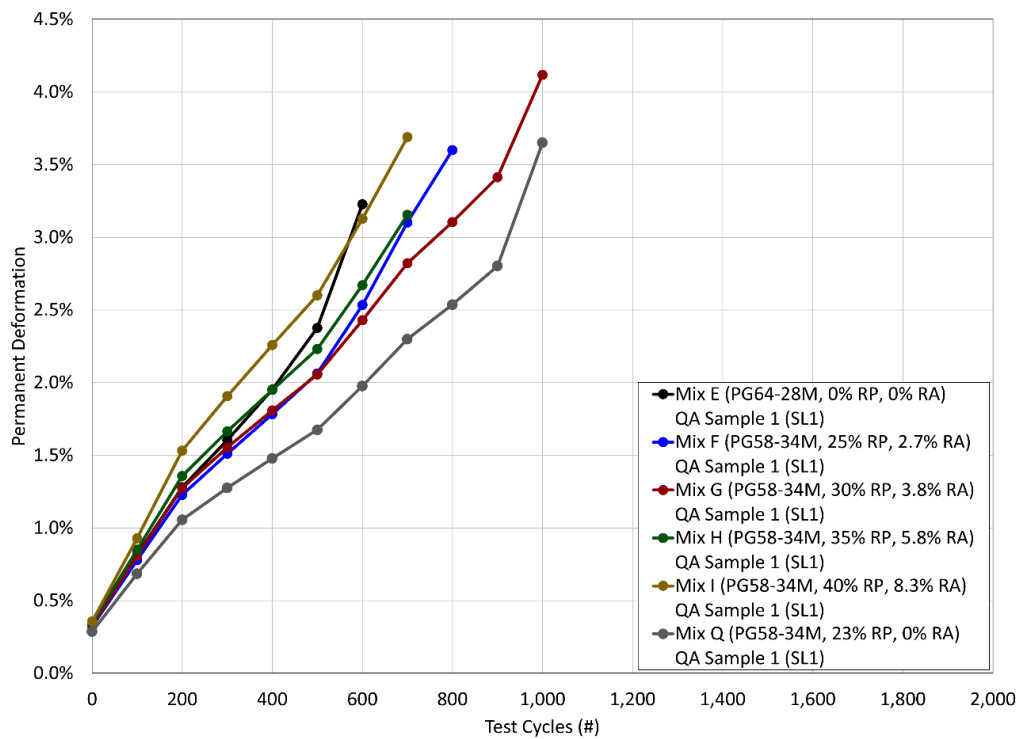


Figure 4.40: Unconfined repeated load triaxial results for QA subplot 1 sampled mixes at 50°C (load cycles and permanent deformation).

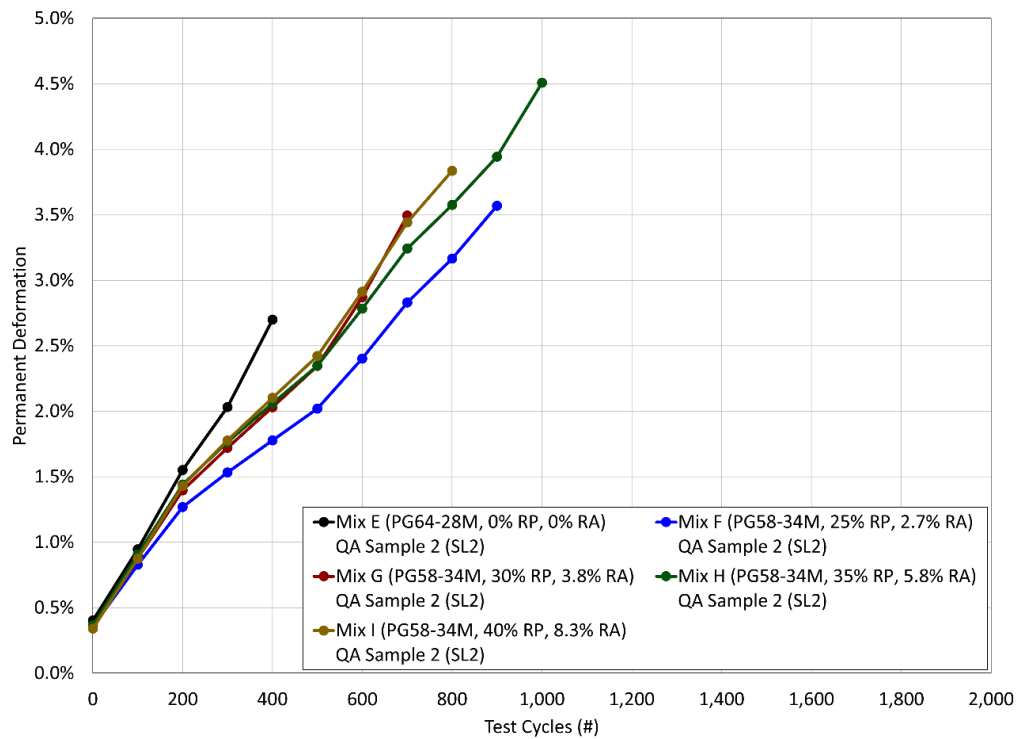


Figure 4.41: Unconfined repeated load triaxial results for QA subplot 2 sampled mixes at 50°C (load cycles and permanent deformation).

4.4.6 Fatigue/Reflective Cracking Resistance: Four-Point Beam Test

Fatigue testing was only performed on the first subplot of QA samples for each mix. Figure 4.42 shows flexural fatigue test results for each of the six mixes. Also shown on the plots are the Wöhler curve trend lines (log of tensile strain versus log of fatigue life). For the range of tensile strain levels used in testing (primarily 400 to 700 microstrain), the mix with 40% RAP and RA (Mix I) and the mainline mix with 25% RAP and no RA (Mix Q) had poorer performance at high strain levels than the other four mixes, which had performances similar to each other. The strain sensitivity of Mixes I, Q, and G (30% RAP and RA) is high, meaning that the fatigue life is more sensitive to the strain for those three mixes than it is for the other three. Extrapolating the results for Mix G to the lowest testing strain, 400 microstrain, it had the best fatigue performance at that strain, and the rest of the mixes had similar performance.

The regressions from Wöhler curves have generally been found over many decades of research and practice to provide reasonable estimates when extrapolated in the approximate range of 200 to 700 microstrain, except for polymer and rubber-modified mixes that tend to have much longer fatigue lives than extrapolation would indicate at strains smaller than 200 microstrain. Figure 4.43 shows the same fatigue test data points and the regression lines for the Wöhler curve through the combined QA sample data sets for each mix, extrapolated to 100 million cycles. As noted previously, Mixes I, Q, and G had similar high strain sensitivity, resulting in long fatigue lives at low strains typical of thick overlays or thick new pavement and short fatigue lives at high strains typical of thin overlays. The control mix with no RAP (Mix E), the mix with 25% RAP and RA (Mix F), and the mix with 35% RAP and RA (Mix H) had similar flatter strain sensitivity, resulting in longer lives predicted for high strains and shorter lives predicted for small strains.

Figure 4.44 shows extrapolated flexural fatigue testing Wöhler curve results for the combined QA sample data sets for the four QA sampled mixes normalized to the results at Mix E versus strain. The results show that at smaller strains, Mix G had the best results, followed by Mix I and Mix Q, while Mixes E, F, and H had similar lesser fatigue lives. At small strains, the results are reversed.

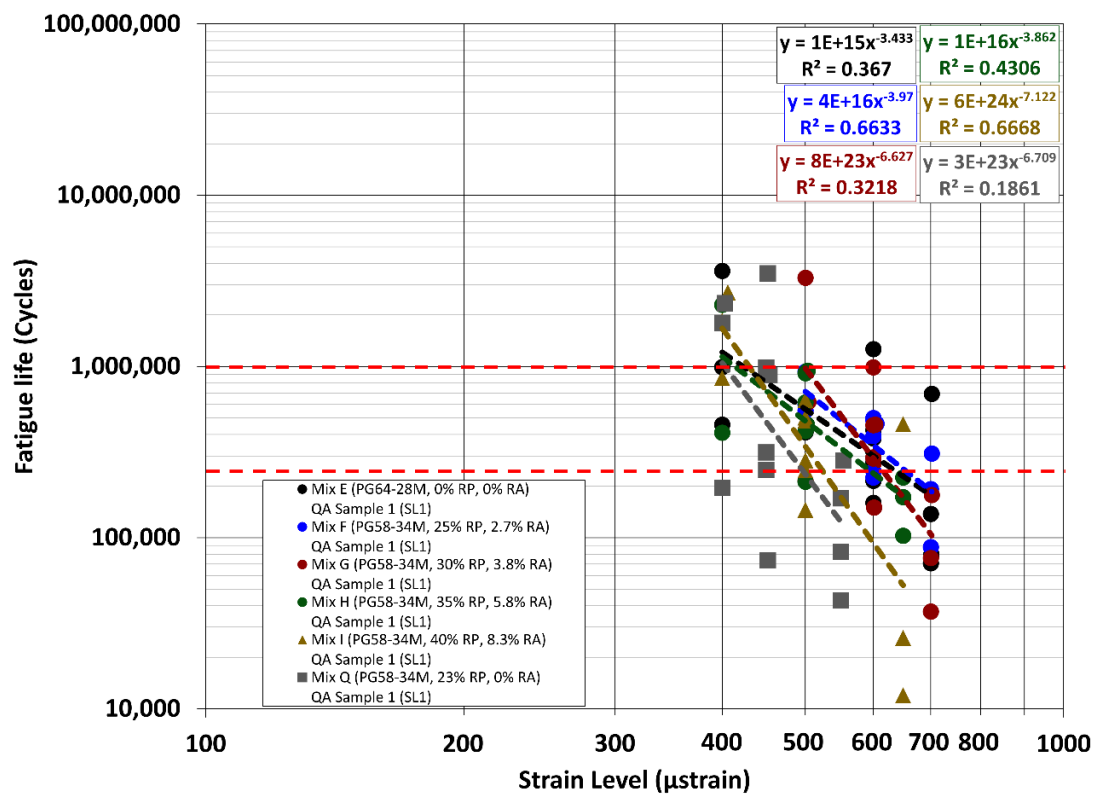


Figure 4.42: Flexural fatigue results for QA sampled mixes (Wöhler curve).

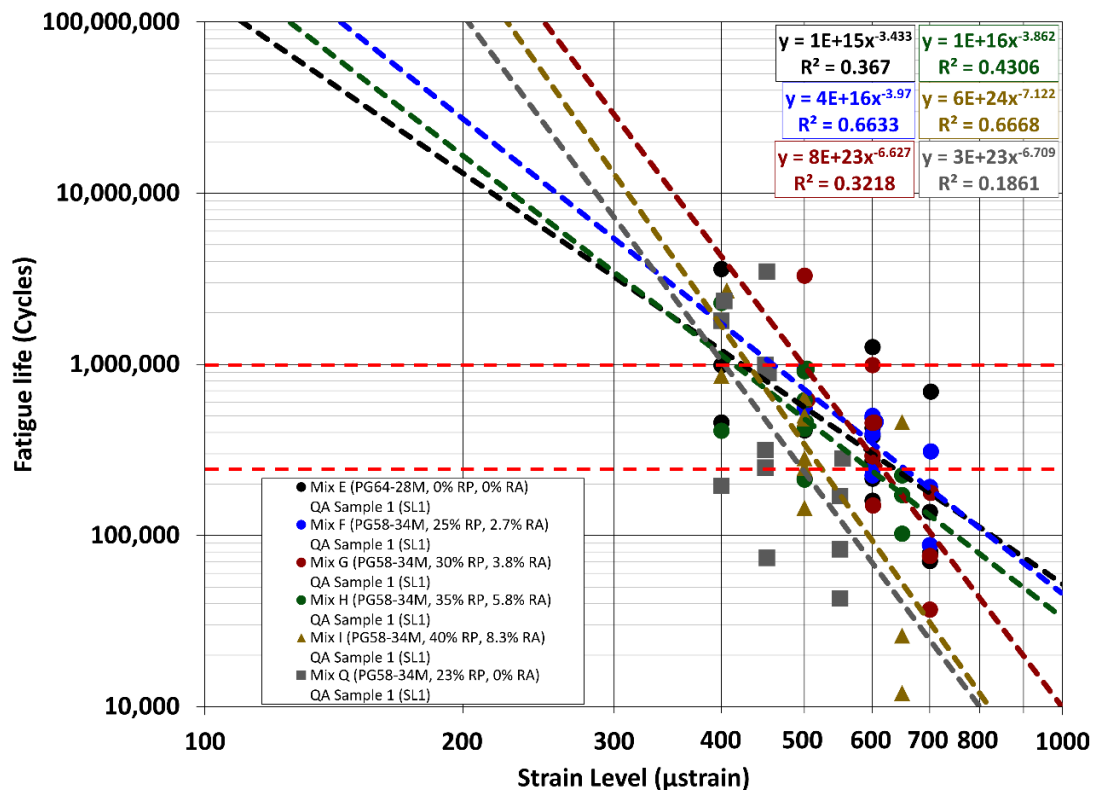


Figure 4.43: Extrapolation of flexural fatigue regression results for QA sampled mixes (Wöhler curve).

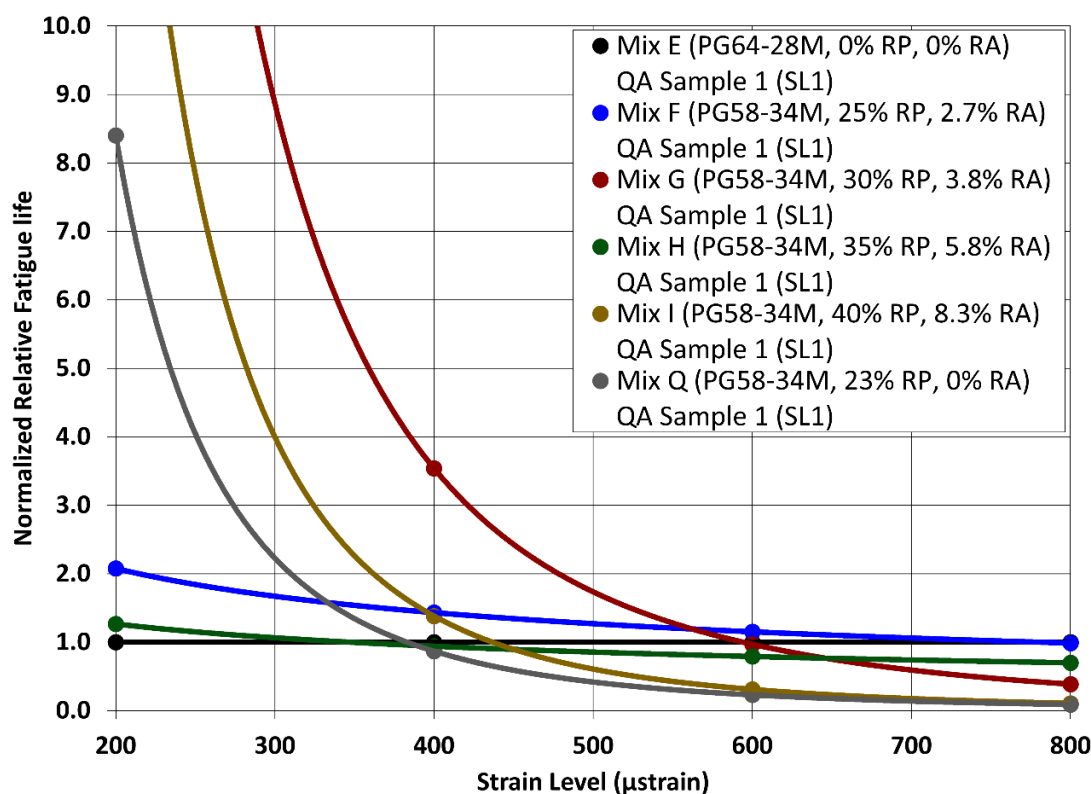


Figure 4.44: Flexural fatigue results for all QA sampled mixes from Wöhler curve regression normalized to Mix E.

