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RESEARCH REPORT

100% RAP Pilot Project on SBD 40: Material Testing, Life Cycle Assessment, Observations, and Findings

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16. ABSTRACT

This report presents data and analysis of a new mix type that has 100% replacement of aggregate and asphalt binder with reclaimed asphalt pavement (RAP) and the addition of a recycling agent. The data were collected from construction of a pilot project on Interstate 40 in San Bernardino County, which included the new mix , HyRAP® (a registered trademark owned by Brooks Construction Company, Inc. and licensed to Manhole Adjusting Inc. but produced under a non-proprietary Caltrans Non-Standard Special Provision), the control gap-graded rubberized hot mix asphalt (RHMA-G), and a dense-graded polymer-modified mix (HMA-M) that was used in wheelpath digouts on the project. The report includes performance-related testing, a life cycle assessment, and a summary of observations from the construction of the pilot project. It also includes deflection testing results for the test sections and outside the test sections to check if they have similar underlying support. The life cycle assessment includes identification of the primary sources of greenhouse gas and other emissions in the mix production. A comparison is made between the early field performance of the test sections for rutting and the performance-related laboratory rutting tests. Recommendations are that further development of HyRAP be done on projects with less risk and that they aim to demonstrate the ability to achieve mix consistency during production. It is also recommended that approaches for reducing the greenhouse gas emissions from the oxidizer used to reduce volatile organic compounds be explored.

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PROJECT OBJECTIVES

The research presented in this report is part of Caltrans-University of California agreement 65A1056 Task Order 5 "Continued Support for Implementation of Performance-Related Tests and Specifications for Balanced Mix Design (BMD), Increased Recycling of Asphalt Mixes, and Integration of Mix Design and Structural Design" (2023-2026). The goals of Task Order 5 are to identify and develop a comprehensive set of performance-related tests that will be used in BMD performance-related specifications framework, and to evaluate new asphalt mix types including mixes with high percentages of reclaimed asphalt pavement (RAP). This report presents data and analysis of a new mix type that has 100% replacement of aggregate and asphalt binder with RAP and the addition of a recycling agent. The data were collected from construction of a pilot project on I-40 in San Bernardino County, which included the new mix (trademarked as HyRAP® but produced under a non-proprietary Caltrans non-standard special provision), the control gap-graded rubberized hot mix asphalt (RHMA-G), and a dense-graded polymer-modified mix (HMA-M) that was used in wheelpath digouts on the project. The report includes performance-related testing, life cycle assessment, and a summary of observations from the construction of the pilot project.

EXECUTIVE SUMMARY

Background

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. One approach under investigation that offers the potential to advance these goals is the use of increased amounts of reclaimed asphalt pavement (RAP) in hot mix asphalt (HMA) materials. The University of California Pavement Research Center (UCPRC) has been investigating for Caltrans the 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 using highly aged, stiff RAP without additional engineering. Research is underway at the UCPRC to study the impact of different RAP sources, varying RAP content, and the addition of recycling agents (RAs) to engineer the performance-related properties of binders and mixes considering the properties of highly aged RAP and RAS.

Caltrans also has the goal of implementation of balanced mix design, which relies on performance-related tests and performance-related specifications to help ensure that the mechanistic properties of asphalt mixes used by Caltrans will perform as expected and that the properties of the asphalt mixes delivered by contractors sufficiently match the properties used as input in mechanistic-empirical pavement structural design. Several performance-related tests have been identified to assess the performance 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 test. Other recently developed tests, such as the indirect tensile asphalt cracking test (IDEAL-CT), 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 purposes.

This report presents the results of a large sampling, testing, and analysis project for an asphalt mix type containing 100% RAP and no virgin asphalt binder or aggregate, known as HyRAP®.[*] This mix was manufactured and placed on a pilot project on I-40 in San Bernardino County by Manhole Adjusting Inc. in 2023. Caltrans wrote a non-proprietary Non-Standard Special Provision (nSSP) for the use of HyRAP® on the I-40 pilot project constructed in 2023. The details of the mix designs using the HyRAP approach (100% RAP plus RA) have changed over time and will likely continue to be adjusted as experience is gained.

Previous HyRAP Project for Caltrans

A version of HyRAP mix was used in a thin overlay as part of an emergency repair on a Caltrans freeway connector in San Diego County in June 2022. That mix was sampled by G3 Quality, Inc. and

[*] HyRAP is a registered trademark owned by Brooks Construction Company, Inc. and licensed to Manhole Adjusting Inc.

subjected to performance-related tests for fatigue resistance, flexural and axial dynamic stiffness, age-related cracking resistance, and permanent deformation resistance as well as permanent deformation resistance combined with moisture damage resistance. The results of that testing were reported to G3 Quality, Inc. in an informal technical memorandum that is included in Appendix A. A brief condition survey was performed by Caltrans in June 2024, which is summarized in Appendix B.

HyRAP Project Studied in This Project

In September 2023, HyRAP was used in short test sections on a pilot project on I-40 in the Mojave Desert in San Bernardino County. The HyRAP mix was sampled by the UCPRC on five days over two weeks along with two other mixes that were used on the project. The mixes were sampled at their production plants and brought to the UCPRC laboratories in Davis and Richmond for testing. The HyRAP mix was subjected to a range of mix tests used on the 2022 samples from San Diego County as well as extracted binder tests, and the results were compared with those of the gap-graded rubberized hot mix asphalt (RHMA-G) with no RAP used as a thin overlay in most of the I-40 project and a polymer-modified hot mix asphalt (HMA-M) with 25% RAP used in the digouts on the I-40 project but representative of HMA-M mixes being used by Caltrans. Some comparisons of fatigue performance and stiffness were also made with the statewide median PG 64 and PG 70 mixes.

Cursory observations were made at the construction location on I-40 when the UCPRC sampling crew visited the site. The Caltrans Office of Asphalt Pavement did a more comprehensive construction observation during a site visit, the results of which are included in Appendix B. Observations of the production of the 5/16 in. HyRAP 100% RAP mix at the Manhole Adjusting Inc. plant in Colton, California, were as follows:

- During the first week of production, when UCPRC was on-site, (Sample 1 collected on September 20 and Sample 2 collected on September 21, 2023), relatively low binder contents were produced.
- Sample 1 was observed to have been produced at a very high temperature, although temperatures were not measured.
- Sample 2 was observed to have been produced at a lower temperature, although temperatures were not measured.
- During the second week of production during which UCPRC was on-site (Sample 3 collected on September 25, Sample 4 collected on September 26, and Sample 5 collected on September 27, 2023), the binder contents were increased and production continued at the lower temperatures than were used for Sample 1.

Observations of the production of the 1/2 in. HMA PG 64-28M with 25% RAP mix (used in the digouts) at the Sully-Miller plant in Victorville, California, were as follows:

- Sample 1 collected on December 3, 2023, had less than two hours of silo time.
- Sample 2 collected on December 4, 2023, had about 12 hours of silo time (it was produced at 5 am and sampled at about 4 pm).

Observations of the production of the ¾ in. RHMA-G mix (used as the overlay on most of the project) at the Sully-Miller plant in Victorville, California, were as follows:

- Sample 1 collected on April 4, 2024, had less than two hours of silo time.
- Sample 2 also collected on April 4, 2024, had about four hours of silo time.

Deflection tests were performed by the Caltrans South Regional Laboratory and analyzed by the UCPRC to determine whether the locations where the RHMA-G and HyRAP were placed had similar subgrade stiffness and similar overall pavement structural capacity. An environmental life cycle assessment (LCA) was performed for the ISO 21930 A1 to A3 life cycle stages (material extraction, material transportation in the supply chain, and material production), also known as "cradle to gate." The LCA primarily focused on global warming impact (GWI, also commonly referred to as global warming potential [GWP]).

Comparisons were made between the performance-related laboratory rutting test results and the observed field rutting performance between construction in September 2023 and July 2024 when the Lane 2 HyRAP mixes were removed because of rutting. The Lane 2 mixes removed were Sample 4 and Sample 5, which had the highest binder contents and did not have high mixing temperatures.