4.4.7 Indirect Tensile Cracking Resistance: IDEAL-CT Test

IDEAL-CT testing was performed on both QA sublots of materials. The results shown are for samples stored, transported, and reheated in sealed steel buckets. For this pilot project, samples were also collected in cardboard boxes for comparison with the samples collected in buckets. Plots for the results of the boxed samples are included in Appendix B. Table 4.10 and Table 4.11 show the IDEAL-CT test results for both box and bucket sampled materials for Sample 1 and Sample 2, respectively. Analysis comparing the box and bucket sample test results from several pilot projects will be included in a separate report. Table 4.12 shows the IDEAL-CT results for MTOA-conditioned specimens for Sample 1 and Sample 2, respectively.

Figure 4.45 shows the IDEAL-CT results in terms of the IDEAL-CT number and peak strength for the first QA sample. The results indicate that the control mix had the greatest cracking tolerance, measured by the IDEAL-CT cracking tolerance (CT #), but that the values for the mixes with 30%, 35%, and 40% RAP and RA were not much lower. The mix with 23% RAP and no RA (mainline Mix Q) and the mix with 25% RAP and RA (Mix F) had somewhat lower values, but all were well above the value set with the control mix in the JMF, which was 39.8. The fact that the QA samples for the control mix (Mix Q) had CT # values that are completely different from those of the JMF is a strong indicator that the binder used during production for paving was not the PG 64-28M used for the JMF plant production and was most likely the PG 58-34M used as the base binder in the other mixes. Figure 4.46 shows the fracture energy and the post-peak slope from the fracture curve. The strength values are

generally similar, except for the control mix that is somewhat lower. The fracture energies are essentially all the same, and the post-peak slopes follow a pattern similar to that of the strengths.

The results from the second QA subplot are shown in Figure 4.47 for CT # and strength and in Figure 4.48 for fracture energy and post-peak slope. The results are very similar to those of the first QA subplot, indicating uniformity across each test section. The exceptions are that the mix with 25% RAP and RA (Mix F) is stronger and has a lower CT # in the second subplot than in the first subplot, and the mix with 40% RAP and RA (Mix I) has a higher CT # in the second subplot than in the first subplot, though the strengths are similar.

The rankings of strengths and the inverse of the rankings of CT # generally follow the rankings of dynamic stiffness from both the flexural (Figure 4.17) and axial (Figure 4.21) frequency sweeps at intermediate frequencies, which correspond to intermediate temperatures similar to those of the 25°C IDEAL-CT test temperature. Figure 4.49 through Figure 4.52 show the results for the same IDEAL-CT parameters and QA sublots as Figure 4.45 through Figure 4.48, except the samples were first subjected to MTOA. The MTOA followed the draft protocol developed by Caltrans' Materials Engineering and Testing Services (METS) and the UCPRC, which also includes instructions for storage and reheating of plant-produced samples. The results for all mixes and sublots generally show the same patterns between mixes as the reheated results and are similar between the two sublots for each mix. This is not unexpected, considering that the same base binder was used in every mix and the same RAP and RA sources were used in those mixes with RAP and/or RA. Exceptions are that the two mixes without RA (control Mix E and mainline Mix Q) appeared to show greater relative reductions in CT # than the mixes with RA for the MTOA results compared with the reheated results for the first QA subplot. The second QA subplot showed changes in aging that were similar for all mixes.

Figure 4.53 and Figure 4.54 show the IDEAL-CT load-displacement curves for the first QA subplot mixes after reheating and MTOA, respectively. Figure 4.55 and Figure 4.56 show the same for the second QA subplot mixes. Mix Q, the mainline mix with 23% RAP and no RA, was not tested in the second QA subplot. The results in Figure 4.53 and Figure 4.55 for the reheated specimens are generally similar, with all of the mixes with RAP having higher peak tensile strengths and somewhat steeper post-peak displacement curves than the control mix with no RAP (Mix E). Mix F had a lower strength in the second QA subplot than in the first. Comparing reheated and MTOA-conditioned specimens for the two QA sublots, in the first subplot, Mix Q had the greatest increase in strength and steepening of the post-peak displacement curve, indicating a greater effect of aging. MTOA generally result in much increase in peak strength or steepening of the post-peak displacement curves, and the mix rankings for reheating and MTOA conditioning were similar.

Table 4.10: IDEAL-CT Buckets Versus Boxes Comparison QA Sample 1 SL1

Mix ID	Average Cracking Tolerance (CT #)	Std Dev Cracking Tolerance (CT #)	Average Strength (psi)	Std Dev Strength (psi)	Average Fracture Energy (Gf)	Std Dev Fracture Energy (Gf)	Average Post-Peak Slope	Std Dev Post-Peak Slope
Mix E (PG64-28M, 0% RP, 0% RA)/ QA Sample 1 (SL1) Bucket	108.7	30.2	92	7	5499	371	1.77	0.36
Mix F (PG58-34M, 25% RP, 2.7% RA)/ QA Sample 1 (SL1) Bucket	71.8	17.6	105	4	5934	327	2.64	0.27
Mix G (PG58-34M, 30% RP, 3.8% RA)/ QA Sample 1 (SL1) Bucket	89.3	20.8	102	7	6140	428	2.39	0.38
Mix H (PG58-34M, 35% RP, 5.8% RA)/ QA Sample 1 (SL1) Bucket	92.8	27.0	109	8	6615	460	2.52	0.44
Mix I (PG58-34M, 40% RP, 8.3% RA)/ QA Sample 1 (SL1) Bucket	88.4	17.3	110	8	6617	882	2.59	0.36
Mix Q (PG58-34M, 23% RP, 0% RA)/ QA Sample 1 (SL1) Bucket	64.5	10.3	116	10	6177	440	2.89	0.46
Mix E (PG64-28M, 0% RP, 0% RA)/ QA Sample 1 (SL1) Box	89.5	17.5	100	11	5780	588	2.15	0.43
Mix F (PG58-34M, 25% RP, 2.7% RA)/ QA Sample 1 (SL1) Box	70.0	13.0	120	6	6504	319	2.88	0.41
Mix G (PG58-34M, 30% RP, 3.8% RA)/ QA Sample 1 (SL1) Box	73.9	22.3	109	7	6142	564	2.66	0.42
Mix H (PG58-34M, 35% RP, 5.8% RA)/ QA Sample 1 (SL1) Box	70.8	15.4	111	7	6375	194	2.98	0.55
Mix I (PG58-34M, 40% RP, 8.3% RA)/ QA Sample 1 (SL1) Box	87.2	17.1	121	8	7432	376	3.06	0.53
Mix Q (PG58-34M, 23% RP, 0% RA)/ QA Sample 1 (SL1) Box	45.8	7.6	137	10	6516	589	4.00	0.61

Table 4.11: IDEAL-CT Buckets Versus Boxes Comparison QA Sample 2 SL2

Mix ID	Average Cracking Tolerance (CT #)	Std Dev Cracking Tolerance (CT #)	Average Strength (psi)	Std Dev Strength (psi)	Average Fracture Energy (Gf)	Std Dev Fracture Energy (Gf)	Average Post-Peak Slope	Std Dev Post-Peak Slope
Mix E (PG64-28M, 0% RP, 0% RA)/ QA Sample 2 (SL2) Bucket	118.9	20.9	87	5	5515	259	1.64	0.23
Mix F (PG58-34M, 25% RP, 2.7% RA)/ QA Sample 2 (SL2) Bucket	92.9	22.5	98	7	5710	478	2.11	0.36
Mix G (PG58-34M, 30% RP, 3.8% RA)/ QA Sample 2 (SL2) Bucket	85.5	13.6	106	9	6226	501	2.46	0.45
Mix H (PG58-34M, 35% RP, 5.8% RA)/ QA Sample 2 (SL2) Bucket	79.9	19.6	114	14	6652	600	2.91	0.72
Mix I (PG58-34M, 40% RP, 8.3% RA)/ QA Sample 2 (SL2) Bucket	62.9	11.6	113	8	6011	284	2.95	0.64
Mix E (PG64-28M, 0% RP, 0% RA)/ QA Sample 2 (SL2) Box	141.7	31.5	101	9	6742	730	1.73	0.26
Mix F (PG58-34M, 25% RP, 2.7% RA)/ QA Sample 2 (SL2) Box	69.7	12.6	109	7	6023	194	2.72	0.47
Mix G (PG58-34M, 30% RP, 3.8% RA)/ QA Sample 2 (SL2) Box	63.9	13.0	119	4	6613	384	3.36	0.34
Mix H (PG58-34M, 35% RP, 5.8% RA)/ QA Sample 2 (SL2) Box	97.6	25.2	109	10	6906	348	2.62	0.52
Mix I (PG58-34M, 40% RP, 8.3% RA)/ QA Sample 2 (SL2) Box	65.7	12.5	126	7	6955	496	3.44	0.40

Table 4.12: IDEAL-CT MTOA Comparison Between Sample 1 SL1 and Sample 2 SL2

Mix ID	Average Cracking Tolerance (CT #)	Std Dev Cracking Tolerance (CT #)	Average Strength (psi)	Std Dev Strength (psi)	Average Fracture Energy (Gf)	Std Dev Fracture Energy (Gf)	Average Post-Peak Slope	Std Dev Post-Peak Slope
Mix E (PG64-28M, 0% RP, 0% RA)/ QA Sample 1 (SL1)	46.6	12.5	117	9	5471	440	3.39	0.53
Mix F (PG58-34M, 25% RP, 2.7% RA)/ QA Sample 1 (SL1)	41.3	9.8	129	8	6197	384	4.18	0.66
Mix G (PG58-34M, 30% RP, 3.8% RA)/ QA Sample 1 (SL1)	47.4	13.1	124	9	6123	888	3.71	0.51
Mix H (PG58-34M, 35% RP, 5.8% RA)/ QA Sample 1 (SL1)	54.4	17.7	135	12	6947	671	4.04	0.96
Mix I (PG58-34M, 40% RP, 8.3% RA)/ QA Sample 1 (SL1)	55.4	10.6	138	11	7091	427	3.96	0.61
Mix Q (PG58-34M, 23% RP, 0% RA)/ QA Sample 1 (SL1)	21.4	5.1	171	10	6329	462	7.09	1.48
Mix E (PG64-28M, 0% RP, 0% RA)/ QA Sample 2 (SL2)	79.1	23.8	113	9	6263	426	2.70	0.62
Mix F (PG58-34M, 25% RP, 2.7% RA)/ QA Sample 2 (SL2)	49.6	11.2	124	10	6113	656	3.74	0.71
Mix G (PG58-34M, 30% RP, 3.8% RA)/ QA Sample 2 (SL2)	46.1	10.7	125	11	6021	619	3.92	0.62
Mix H (PG58-34M, 35% RP, 5.8% RA)/ QA Sample 2 (SL2)	52.9	4.8	128	3	6499	158	3.68	0.43
Mix I (PG58-34M, 40% RP, 8.3% RA)/ QA Sample 2 (SL2)	42.1	4.9	136	9	6598	147	4.52	0.57

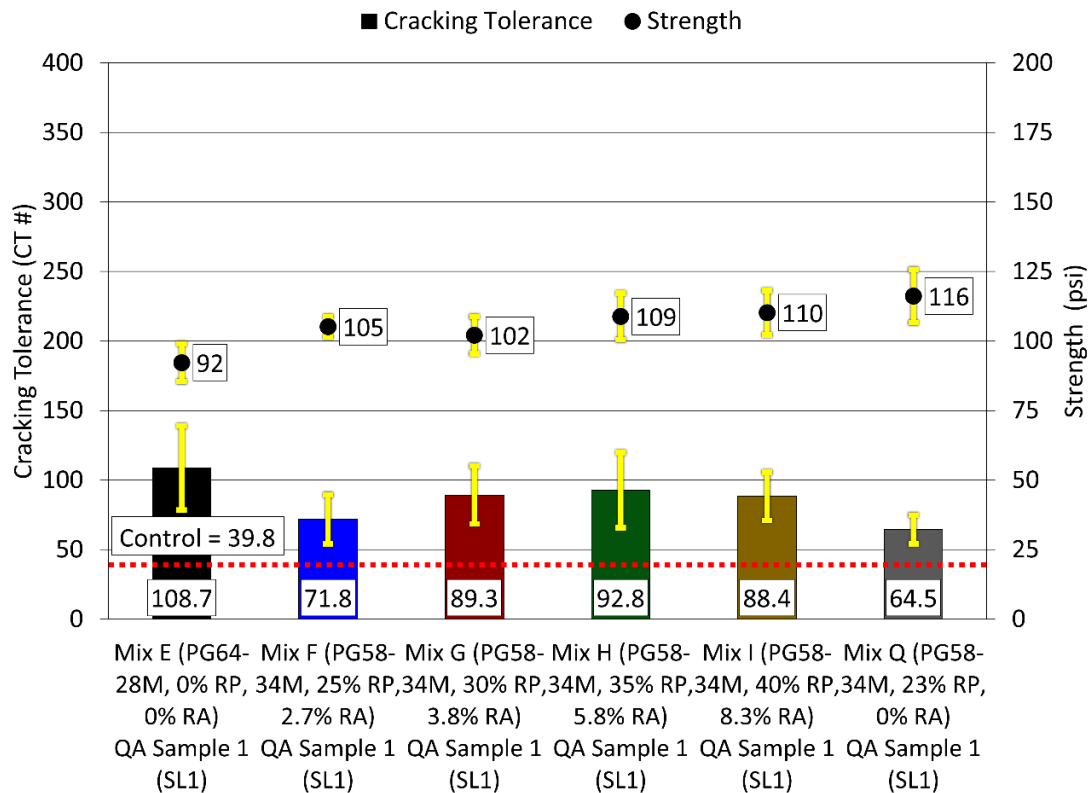


Figure 4.45: IDEAL-CT results for subplot 1 QA bucket mixes (cracking tolerance index and indirect tensile strength).

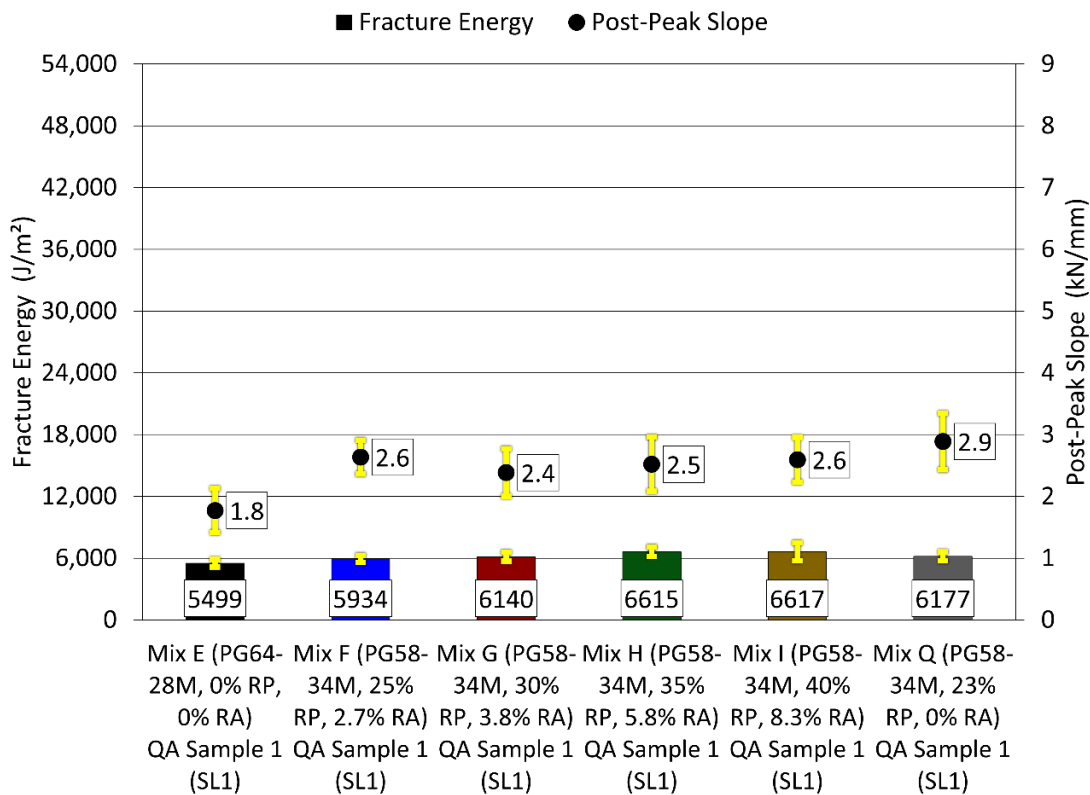


Figure 4.46: IDEAL-CT results for subplot 1 QA bucket mixes (fracture energy and post-peak slope).

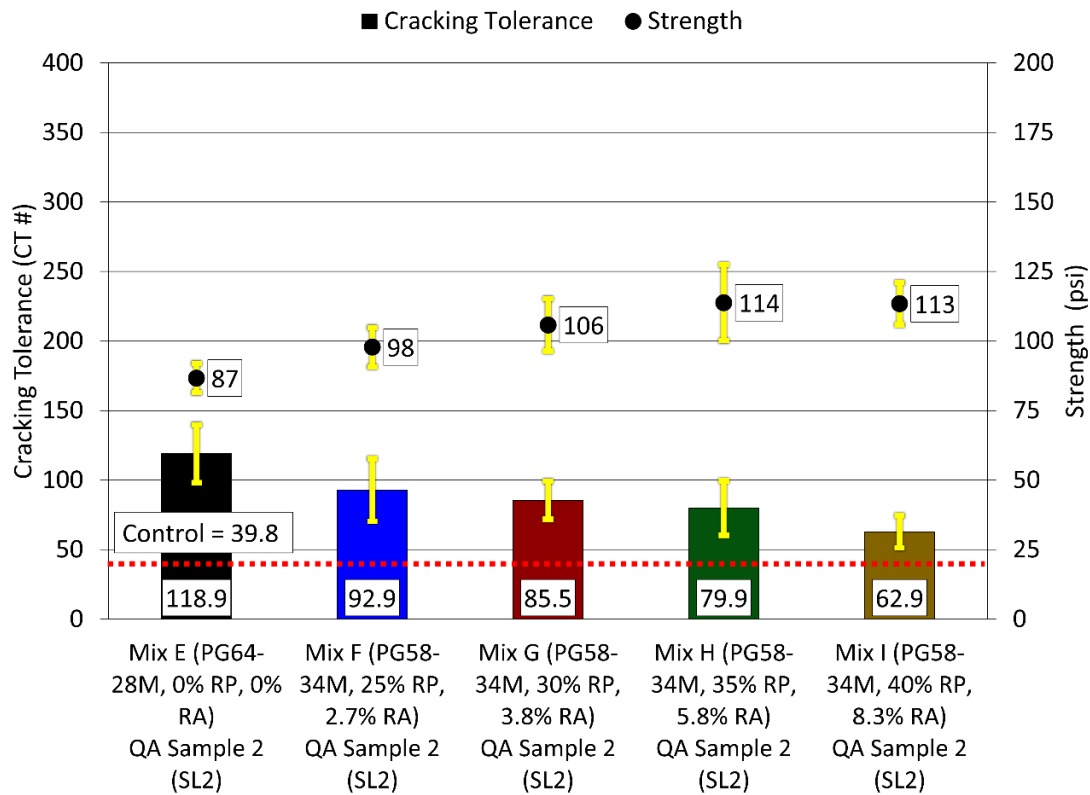


Figure 4.47: IDEAL-CT results for subplot 2 QA bucket mixes (cracking tolerance index and indirect tensile strength).

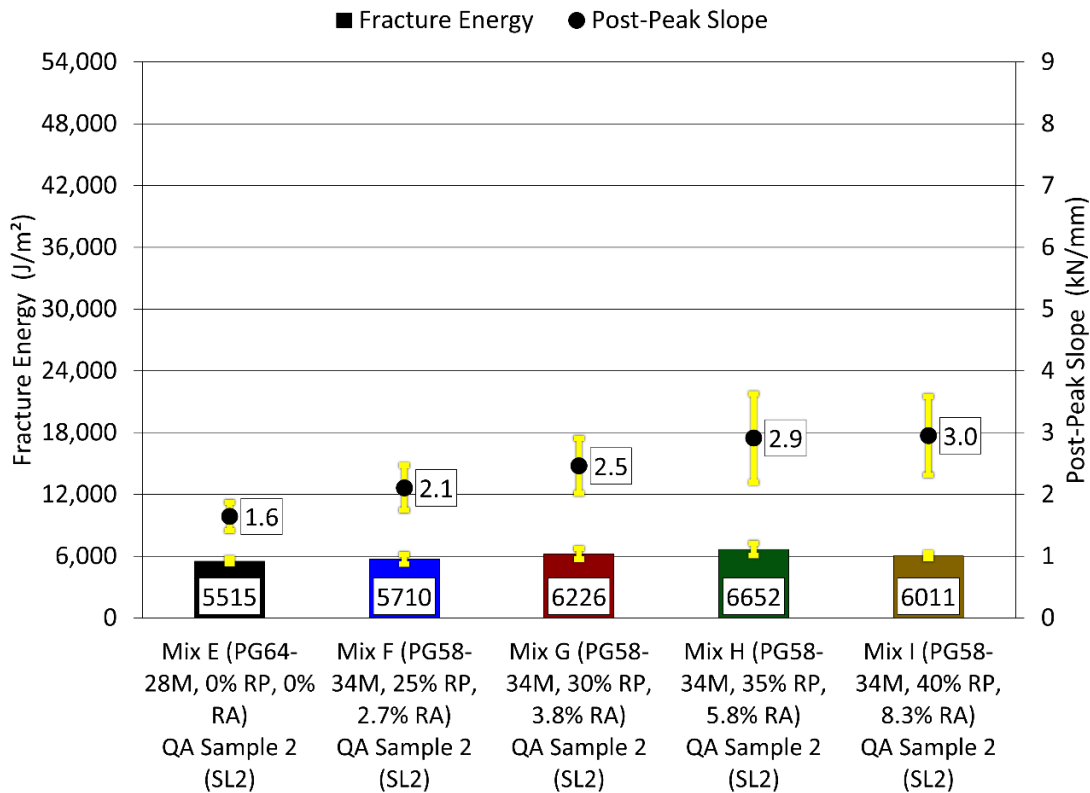


Figure 4.48: IDEAL-CT results for subplot 2 QA bucket mixes (fracture energy and post-peak slope).

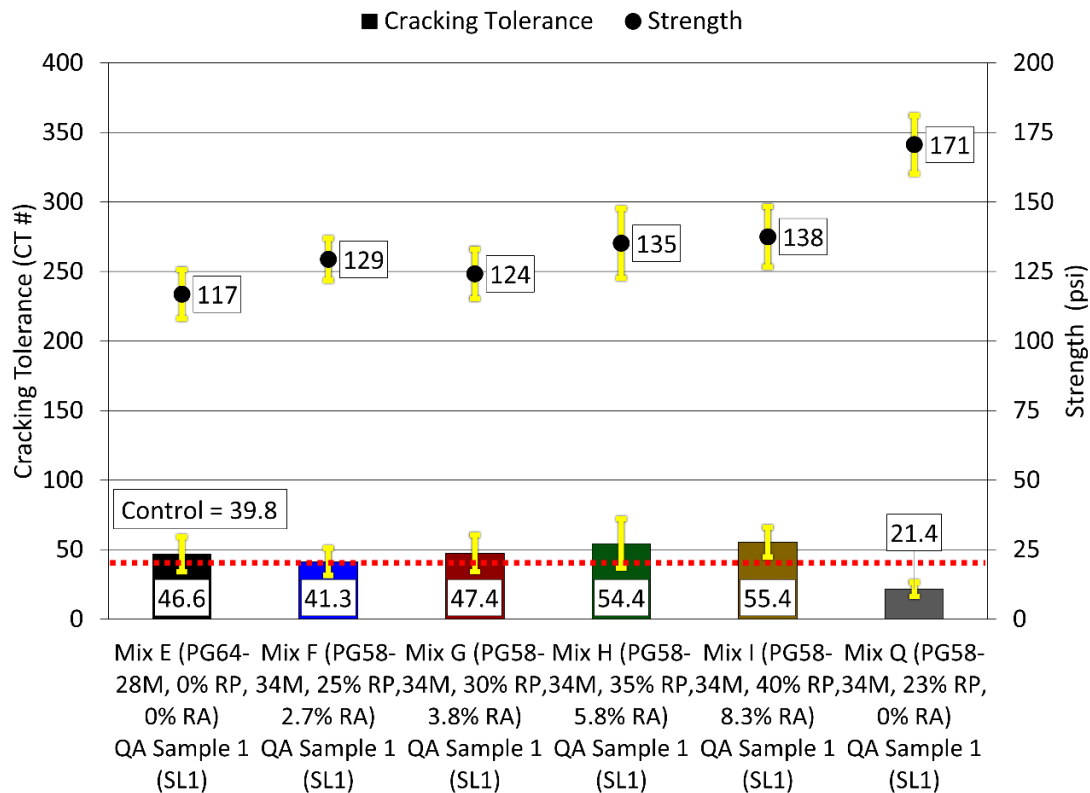


Figure 4.49: IDEAL-CT results for subplot 1 QA MTOA mixes (cracking tolerance index and indirect tensile strength).

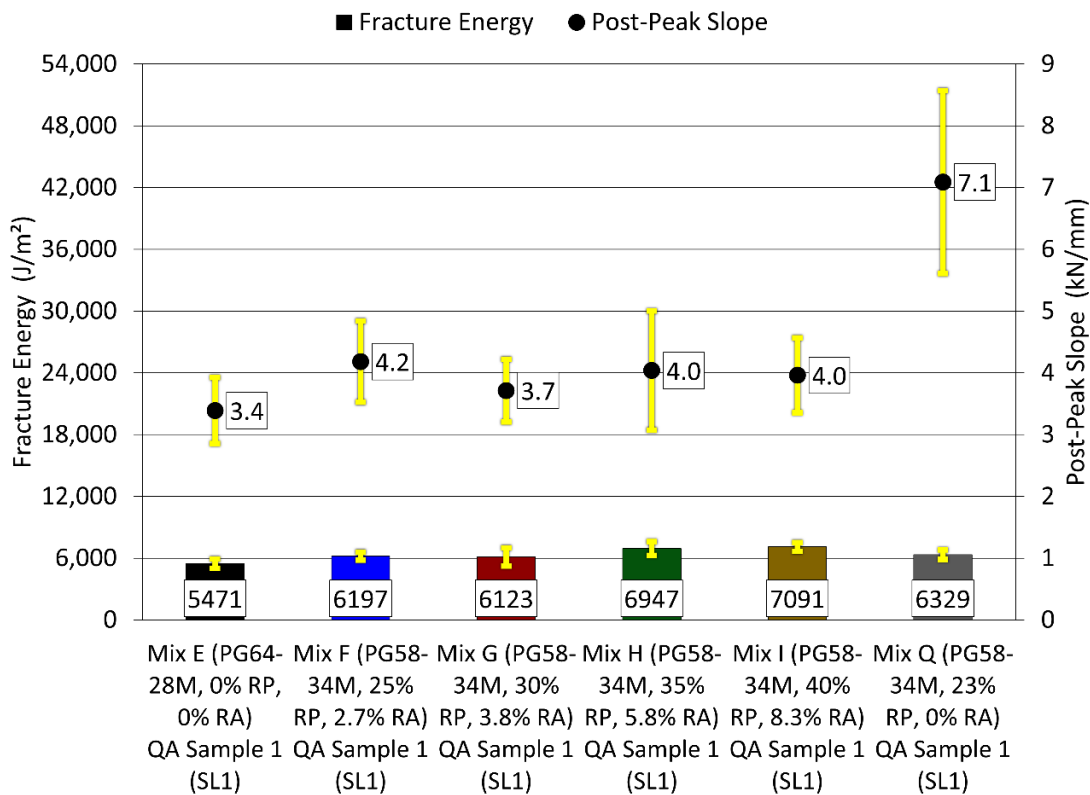


Figure 4.50: IDEAL-CT results for subplot 1 QA MTOA mixes (fracture energy and post-peak slope).

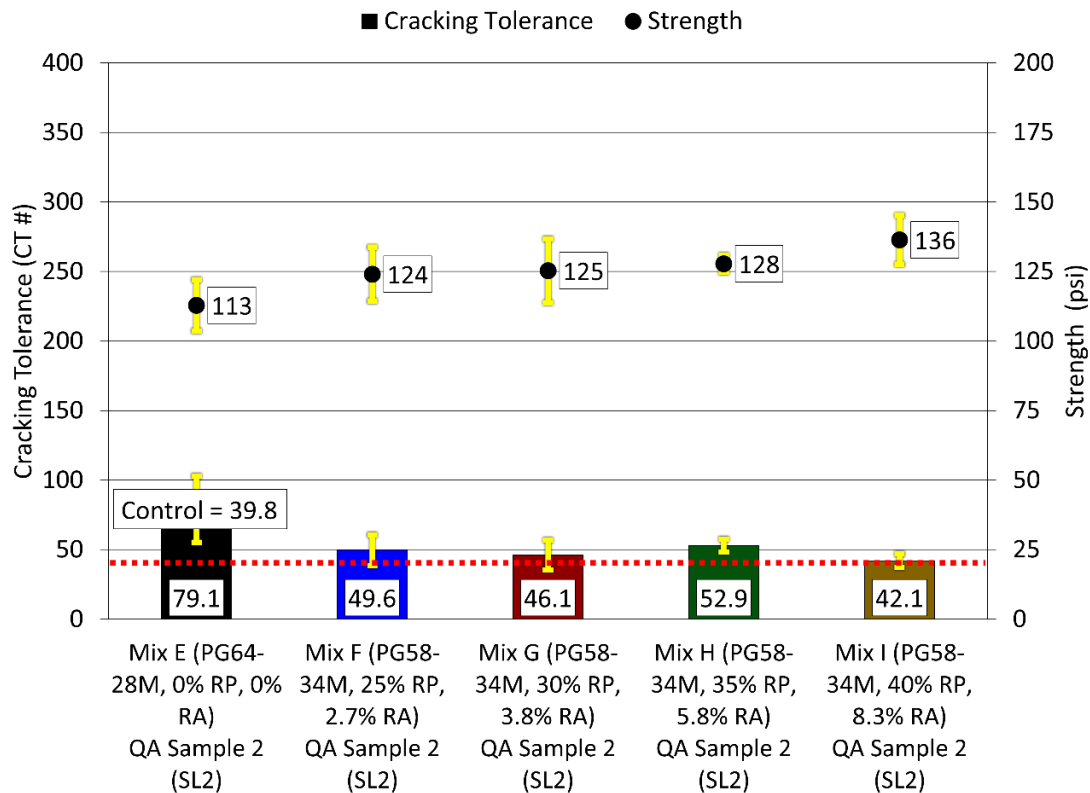


Figure 4.51: IDEAL-CT results for subplot 2 QA MTOA mixes (cracking tolerance index and indirect tensile strength).