Research Questions Answers

A set of questions was developed as part of the problem statement for the study. They are answered in the conclusions, along with summary conclusions. The questions addressed in the report and answered in the conclusions are the following:

1. **What are the results of performance-related testing of the extracted binder from the HyRAP mix sampled on I-40 project compared with the extracted binder from the HMA-M mix and the plant produced rubberized binder for the RHMA-G mix prior to mixing?**
    a. What are the performance grade (PG) high, intermediate, and low temperatures of the extracted binders?
    b. What is the aging of the binder, which controls its stiffness and viscoelastic response (phase angle) as measured by the carbonyl and sulfoxide contents, including after long-term aging using a pressure aging vessel (PAV)?
2. **What are the results of performance-related testing of the HyRAP mix sampled on the I-40 project compared with the RHMA-G and HMA-M mixes also used on the project and with the statewide median PG 64 and PG 70 HMA mixes?**
    a. Axial dynamic stiffness under different conditions of temperature and frequency of loading?
    b. Flexural dynamic stiffness under different conditions of temperature and frequency of loading?
    c. Flexural fatigue performance?

d. IDEAL-CT strength related to stiffness and age-related cracking at intermediate temperatures after both reheating and medium-term oven aging (related to aging in the field) conditioning?

e. IDEAL-CT index value related to age-related cracking at intermediate temperatures after both reheating and medium-term oven aging (related to aging in the field) conditioning?

f. Repeated load triaxial permanent deformation (rutting) resistance under both confined and unconfined conditions?

g. IDEAL-RT index value related to rutting at intermediate temperatures after both reheating and medium-term oven aging (related to aging in the field) conditioning?

h. IDEAL-CT strength results after moisture-induced stress tester (MiST) moisture conditioning?

i. Hamburg Wheel-Tracking testing related to permanent deformation and moisture damage resistance?

3. **What is the stiffness of the overall pavement and subgrade and the stiffness of the subgrade in the locations with HyRAP mix as measured by deflection testing compared with the stiffnesses (corresponding to structural capacity) where the control RHMA-G mix was placed the I-40 project?**

4. **How do the laboratory rutting test results for the different samples relate to the rutting performance of the sections where those materials were placed from construction in September 2023 to removal of Lane 2 mixes in July 2024?**

5. **What is the global warming impact calculated from modeling using known job mix formulas of the different mixes used on the I-40 project, and how do they compare with each other and with other mixes used in California, assuming the same performance?**

   a. HyRAP mix considered with and without use of the natural gas-burning oxidizer used to reduce air pollution from the mixing plant, and considering two sources of natural gas data?

   b. Compared with that of the I-40 PG 64-28M HMA with 24% RAP and RHMA-G mix designs?

   c. Compared with that of hypothetical default HMA mixes in the Caltrans life cycle assessment software *eLCAP* (*environmental Life Cycle Assessment for Pavement*) with HMA with no RAP, with 15% RAP, with no RAP/polymer-modified binder, and with an RHMA-G mix with no RAP; compared with HMA and RHMA-G mixes with California EPDs; and compared with a 30% RAP mix from the National Asphalt Pavement Association (NAPA) life cycle assessment tool?

Experimental Approaches

The following are the experimental approaches used for this research project:

- The approach for measurement and comparison of the performance-related properties of the mixes was to sample the mixes in the field, transport them in cardboard boxes and metal buckets to the UCPRC laboratories in Davis and Richmond, reheat the buckets to split the samples and compact the test specimens, and test them, including testing after medium-term oven aging of the loose mix for IDEAL-CT testing. The approach for the measurement and comparison of the performance-related properties of the binders was to chemically extract the binders after reheating and splitting and test them, including after different conditions of long-term aging.
- The approach for comparison of laboratory test results with observed rutting performance was to identify where the different samples of materials were placed, where rutting was observed the next summer, and where the rutted materials were removed and replaced.
- The approach for the comparison of the structural capacity of the pavement in the project was to perform deflection testing throughout the project and analyze and compare the deflection data.
- The approach for the LCA GWI comparisons was to use the mix designs to identify quantities of mix components and energy used for manufacture per declared unit of mix (one metric tonne) and GWI emissions factors for each to calculate the total A1 to A3 (per ISO 21930 definitions for material extraction, material transport to production plant, mix production) GWI for the mixes.