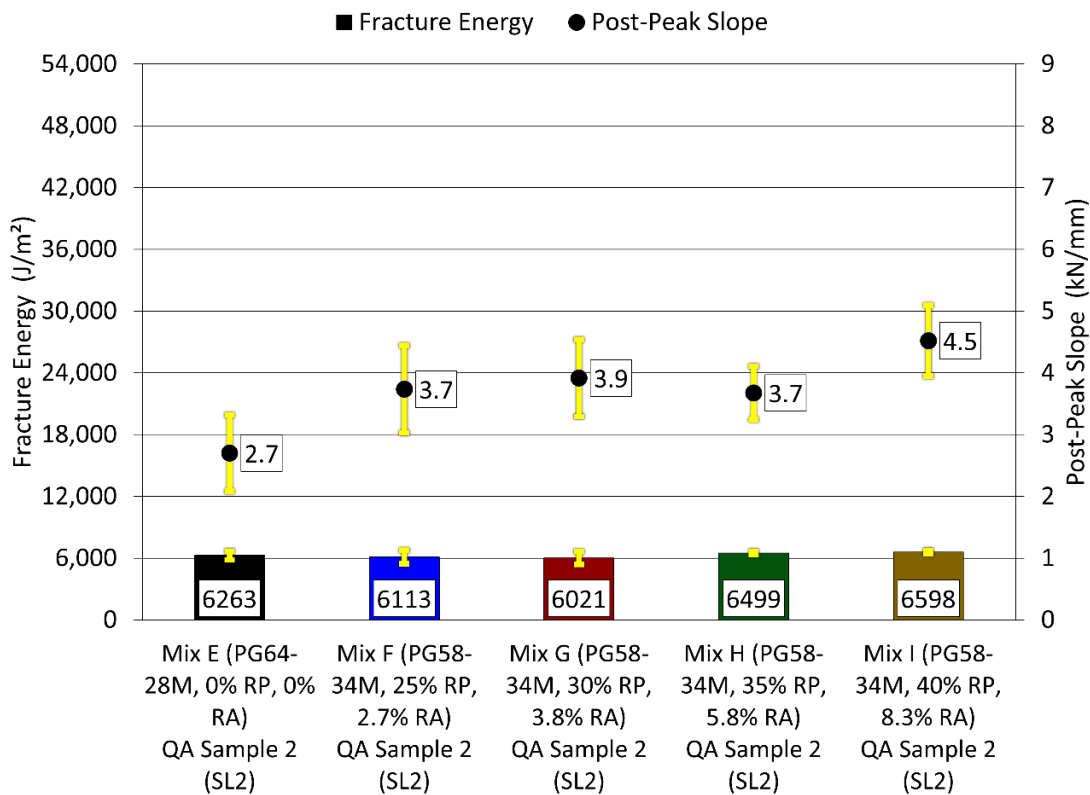


Figure 4.52: IDEAL-CT results for subplot 2 QA MTOA mixes (fracture energy and post-peak slope).

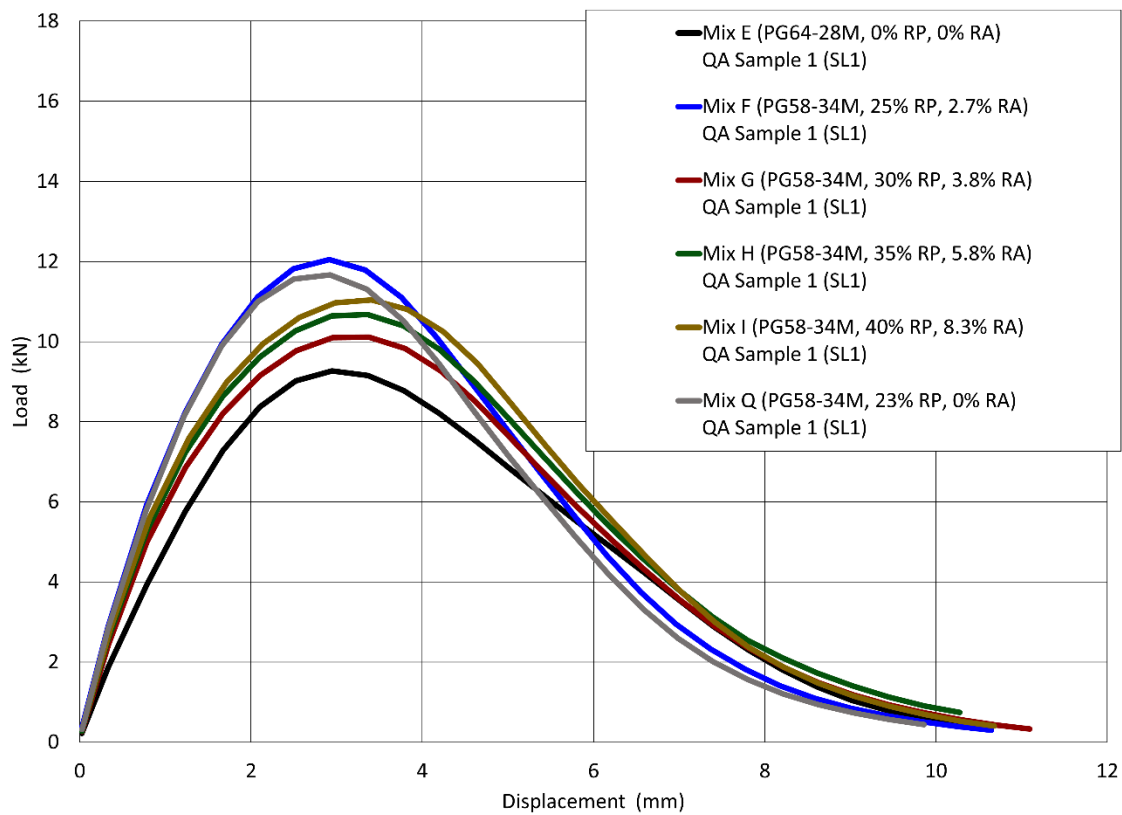


Figure 4.53: IDEAL-CT results for subplot 1 QA bucket mixes (load-displacement graph).

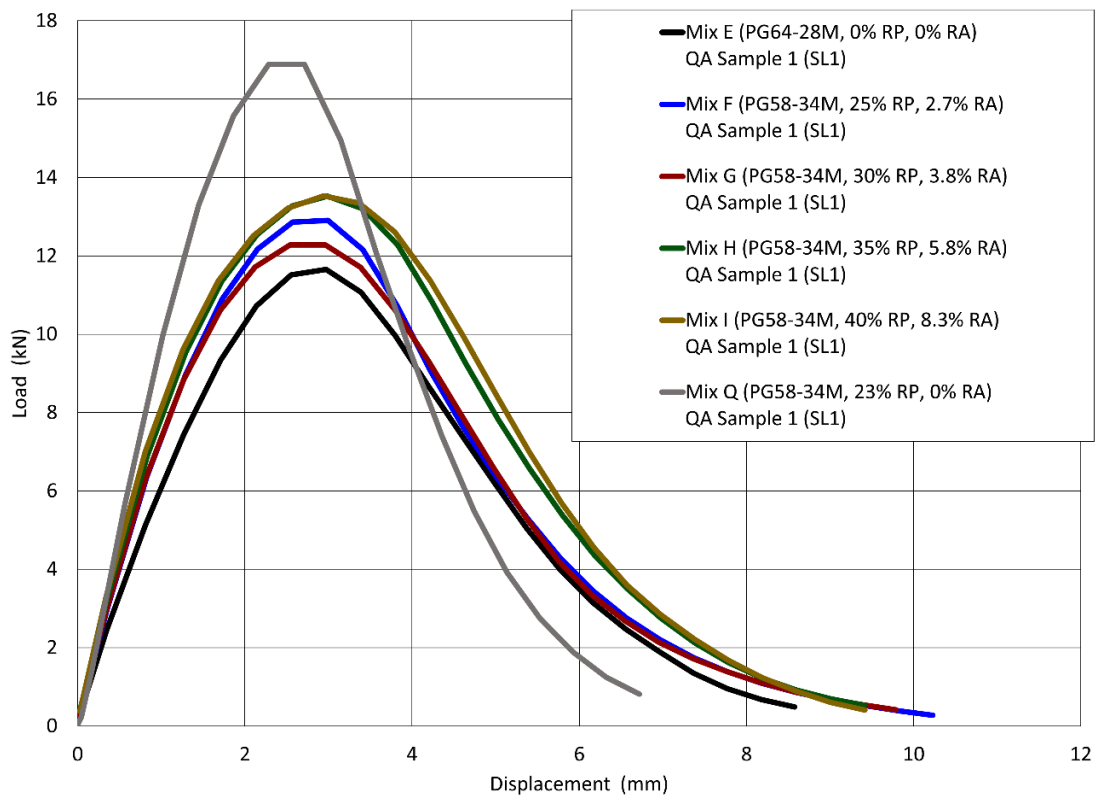


Figure 4.54: IDEAL-CT results for subplot 1 QA MTOA mixes (load-displacement graph).

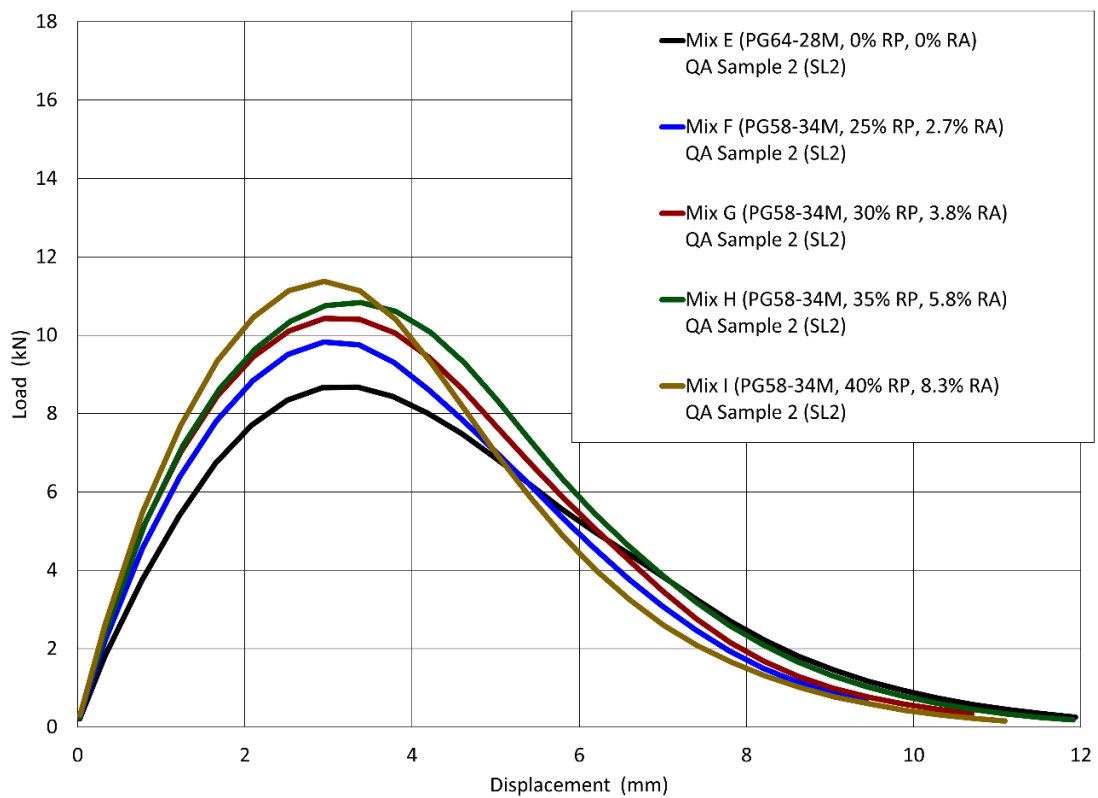


Figure 4.55: IDEAL-CT results for subplot 2 QA bucket mixes (load-displacement graph).

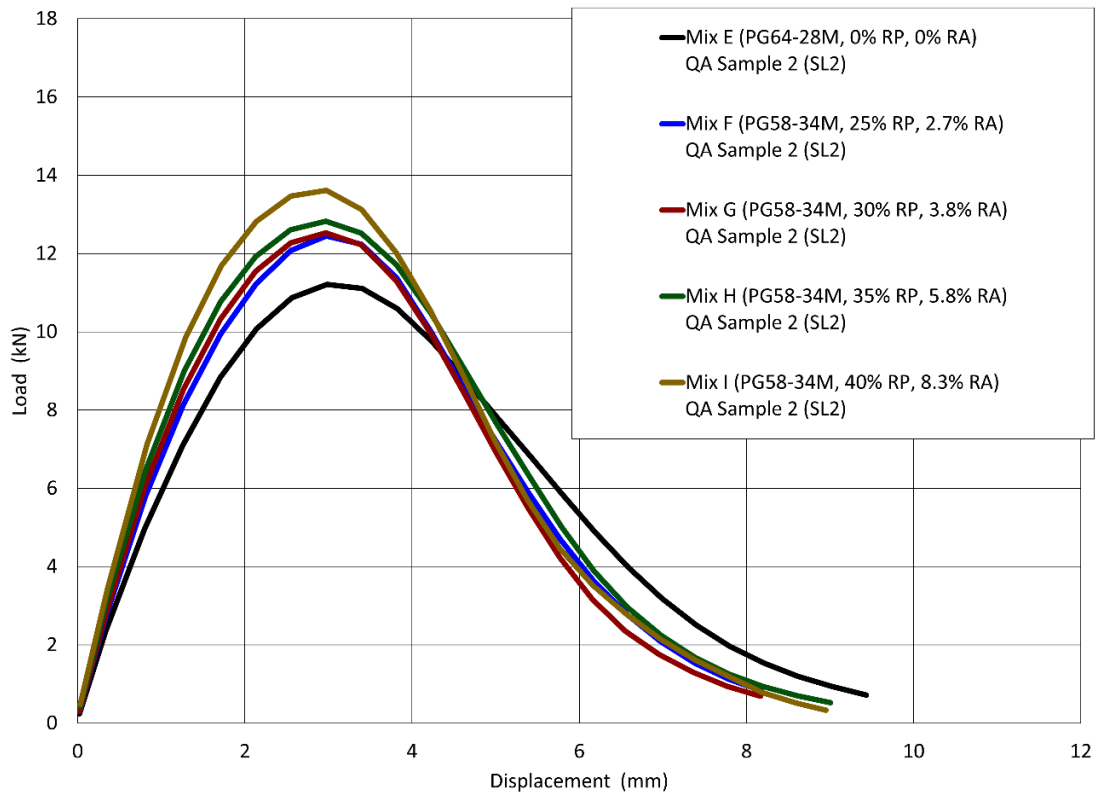


Figure 4.56: IDEAL-CT results for subplot 2 QA MTOA mixes (load-displacement graph).

4.4.8 Hamburg Wheel-Tracking Test

The results of the HWT test are shown in terms of the rut depth at 15,000 wheel passes in Table 4.13 and Figure 4.57, and in Table 4.14 and Figure 4.58, for the first and second QA sublots, respectively. Figure 4.59 and Figure 4.60 show plots of cumulative rut depth versus wheel passes for the first and second QA subplot samples, respectively. The results are generally similar between all mixes and both QA sublots, except that the first sample of the control mix from the first QA subplot had much greater rutting and an early inflection point that indicated moisture damage. Some inflection was shown in the second QA subplot results for the control mix, the mix with 25% RAP and RA, and the mix with 30% RAP and RA.

Table 4.13: Hamburg Wheel-Tracking Test Results for QA Sample 1 SL1 at 15,000 Cycles

Mix ID	AVG Wheel 1 Rut Depth (in.)	AVG Wheel 2 Rut Depth (in.)	AVG Rut Depth Wheel 1 and 2 (in.)	STD Rut Depth (in.)
Mix E (PG64-28M, 0% RP, 0% RA)/ QA Sample 1 (SL1)	0.343	0.158	0.250	0.092
Mix F (PG58-34M, 25% RP, 2.7% RA)/ QA Sample 1 (SL1)	0.094	0.095	0.095	0.001
Mix G (PG58-34M, 30% RP, 3.8% RA)/ QA Sample 1 (SL1)	0.107	0.095	0.101	0.006
Mix H (PG58-34M, 35% RP, 5.8% RA)/ QA Sample 1 (SL1)	0.087	0.078	0.083	0.004
Mix I (PG58-34M, 40% RP, 8.3% RA)/ QA Sample 1 (SL1)	0.090	0.102	0.096	0.006
Mix Q (PG58-34M, 23% RP, 0% RA)/ QA Sample 1 (SL1)	0.056	0.057	0.056	0.000

Table 4.14: Hamburg Wheel-Tracking Test Results for QA Sample 2 SL2 at 15,000 Cycles

Mix ID	AVG Wheel 1 Rut Depth (in.)	AVG Wheel 2 Rut Depth (in.)	AVG Rut Depth Wheel 1 and 2 (in.)	STD Rut Depth (in.)
Mix E (PG64-28M, 0% RP, 0% RA)/ QA Sample 2 (SL2)	0.082	0.119	0.100	0.018
Mix F (PG58-34M, 25% RP, 2.7% RA)/ QA Sample 2 (SL2)	0.126	0.097	0.111	0.014
Mix G (PG58-34M, 30% RP, 3.8% RA)/ QA Sample 2 (SL2)	0.092	0.103	0.098	0.006
Mix H (PG58-34M, 35% RP, 5.8% RA)/ QA Sample 2 (SL2)	0.104	0.098	0.101	0.003
Mix I (PG58-34M, 40% RP, 8.3% RA)/ QA Sample 2 (SL2)	0.075	0.080	0.078	0.002

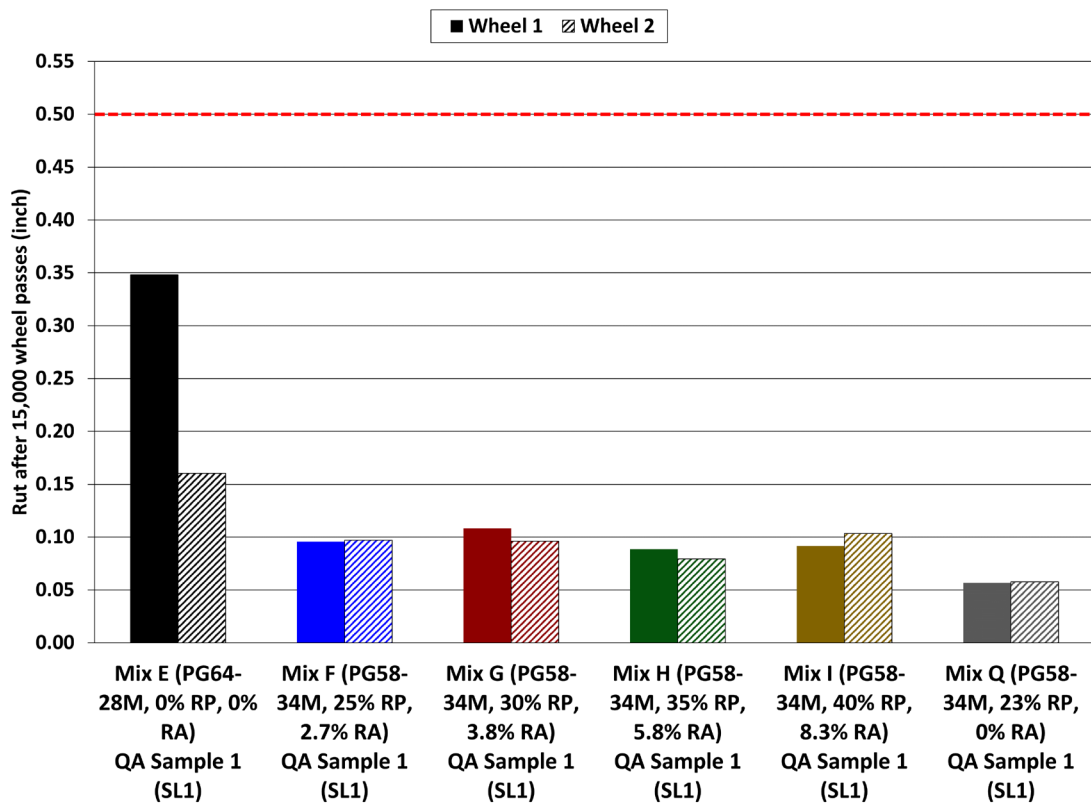


Figure 4.57: HWT test results for QA sample 1 (rutting after 15,000 wheel passes).

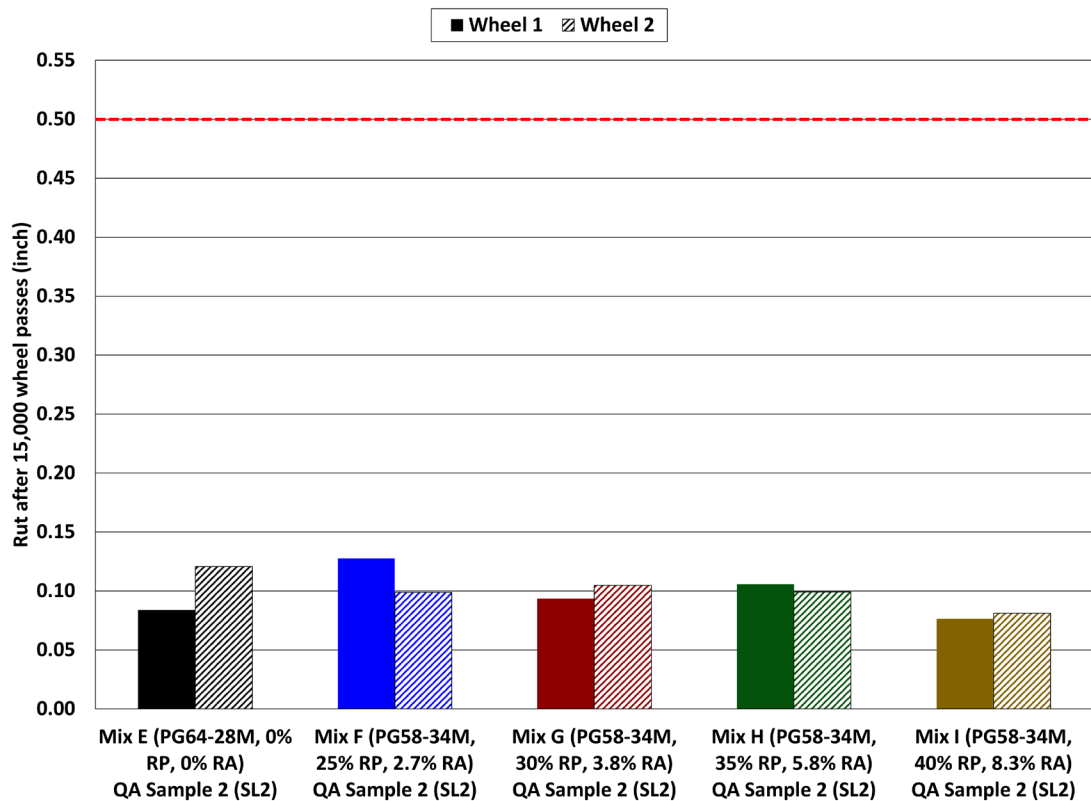


Figure 4.58: HWT test results for QA sample 2 (rutting after 15,000 wheel passes).

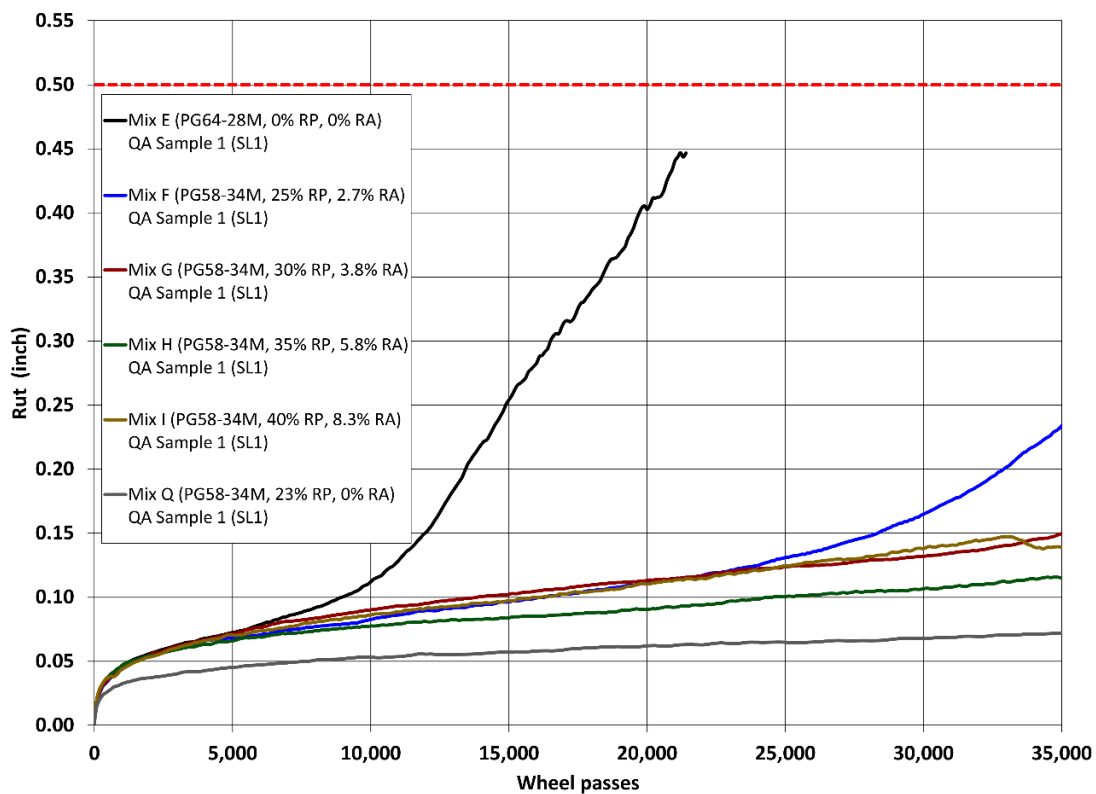


Figure 4.59: HWT test results for QA sample 1 (wheel passes and rut depth).

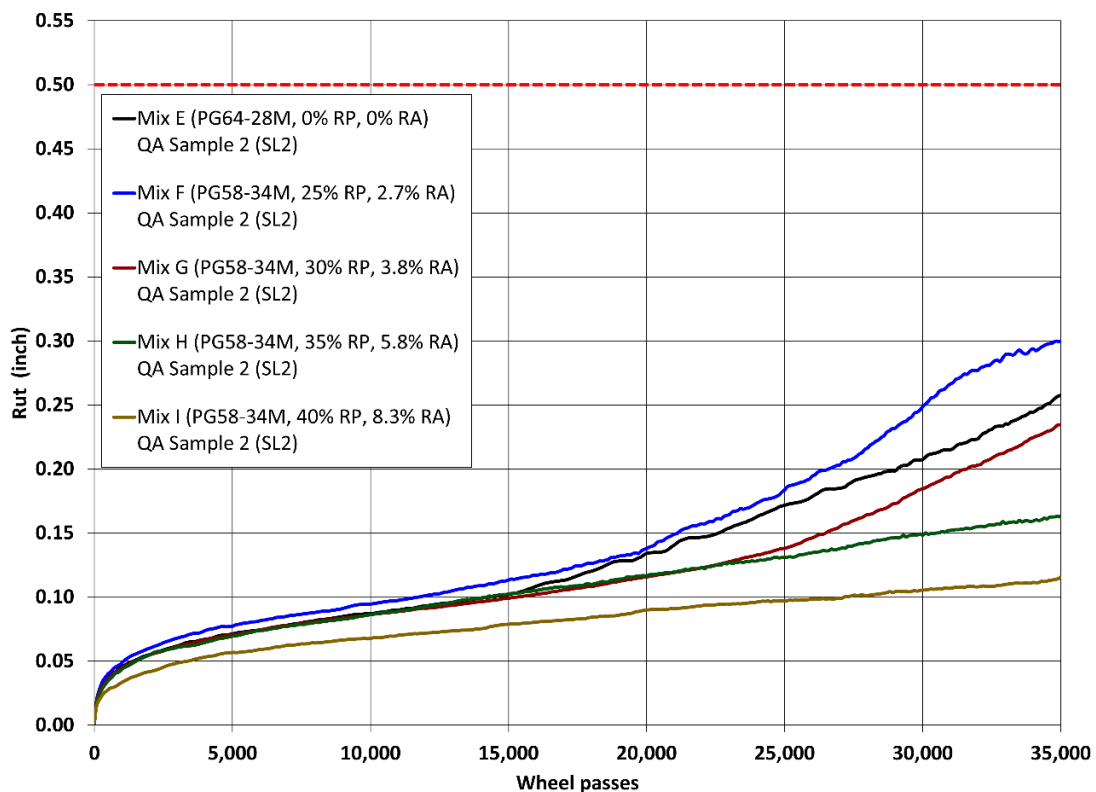


Figure 4.60: HWTT test results for QA sample 2 (wheel passes and rut depth).

4.4.9 Selected Performance-Related Test Comparisons

A few comparisons were made between alternative performance-related test results. More comprehensive comparisons will be included in a later report summarizing results across all pilot projects. Figure 4.61 compares dynamic modulus from the flexural and axial frequency sweeps at similar intermediate frequencies and temperatures. The results show a very strong correlation, as expected. Figure 4.62 compares the flexural stiffness from fatigue tests at 10 Hz and 20°C versus the CT # for both bucket- and box-collected samples. The limited results indicate general overlap between the results for the two storage methods and a weak correlation between the two parameters. Figure 4.63 shows a similar comparison of flexural stiffness and IDEAL-CT strength, showing general overlap between the specimen collection methods and a clearer correlation between the two parameters. Figure 4.64 shows a plot of CT # and strength from the IDEAL-CT test, showing a strong correlation between the two parameters for both reheated and MTOA results.

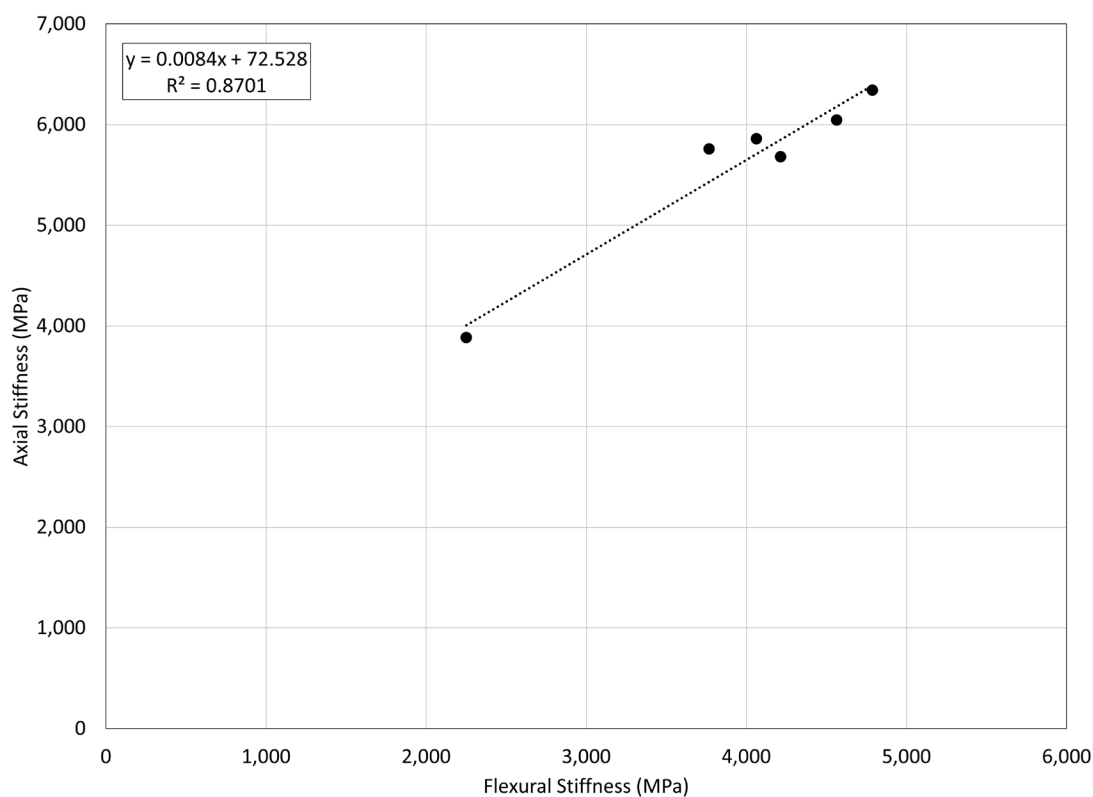


Figure 4.61: Comparison of four-point bending beam and dynamic modulus from AMPT of combined QA sample (flexural stiffness and axial stiffness).