Summary and Conclusions

The HyRAP mix had high variability of performance-related properties during its production for the I-40 project. Its potential performance is completely dependent on that variability, swinging from a high potential for cracking and low potential for rutting, to the opposite and in between, compared with the alternative HMA-M and RHMA-G mixes. The results indicate that construction variability of the binder properties in the HyRAP mix is subject to larger ranges of variability within the sources of variability than conventional mixes and that efforts should be made to reduce those. Some of the same issues (variability of RAP binder contents and aging, control of RAP and RA during mixing) will arise as RAP contents are increased in all HMA mixes, proportional to the amount of RAP and recycling agent included in the mixes.

In general, the RHMA-G mix produced and used on the project had the best overall and consistent performance-related properties. However, the RHMA-G mix had a high GWI because of its higher binder content and the lime treatment applied to the aggregate.

The HyRAP mix offers potential substantial reductions in GWI if it can be produced using RAP sources that have been stockpiled at the mix production plant and produced without use of the oxidizer to reduce volatile organic compound (VOC) emissions causing air pollution or if a heat exchanger can substantially reduce natural gas usage in the oxidizer. It was assumed in the LCA comparing the HyRAP mix with the other mixes that the RAP was already at the mixing plant site and was not transported. The LCA also showed that transporting RAP long distances can nullify the benefits of using the 100% RAP mix with respect to GWI. The same analysis indicates that use of HyRAP is especially beneficial when there are limited virgin aggregate sources nearby and aggregate must be transported long distances. Urban areas tend to have higher quantities of RAP compared with rural areas because of the need to mill old asphalt off city streets and urban freeways to match the existing curb and gutter and other grade elevation restrictions. If the HyRAP mix must be produced using the oxidizer and without the heat exchanger, then it will cause more GWIs compared with HMA alternatives unless the virgin aggregate for the other mixes is being hauled more than 100 miles.

Recommendations

The use of HyRAP can potentially offer major environmental benefits or increase environmental impacts, depending on how it is produced and what it is being compared with and assuming it performs as well as those alternatives. However, production consistency needs to be improved. Part of the reason for the highly inconsistent properties of the HyRAP mixes over the five days of paving was that many of the decisions made for the HyRAP production were driven by the long haul distance and use of HyRAP on a high truck traffic project in the hot desert.

It is recommended that any further work in the development of HyRAP be done for use on projects closer to the HyRAP plant and with less risk from heavy truck traffic. The ability to achieve mix consistency during production through management RAP stockpiles and the process controls for the RAP, the RA, and the mixing process should be demonstrated on a lower-risk project. This project could include streets, passenger car lanes of routes with higher traffic, ramps, parking lots, and other locations that meet these criteria. The focus should be on reducing production variability and using mix designs that are able to balance the risk of age-related cracking with rutting. It is recommended that the age-related cracking and moisture susceptibility of these HyRAP mixes should be evaluated for several years to verify aging and moisture related performance.

It is also recommended that it be determined if HyRAP can be produced without the oxidizer for VOCs and not have unallowable VOC emissions or with a heat exchanger. If it cannot, then there is little current possibility of achieving the desired GWI benefits and the primary benefit is the preservation of aggregate resources where they are scarce and RAP is plentiful.

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LIST OF ABBREVIATIONS

AMPT	Asphalt Mixer Performance Tester
BBR	Bending beam rheometer
BMD	Balanced mix design
CA	Carbonyl area
CT	Cracking tolerance
DSR	Dynamic shear rheometer
EPD	Environmental product declaration
FTIR	Fourier transform infrared
FTIR-ATR	Fourier transform infrared spectroscopy with attenuated total reflection
FWD	Falling weight deflectometer
GWI	Global warming impact
HMA	Hot mix asphalt
HMA-M	Polymer-modified hot mix asphalt
HyRAP	Hot mix asphalt with 100% reclaimed asphalt pavement
HWT	Hamburg Wheel-Track
IDEAL-CT	Indirect tensile asphalt cracking test
ITS	Indirect tensile strength
JMF	Job mix formula
LAS	Linear amplitude sweep
LCA	Life cycle assessment
ME	Mechanistic-empirical
MiST	Moisture-induced stress tester
MTOA	Medium-term oven aging
NMAS	Nominal maximum aggregate size
PAV	Pressurized aging vessel
PG	Performance grade
QA	Quality assurance
QC	Quality control
RA	Recycling agent
RAP	Reclaimed asphalt pavement