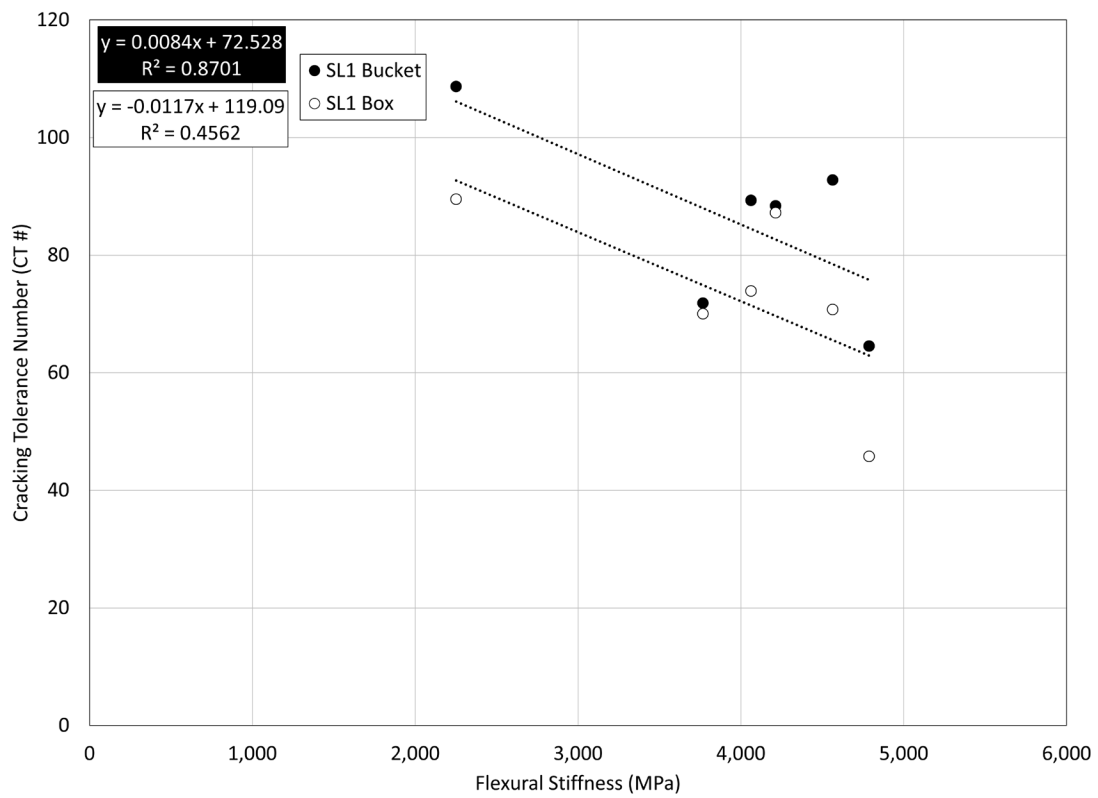


Figure 4.62: Comparison of flexural stiffness and cracking tolerance number of combined QA samples.

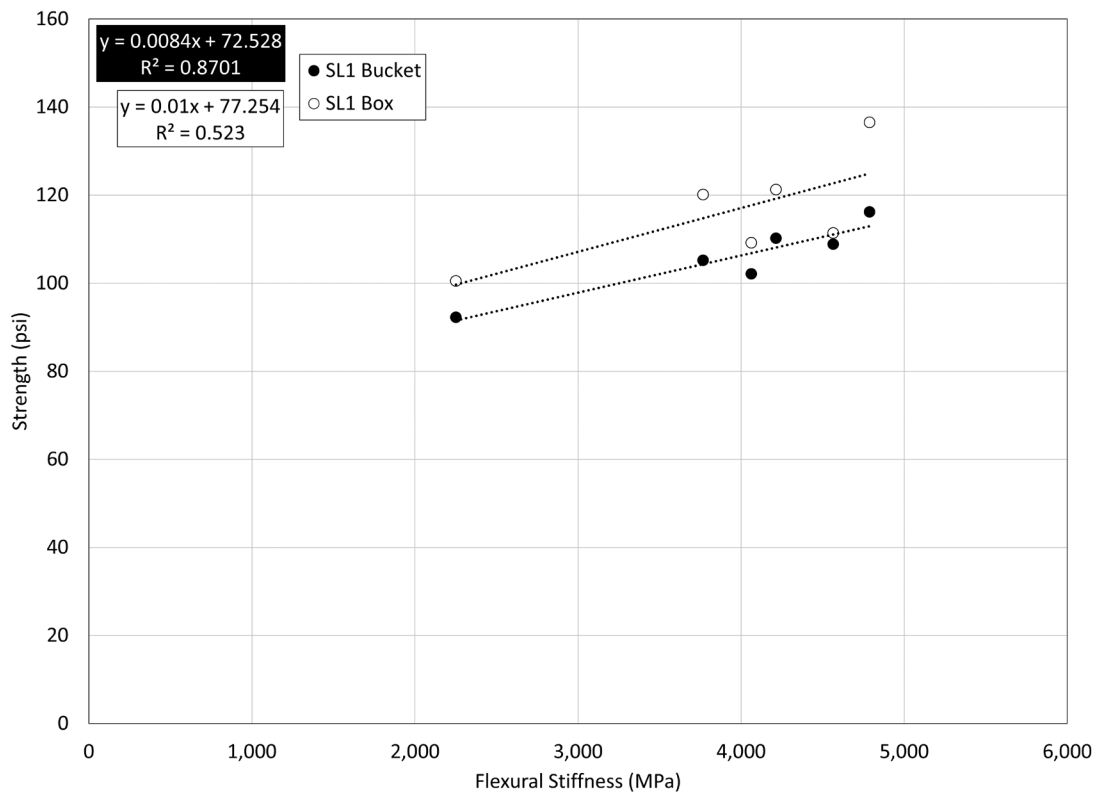


Figure 4.63: Comparison of flexural stiffness and IDEAL-CT strength of combined QA samples.

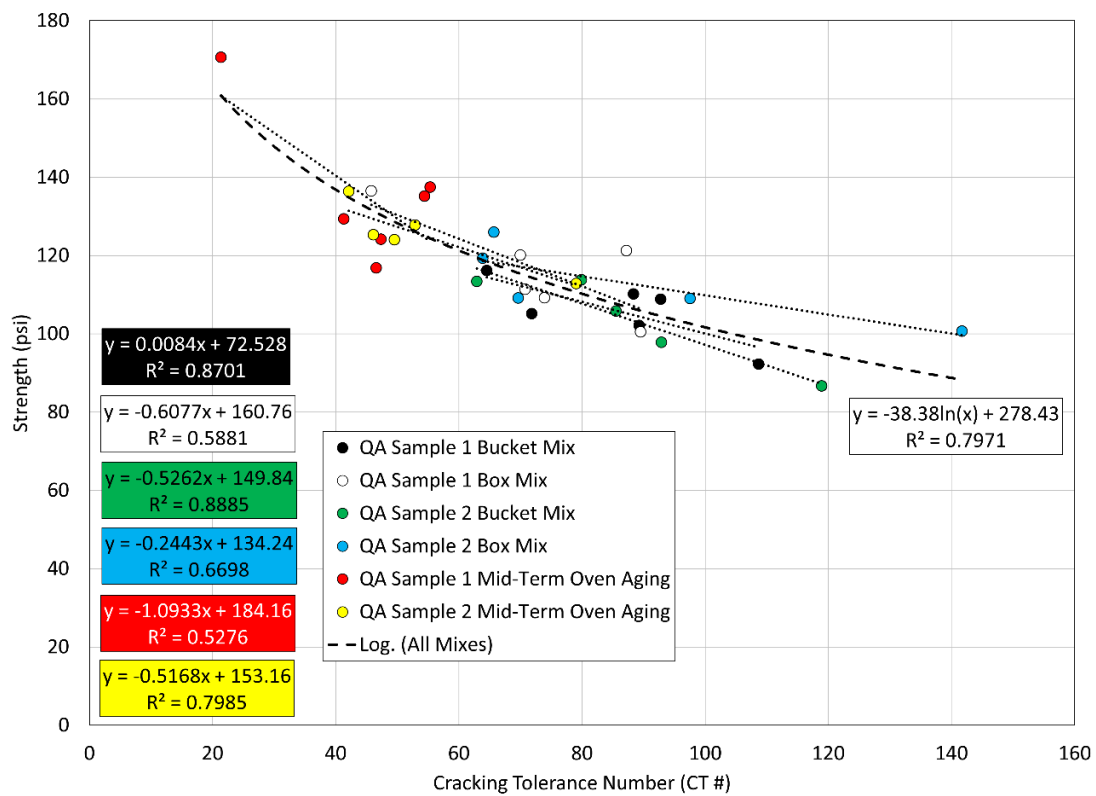


Figure 4.64: Comparison of IDEAL-CT of combined QA samples (cracking tolerance number and indirect tensile strength).

5 OBSERVATIONS FROM CONSTRUCTION

5.1 Overlay Construction

5.1.1 Milling Operations

Figure 5.1 shows the milling equipment, and Figure 5.2 shows sweeping after milling. There was nothing seen that was out of the ordinary.



Figure 5.1: Milling operation.



Figure 5.2: Sweeping prior to tacking and paving.

5.1.2 Plant Operations

There were no problems at the mixing plant that were out of the ordinary for a paving project of this type. The mixing temperature of the drum can be seen in Figure 5.3. The mixing temperature was approximately 315°F (157°C).

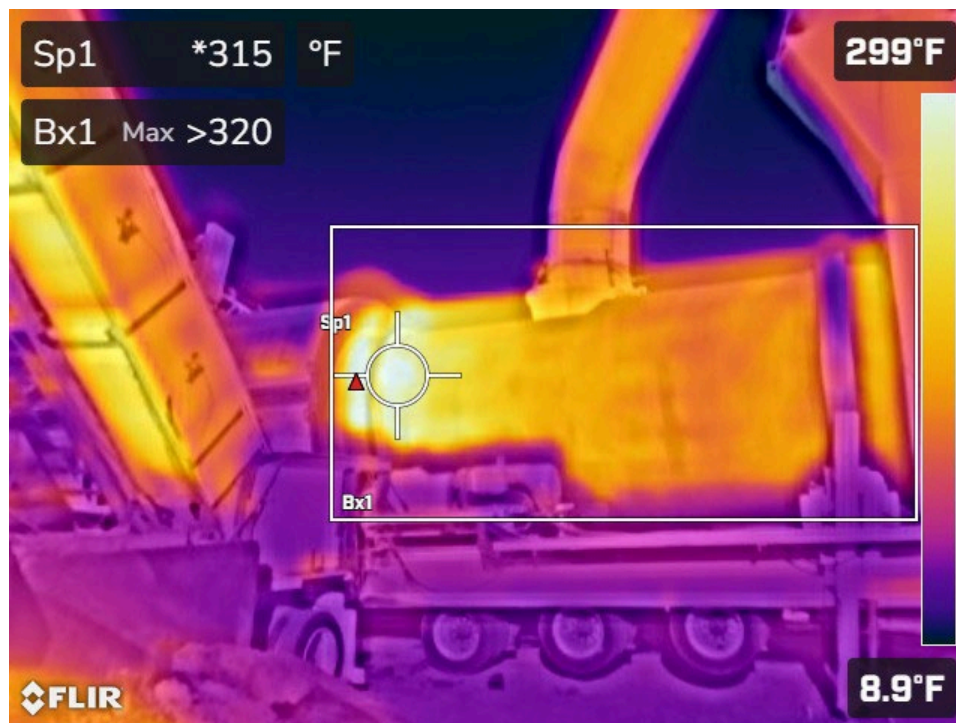


Figure 5.3: Thermal image of mixing drum.

5.1.3 Paving Operations

Figure 5.4 shows the shuttle buggy used during paving. Figure 5.5 shows placement of hot mix from the transfer truck into the shuttle buggy, and Figure 5.6 is a thermal image of that operation showing that the mix was at approximately 320°F. Figure 5.7 is a thermal image of placement from the shuttle buggy into the paver hopper at a temperature between 257°F and 312°F. Figure 5.8 shows a thermal image of the mix at the screed of the paver at a temperature between 257°F and 307°F.

Figure 5.9 shows the paver and the breakdown roller operating just behind the paver, and Figure 5.10 and Figure 5.11 are thermal images showing that the temperature of the mat was between approximately 295°F and 225°F at breakdown. Figure 5.12 shows the pneumatic-tired roller used for intermediate compaction, and Figure 5.13 is a thermal image showing that the temperature under intermediate rolling was approximately 195°F. Figure 5.14 shows the finish roller, and Figure 5.15 is a thermal image showing that the temperature at finish rolling was approximately 175°F. Figure 5.16 shows the completed overlay.



Figure 5.4: Shuttle buggy.



Figure 5.5: Placement of material from transfer to shuttle buggy.



Figure 5.6: Thermal image of placement of mix into shuttle buggy.



Figure 5.7: Mix exiting the shuttle buggy to the hopper of the paver.



Figure 5.8: Mix feeding through the paver auger to the screed.



Figure 5.9: Breakdown roller.

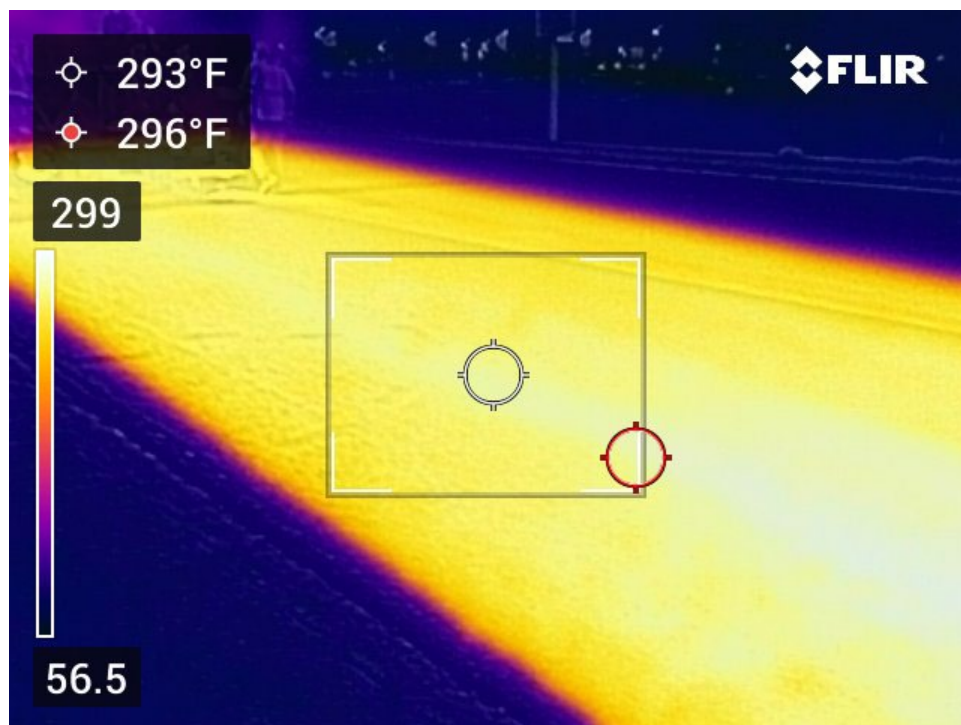


Figure 5.10: Mat temperature after breakdown.



Figure 5.11: Second image of mat after breakdown.



Figure 5.12: Pneumatic-tired intermediate roller.



Figure 5.13: Thermal image of mat under intermediate pneumatic-tired roller compaction.



Figure 5.14: Finish roller.

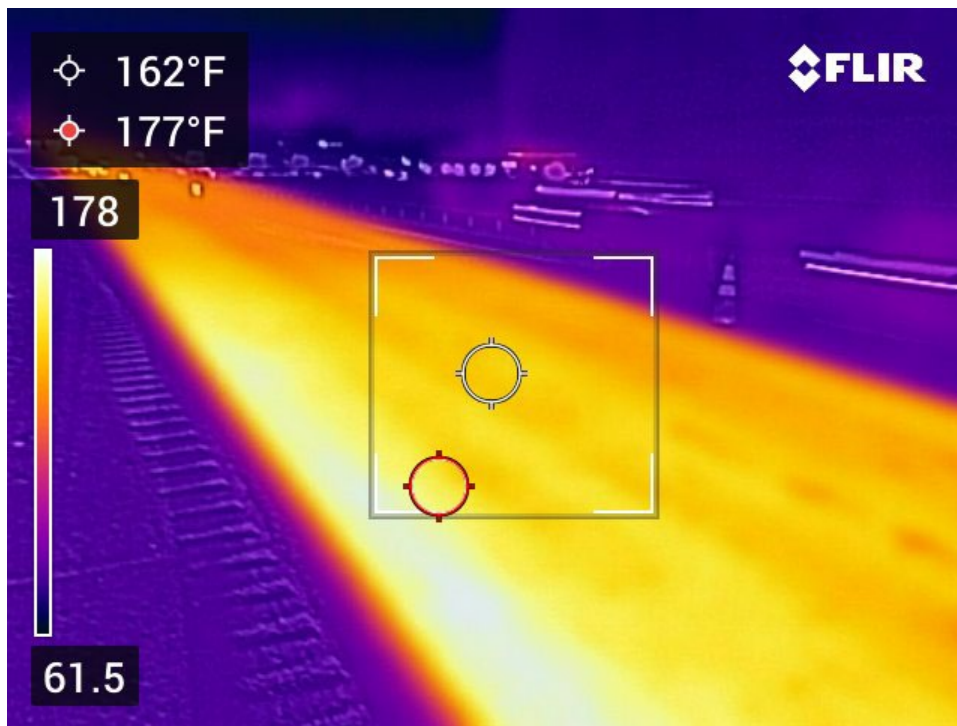


Figure 5.15: Mat temperature at finish rolling.



Figure 5.16: Completed overlay.

6 CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

The following conclusions are drawn from the data collected during JMF verification and QA testing for six mixes included in the SBD 215 pilot project. For reference, the six mix designs are summarized as follows:

- Mix E, with PG 64-28M binder and used as the control mix for this project, containing 0% RAP aggregate and binder and 0.5% LAS (amine type)—although mixes without RAP are not typically used on Caltrans projects
- Mix Q, the mix used for the project outside of the test section and typical of Caltrans HMA mixes in terms of use of RAP and RAS, containing 23% RAP aggregate and 0.5% LAS
- Mix F, containing 25% RAP aggregate and 2.7% RA (refined tall oil)
- Mix G, containing 30% RAP aggregate and 3.8% RA (refined tall oil)
- Mix H, containing 35% RAP aggregate and 5.8% RA (refined tall oil)
- Mix I, containing 40% RAP aggregate and 8.3% RA (refined tall oil)

6.1.1 Performance-Related Properties of the Six Mixes

Conclusions based on the results from the performance-related binder and mix tests are the following:

- JMF binder tests:
 - The extracted binders consisting of base binder, RAP binder, and RA sampled for JMF review passed the high, low, and intermediate temperature specifications.
 - Only the control mix binder consisting only of virgin PG 64-28M base binder and Mix F with PG 58-34M, 25% RAP, and RA passed the delta T_c specification. There is FHWA guidance and past UCPRC experience with other polymer-modified Caltrans mixes that indicate delta T_c may not be a good parameter to use with modified binders.
 - High temperature stiffnesses were similar between the different mixes, as expected since the RA doses were primarily based on meeting the high temperature grade of the PG 64-28M binder in the control mix. The intermediate temperatures were also similar. However, the low temperature true grades varied more widely, and those of the mixes with 30%, 35%, and 40% RAP and RA (Mixes G, H, and I, respectively) did not meet the PG specification limit. It should be noted that the mainline mix (Mix Q) with 23% RAP and no RA but a stepped-down base binder grade (PG 58-34M) also did not pass the low temperature specification by 6°C, indicating that the current specification resulted in greater risk of low temperature cracking than did Mixes G, H, and I.
- JMF mix tests:
 - All the mixes with RAP and RA in the test sections (Mixes F through I) met the IDEAL-CT cracking tolerance index (CT #) value in the specification, which was set based on the

control mix (Mix E). This was the only JMF mix test performed because it is the only mix test in the specification.

- QA binder tests:
 - The control mix (Mix E) binder that was supposed to be PG 64-28M binder with no RAP or RA did not meet the high temperature requirement. This, and all other test results in this report, strongly suggest that the PG 58-34M binder used in all the other mixes in the project was accidentally used instead of the specified binder.
 - The high, intermediate, and low temperature true grades were consistent between the two QA samples.
 - Mix H and Mix I, with 35% and 40% RAP, respectively, as well as RA, met the high temperature requirements for the PG 70 binder, which does not meet the intention of the specification that the blended binder be a PG 64 binder.
 - In production, all of the mixes except the mainline mix (Mix Q) and one of the QA samples for the mix with 40% RAP (Mix I) met the low temperature criteria for PG 64-28M.
 - The extracted binder from the mix with 40% RAP and RA (Mix I) had a much stiffer binder stiffness master curve than those of the other binders with RAP and RA.
- QA mix tests:
 - QA volumetric mix properties were measured and averaged for the test section mixes (all but Mix Q). Overall, the results of UCPRC testing of the aggregate gradations, binder contents, and air-voids under gyratory compaction indicate that the mixes mostly met specifications and were generally consistent between QA sublots. Differences observed between the binder contents from UCPRC extraction and from the contractor's laboratory ignition oven are concerning and indicate that the ignition oven method did not produce consistent results for some of these mixes. The air-voids under gyratory compaction are also different for the contractor's results and the UCPRC results, with UCPRC results indicating that the mixes are generally within specification or somewhat lower for the two mixes with the highest RAP content, while the contractor's data show very low air-voids for the second QA subplot for the two high RAP mixes. The QA aggregate gradations for the high RAP mixes are at the fine limit of the gradation specification.
 - Flexural dynamic modulus master curves were similar for all the mixes, except for the control mix (Mix E), which appears to have the wrong binder. The mix stiffnesses at intermediate and higher temperatures rank from stiffest to softest in the same approximate order as highest RAP to lowest RAP content, except for the mainline mix (Mix Q) with 23% RAP and no RA, which is the stiffest. The axial dynamic modulus master curves are even more similar to each other, except for the control mix (Mix E), which is much softer, and also generally follow the same order as the flexural master curves, except that Mix I with 40% RAP is not one of the stiffest.

- The extracted binders are fully diffused by the extraction process, while in the mix there may be less than complete diffusion. The extracted binder and mix frequency sweep results had similar rankings and trends indicating good diffusion of the RAP, RAS, and virgin binders, except in Mix I, which had 40% RAP and RA.
- The RLT test results for the high RAP mixes could not be compared well with the control mix (Mix E) because the control mix likely had the wrong (softer) binder. The mix with 40% RAP and RA (Mix I) also generally had poorer performance in this high temperature rutting test. This finding may be related to the possibility that this mix did not have the RAP binder fully diffused with virgin binder.
- The flexural fatigue test results showed greater variability than is typical. On average, the fatigue results of the different mixes varied depending on the strain level, generally doing better than the soft control mix at low frequencies and not as well at higher strain levels.
- Regarding the IDEAL-CT results, the IDEAL-CT cracking tolerance index (CT #) values of the high RAP mixes with RA all exceeded the JMF control mix with no RAP or RA and the correct binder, as did the mainline mix (Mix Q) with 23% RAP and no RA. IDEAL-CT indirect tensile strengths generally followed an inverse pattern to the CT # values, as expected.
- IDEAL-CT test results for mixes subjected to MTOA following the draft protocol developed by METS and UCPRC showed similar patterns between mixes as the reheated results and were similar between the two sublots for each mix. That finding is not unexpected considering that the same base binder was used in every mix and the same RAP and RA sources were used in those mixes with RAP and/or RA.
- HWT test results are generally similar between all mixes and both QA sublots, except that the first sample of the control mix from the first QA subplot had much greater rutting and had an early inflection point that indicated moisture damage.

6.1.2 The Six Mixes and Their Specifications

Conclusions based on experience in this pilot project and review of the specifications are the following:

- The contractor used a combination of the PG grade of the base binder and different dosages of RA to produce mixes to try to meet the specifications for delta T_c . The results indicate that there was varying success in meeting all criteria. Matching the high temperature PG grade resulted in mixes that did not consistently meet the low temperature PG grade in JMF review, but which much more consistently met it during production. It was also seen that the polymer-modified base binder had a delta T_c value that was very near the specified limit, and this requirement was not consistently met in the QA samples for the mixes with RAP and RA using this binder.
- It is uncertain how setting the specification for the IDEAL-CT value based on test results for a control mix that has no RAP or RAS can be carried forth into future specifications, due to

practical considerations. There are also practical considerations for the use of this approach in routine practice.

- The practice of requiring same high temperature blended binder properties as a method of avoiding binder testing at intermediate and low temperatures indicates that for some binders the corresponding meeting of low and intermediate temperature properties will occur.
- Mix test variability was similar for this project as for previous projects, with the exception that the fatigue test data were somewhat more variable.
- Carbonyl content was found to be a good predictor of binder stiffness, the Glover-Rowe parameter related to block cracking, and the crossover modulus related to low temperature creep with aging.

6.1.3 Prior Condition and Construction of the Test Sections

Conclusions from observations during construction, including at the mixing plant and at the test sections during paving, are the following:

- The test sections were placed in Lane 1 in both directions of travel. According to the most recent APCS data prior to construction, the existing pavement had nearly zero wheelpath cracking distress in Lane 1 in both directions, and rut depths were 10 to 12 mm in Lane 1 in both directions prior to placement of the overlay. In the adjacent Lane 2 in the northbound direction, there was no wheelpath cracking, and nearly 25% of the Lane 2 wheelpath was cracked in the southbound direction. In addition, rut depths were nearly 20 mm in Lane 2 in both directions.
- There were no problems observed during mix production and paving of the test sections.
- The final paved test section surfaces exhibited good condition with no observable problems.

6.2 Preliminary Recommendations

The following recommendations are based on the conclusions presented above:

- Use of the high temperature grade to control intermediate and low temperature properties of blended binders should be reconsidered. This approach to specification may increase the risk of rutting without obtaining better cracking resistance, and it does not necessarily guarantee that low and intermediate temperature properties will be met.
- Valuable information was gathered in this pilot project, and additional pilot projects for high RAP and RAS should be built and monitored to gain additional information regarding mixes and simplified performance tests. Mix types containing less than 15% RAP or a stepped-down binder grade and up to 25% RAP should be considered for use as the control since they represent current practice.
- The scope of testing was somewhat reduced for this pilot project compared to the El Dorado 49 pilot project. This somewhat reduced scope can be completed with available resources on future projects.

- The potential performance-related tests should continue to be assessed for efficiency, variability, sensitivity to important variables, and practicality.
- The protocol for laboratory MTOA of loose mix was used for the IDEAL-CT tests in addition to tests on reheated plant-sampled mix. It is recommended that this be continued in future pilot projects.

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APPENDIX A PROVISIONAL REHEATING MEDIUM-TERM OVEN AGING PROTOCOL

The test method shown in this appendix substantially corresponds to the subsequent Caltrans Test Method 320. It does not reflect requirements in CT 320 regarding time that the mix can spend at room temperature and the need to cover the samples.²

² The Provisional Method of Test for Laboratory Conditioning of Dense-Graded Asphalt Mixtures (Expires 01/07/2026) document is available at <https://dot.ca.gov/-/media/dot-media/programs/engineering/documents/californiatestmethods-ctm/ct-320-jan2025-a11y.pdf>.

DEPARTMENT OF TRANSPORTATION

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**PROVISIONAL METHOD OF TEST FOR LABORATORY CONDITIONING OF
DENSE-GRADED ASPHALT MIXTURES****EXPIRES 01/07/2026****A. SCOPE**

This provisional test method describes the procedure for laboratory conditioning of dense-graded asphalt mixture prior to compaction in the laboratory. The loose mixture from this test method is used to estimate the volumetric properties, cracking, rutting, and moisture damage resistance of the asphalt mixture soon after production and/or after in-service aging in the field.

B. REFERENCES

AASHTO R 47	Reducing Samples of Asphalt Mixtures to Testing Size
AASHTO R 30	Standard Practice for Short-Term Laboratory Conditioning of Asphalt Mixtures
AASHTO T 209	Standard Method of Test for Theoretical Maximum Specific Gravity (G_{mm}) and Density of Asphalt Mixtures
AASHTO T 312	Standard Method of Test for Preparing and Determining the Density of Asphalt Mixture Specimens by Means of the Superpave Gyratory Compactor
CT 125	Method of Test for Sampling Highway Materials and Products Used in the Roadway Pavement Structure Sections

C. SIGNIFICANCE AND USE

Asphalt mixtures have varying asphalt binder contents, different combinations of additives, aggregates, reclaimed asphalt pavement (RAP), reclaimed asphalt shingles (RAS), and other components. Mixtures may be prepared in the laboratory or may be produced in the plants. Mixtures may also be sampled and tested shortly after production; however, their performance may significantly change after several years of in-service aging in the field.

The short-term oven conditioning (STOC) for laboratory prepared mix is designed to allow for binder absorption during the mixture design and to simulate the plant-mixing effects on the mixture. The mid-term oven aging (MTOA) test is designed to simulate the field aging of mixtures in an accelerated manner. It specifically applies to cracking tests, as the cracking performance of mixtures is more sensitive to long-term aging. The rapid mid-term oven aging (RMTOA) is an accelerated alternative to the MTOA, offering a quicker turnaround time during production. This is a provisional test method to be used on selected pilot projects only.

D. APPARATUS

1. Pan – Shallow metal pan for heating 1-2 in. of the sample size of uncompacted asphalt mixtures. The pan must be large enough to hold the sample test size.
2. Boxes – Sample containers must be cardboard boxes 8 in. x 8 in. x 4 in. or 8-1/2 in. x 8-1/2 in. x 4-1/2 in.
3. Oven – Forced-draft oven, thermostatically controlled, capable of maintaining any desired temperature setting from room temperature to $176 \pm 3^{\circ}\text{C}$ ($348 \pm 5^{\circ}\text{F}$).
4. Spatula – Metal spatula or spoon suitable for stirring heated loose asphalt mixtures.

E. LABORATORY CONDITIONING PROCEDURES

E.1. REHEATING OF PLANT PRODUCED MIXTURES

The reheating procedure applies only to plant produced loose mixtures that have been sampled in accordance with CT 125.

Preheat oven for a minimum of 2 hours prior to conditioning so that when the oven is fully loaded and the air is on, the oven will equilibrate at $135 \pm 3^{\circ}\text{C}$ ($275 \pm 5^{\circ}\text{F}$) or to the mixture's compaction temperature $\pm 3^{\circ}\text{C}$ ($\pm 5^{\circ}\text{F}$), whichever is lower. Keep boxes folded closed during reheat to avoid excessive oxidation.

1. **In-box fresh sample:** Place boxes of the mixture in a preheated oven. Reheat the mixture for 1 hour. Mixtures in boxes will be considered as fresh if the mixture is workable enough to be split.
2. **In-box cold sample:** Place boxes of the mixture in a preheated oven. Reheat the mixture for 2 hours. Continue reheating for an additional 1 hour if the mixture is not sufficiently workable.
3. If the boxes have not been combined in the field, combine them in accordance with California Test 125.

4. Split the boxes of mixture to individual sample sizes in accordance with AASHTO R 47.

Note 1: The reheating process must only be applied to boxes that can be split immediately after reheating.

Note 2: Separate an appropriate amount of loose mix to measure the maximum specific gravity (G_{mm}) using AASHTO T 209. The oven conditioning of samples used for G_{mm} measurement must be consistent with the oven conditioning of samples used for compaction of specimens.

5. Place the test sample in a pan, and spread it to an even thickness equal to approximately 1-2 in.
6. Keep the pan with the mixture at controlled room temperature $25 \pm 6^{\circ}\text{C}$ ($77 \pm 10^{\circ}\text{F}$) for a minimum of 1 hour and not to exceed 72 hours. Samples left out for longer than 3 hours must be covered with aluminum foil or any suitable cover and kept out of direct sunlight to avoid excessive oxidation.

E.2. SHORT-TERM OVEN CONDITIONING (STOC) OF LABORATORY PREPARED MIXTURES

The Short-Term Oven Conditioning (STOC) procedure applies only to laboratory-prepared loose mixtures. STOC should be used to determine volumetric properties and conduct mechanical tests during mix design stage.

Preheat oven for a minimum of 2 hours prior to conditioning so that when the oven is fully loaded and the air is on, the oven will equilibrate at a temperature of $135 \pm 3^{\circ}\text{C}$ ($275 \pm 4.5^{\circ}\text{F}$) or to the mixture's mixing temperature $\pm 3^{\circ}\text{C}$ ($\pm 5^{\circ}\text{F}$), whichever is lower.