RAS	Recycled asphalt shingles
RHMA	Rubberized hot mix asphalt
RLT	Repeated load triaxial
RT	Rutting tolerance
RTFO	Rolling thin-film oven
SBS	Styrene-butadiene-styrene
SSD	Saturated surface-dry
SULF	Sulfoxide
TCE	Trichloroethylene
VOC	Volatile organic compound
WMA	Warm mix additive

LIST OF TEST METHODS AND SPECIFICATIONS

AASHTO M 320	Standard Specification for Performance-Graded Asphalt Binder
AASHTO PP3	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 29	Standard Practice for Grading or Verifying the Performance Grade (PG) of an Asphalt Binder
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 275	Standard Method of Test for Bulk Specific Gravity (Gmb) of Compacted Asphalt Mixtures Using Paraffin-Coated Specimens
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 (BBR)
AASHTO T 321	Standard Method of Test for Determining the Fatigue Life of Compacted Asphalt Mixtures Subjected to Repeated Flexural Bending
AASHTO T 324	Standard Method of Test for Hamburg Wheel-Track Testing of Compacted Asphalt Mixtures
AASHTO T 331	Bulk Specific Gravity (Gmb) and Density of Compacted Hot Mix Asphalt (HMA) Using Automatic Vacuum Sealing Method
AASHTO T 378	Standard Method of Test for Determining the Dynamic Modulus and Flow Number for Asphalt Mixtures Using the Asphalt Mixture Performance Tester (AMPT)
AASHTO T 391	Standard Method of Test for Estimating Fatigue Resistance of Asphalt Binders Using the Linear Amplitude Sweep
ASTM D5148	Standard Test Method for Centrifuge Kerosine Equivalent
ASTM D5404	Standard Practice for Recovery of Asphalt from Solution Using the Rotary Evaporator
ASTM D7870	Standard Practice for Moisture Conditioning Compacted Asphalt Mixture Specimens by Using Hydrostatic Pore Pressure
ASTM D8159	Standard Test Method for Automated Extraction of Asphalt Binder from Asphalt Mixtures

ASTM D8225	Standard Test Method for Determination of Cracking Tolerance Index of Asphalt Mixture Using the Indirect Tensile Cracking Test at Intermediate Temperature
ASTM D8360	Standard Test Method for Determination of Rutting Tolerance Index of Asphalt Mixture Using the Ideal Rutting Test
ASTM E131	Standard Terminology Relating to Molecular Spectroscopy
ASTM E168	Standard Practices for General Techniques of Infrared Quantitative Analysis
ISO 21930	Sustainability in Buildings and Civil Engineering Works — Core Rules for Environmental Product Declarations of Construction Products and Services

CONVERSION FACTORS

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

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

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

1 INTRODUCTION

1.1 Background

The California Department of Transportation (Caltrans) is interested in finding, developing, and implementing approaches to reduce life cycle cost and improve life cycle environmental performance. One approach under investigation that offers the potential to advance these goals is the use of increased amounts of reclaimed asphalt pavement (RAP) in hot mix asphalt (HMA) materials. Caltrans is investigating the performance of high RAP content mixes, which are mixes containing more than 25% RAP aggregates with and without the use of recycling agents, mixes containing recycled asphalt shingles (RAS), the use of RAP in surface mixes containing recycled tire rubber (gap-graded rubberized asphalt hot mix asphalt [RHMA-G]), and dense-graded mixes with recycled tire rubber and RAP. The University of California Pavement Research Center (UCPRC) has been investigating for Caltrans the 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 using highly aged, stiff RAP without additional engineering. Research is underway at the UCPRC to study the impact of different RAP sources, varying RAP content, and the addition of recycling agents to engineer the performance-related properties of binders and mixes considering the properties of highly aged RAP and RAS.