1. Place the uncovered pan with the mixture in a pre-heated oven for $4 \text{ h} \pm 5 \text{ min}$.
2. At the end of $4 \text{ h} \pm 5 \text{ min}$, remove the samples from the oven. Keep the pan with the mixture at controlled room temperature ($77 \pm 9^{\circ}\text{F}$) for a minimum of 1 hour and not to exceed 72 hours. Samples left out for longer than 3 hours must be covered with aluminum foil or any suitable cover and kept out of direct sunlight to avoid excessive oxidation.

E.3. MID-TERM OVEN AGING (MTOA)

The Mid-Term Oven Aging (MTOA) procedure applies to both lab-prepared and plant produced loose mixtures. MTOA should be used only for mixtures that will be compacted for cracking tests during mix design, and mix design verification.

Note 3: For mix design verification, MTOA applies only to plant-produced loose mixtures.

Preheat oven for a minimum of 2 hours prior to conditioning so that when the oven is fully loaded and the air is on, the oven will equilibrate at $100 \pm 3^{\circ}\text{C}$ ($212 \pm 4.5^{\circ}\text{F}$).

1. Place the uncovered pan with the mixture in a pre-heated oven for $20 \text{ h} \pm 30 \text{ min}$.
2. At the end of $20 \text{ h} \pm 30 \text{ min}$, remove the samples from the oven. Keep the pan with the mixture at controlled room temperature ($77 \pm 9^{\circ}\text{F}$) for a minimum of 1 hour and not to exceed 72 hours. Samples left out for longer than 3 hours must be covered with aluminum foil or any suitable cover and kept out of direct sunlight to avoid excessive oxidation.

E.4. RAPID MID-TERM OVEN AGING (RMTOA)

The Rapid Mid-Term Oven Aging (RMTOA) procedure applies only to plant produced loose mixtures. RMTOA should be used for mixtures that will be compacted for cracking tests during production.

Note 4: RMTOA may also be used during mix design verification to establish a correlation between MTOA and RMTOA.

Refer to the Safety Manual for your Laboratory.

Preheat oven for a minimum of 2 hours prior to conditioning so that when the oven is fully loaded and the air is on, the oven will equilibrate at $135 \pm 3^{\circ}\text{C}$ ($275 \pm 4.5^{\circ}\text{F}$).

1. Place the uncovered pan with the mixture in a pre-heated oven for $3 \text{ h} \pm 5 \text{ min}$.
2. At the end of $3 \text{ h} \pm 5 \text{ min}$, remove the samples from the oven. Keep the pan with the mixture at controlled room temperature ($77 \pm 9^{\circ}\text{F}$) for a minimum of 1 hour and not to exceed 72 hours. Samples left out for longer than 3 hours must be covered with aluminum foil or any suitable cover and kept out of direct sunlight to avoid excessive oxidation.

Note 5: It is recommended that RMTOA specimens be placed in the oven on a schedule matched to the time needed to compact gyratory specimens.

E.5. HEATING TO COMPACTION TEMPERATURE

Preheat oven for a minimum of 2 hours prior to testing so that when the oven is fully loaded and the air is on, the oven will equilibrate at the mixture's compaction temperature $\pm 3^{\circ}\text{C}$ ($\pm 5^{\circ}\text{F}$).

1. Place the uncovered pan with the mixture from E.1, E.2, E.3, or E.4 in a preheated oven for $2\text{ h} \pm 15\text{ min}$.
2. Stir the mixture after $1\text{ h} \pm 5\text{ min}$ to maintain uniform heating.
3. Proceed to compaction in accordance with AASHTO T 312.

Note 6: Any mixture that has been in the oven at compaction temperature for greater than $2\text{ h} + 15\text{ min}$ must be discarded.

F. REPORTING OF RESULTS

If required by the contract documents, submit test results electronically in accordance with the guidance documents found at the following link:

[DIME Website](#)

G. HEALTH AND SAFETY

It is the responsibility of the user of this test method to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use. Prior to handling, testing or disposing of any materials, testers must be knowledgeable about safe laboratory practices, hazards and exposure, chemical procurement and storage, and personal protective apparel and equipment.

End of Text
(California Test 320 contains 5 pages)

APPENDIX B IDEAL-CT BOX SAMPLE RESULTS

The following results are for IDEAL-CT tests on samples that were stored and reheated from cardboard boxes. These results correspond to samples taken at the same time in the field and stored and reheated in 3.5-gallon sealed steel buckets, shown in Figure 4.45 through Figure 4.48 in the main body of this technical memorandum.

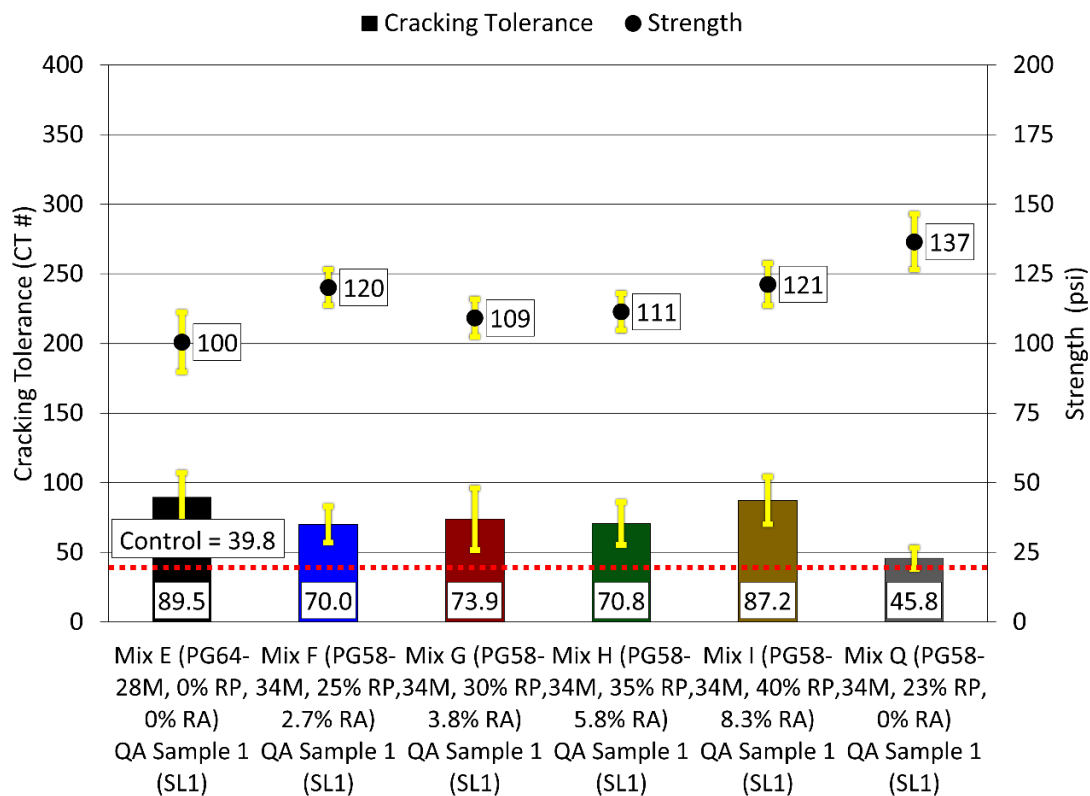


Figure B.1: IDEAL-CT results for subplot 1 QA box mixes (cracking tolerance index and indirect tensile strength).

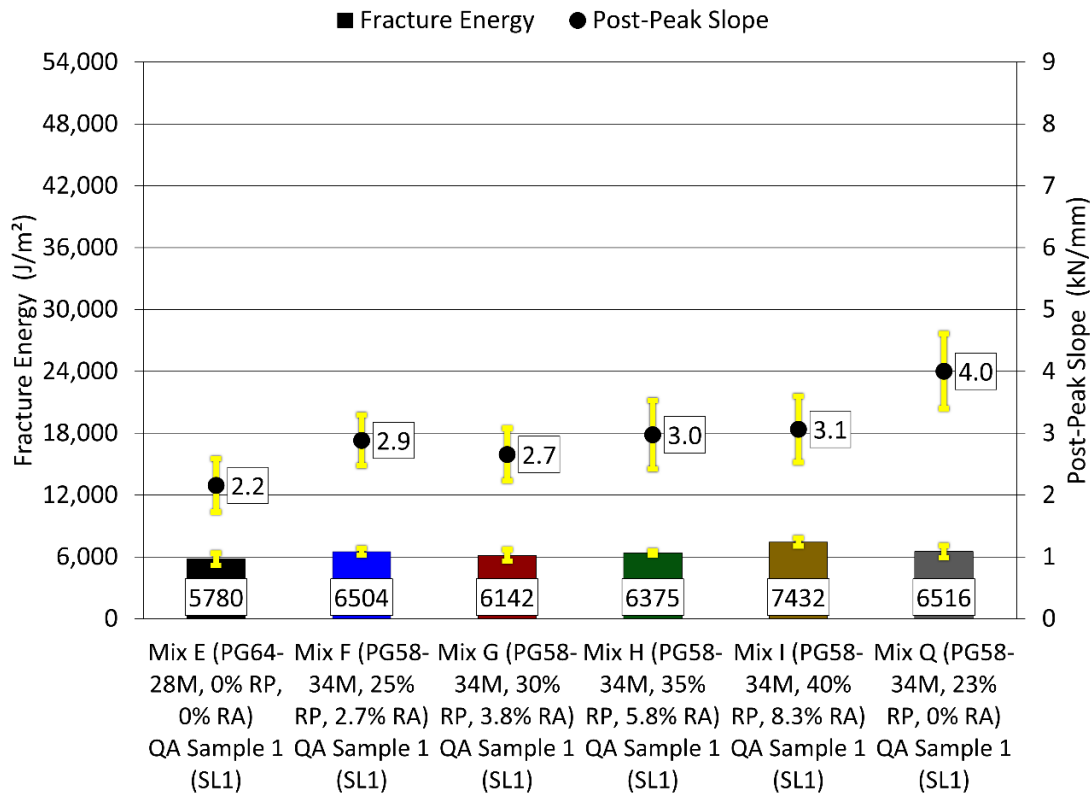


Figure B.2: IDEAL-CT results for subplot 1 QA box mixes (fracture energy and post-peak slope).

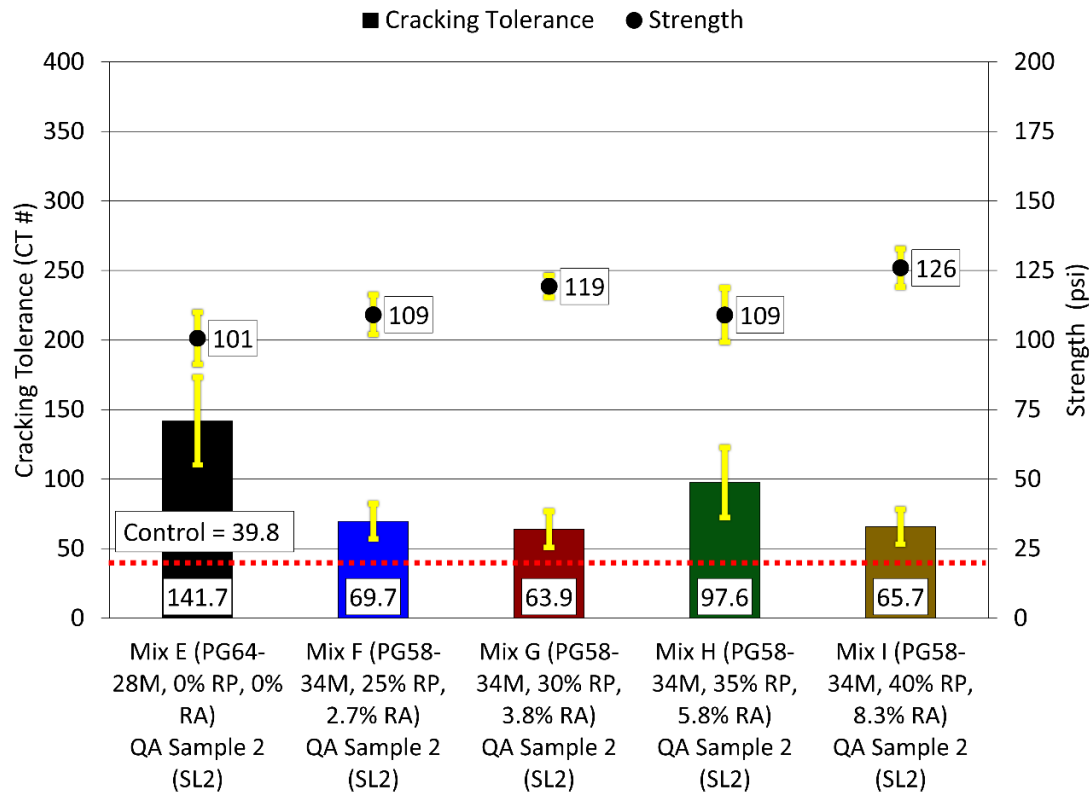


Figure B.3: IDEAL-CT results for subplot 2 QA box mixes (cracking tolerance index and indirect tensile strength).

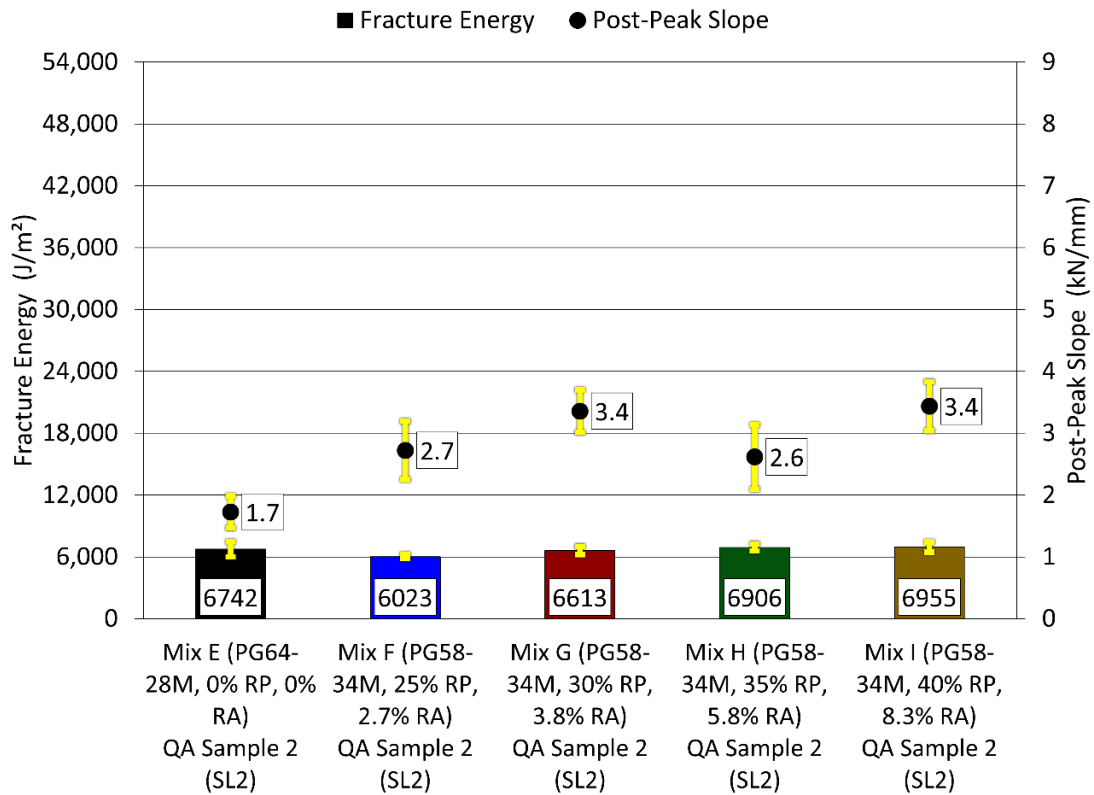


Figure B.4: IDEAL-CT results for subplot 2 QA box mixes (fracture energy and post-peak slope).