Caltrans also has the goal of implementation of balanced mix design (BMD), which relies on performance-related tests and performance-related specifications to help ensure that the mechanistic properties of asphalt mixes used by Caltrans will perform as expected and that the properties of the asphalt mixes delivered by contractors sufficiently match the properties used as input in mechanistic-empirical (ME) pavement structural design. Several performance-related tests have been identified to assess the performance 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 test. Other recently developed tests, such as the indirect tensile asphalt cracking test (IDEAL-CT), 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.

These goals are being advanced through research, development and implementation work included in Task Order 005 (TO-005) of the Partnered Pavement Research Center 2023-26 contract. The work presented in this report is part of Subtask 2A, Sampling and Testing of Pilot Projects with Asphalt Mixes with High RAP and/or RAS, and Subtask 2G, Summary of Pilot Projects Performance and Environmental Impacts, CalME Simulations, BMD Recommendations, of TO-005.

1.2 Scope of this Study

The subject of this report is the sampling and testing of a new type of mix that consists of 100% aggregate and virgin binder replacement with RAP and recycling agent (RA). This 100% RAP approach, known as HyRAP®,[1] was manufactured and placed by Manhole Adjusting Inc. on a pilot project on I-40 in San Bernardino County in 2023. Caltrans wrote a non-proprietary Non-Standard Special Provision (nSSP) for its use. The details of the mix designs using the HyRAP approach (100% RAP plus RA) have changed over time and will likely continue to be adjusted as experience is gained.

1.2.1 Previous Results from Interstate 5/State Route 163 Connector in San Diego County

Caltrans' evaluation of a 5/16" nominal maximum aggregate size (NMAS) HyRAP product produced using three bins with different gradations of RAP started in the summer of 2022 when a HyRAP material produced by Manhole Adjusting, Inc. was placed on the Hawthorn Street exit ramp (exit 17A) from northbound Interstate 5 onto State Route 163 in San Diego County. The UCPRC was contacted by G3 consultants to sample and test that material using performance-related tests, and it did so under advisement of the Caltrans Office of Asphalt Pavement (OAP) and District 11. In February 2023, the UCPRC sampled material following the same mix design used in the previous summer's construction by "hot drop" at the plant and tested that material after reheating for compaction using performance-related testing. The performance-related test results were compared with five conventional HMA (Type A) materials with RAP contents between 15% and 25% and two polymer-modified HMA materials with 15% and 25% RAP from the Caltrans Standard Materials Library. The technical memorandum with the test results was delivered to G3 and G3 delivered those results to District 11 and the OAP. That technical memorandum is included in Appendix A of this research report.

The comparison of results showed that the District 11 HyRAP mix was promising in terms of flexural stiffness, flexural fatigue, axial stiffness, IDEAL-CT strength (related to stiffness), RLT testing for rutting under confined and unconfined conditions, and Hamburg Wheel-Tracking testing for rutting and moisture sensitivity. Test results for the IDEAL-CT index value indicated that the HyRAP material was more at risk for environmental-related cracking than the HMA and polymer-modified HMA materials.

A surface condition evaluation two years after construction was performed by the OAP in June 2024. The informal technical memorandum prepared by OAP made the following observations:

- Both sections appear lighter in color, indicating early oxidation.
- Field review indicated the following distresses within the HMA control section:
  - Longitudinal cracking in wheel path
  - Longitudinal cracking in the outer wheel path, loss of fines from the surface
  - Low severity fatigue cracking

[1] HyRAP is a registered trademark owned by Brooks Construction Company, Inc. and licensed to Manhole Adjusting Inc.

  - Low intensity fatigue cracking in the outer wheel path of the narrowed section of control section

- The HyRAP section surface, on the other hand, appeared quite dense and tight without indicating surface aggregate loss. Surface distresses observed were the following:
  - Medium to high severity fatigue cracking
  - Pumping

Overall, the extent and intensity of distresses in HyRAP section exceeded those observed in the HMA control section. Considering the age of both sections, less than two years, the HMA section is performing better than the HyRAP test section at this time.

1.2.2 Interstate 40 Test Sections Sampled for This Technical Memorandum

Another HyRAP material test section was constructed on September 25-27, 2023, on Interstate 40 (I-40) in San Bernardino County near Newberry Springs (District 8) using an nSSP updated by the OAP. The mix design was changed by the supplier, Manhole Adjusting Inc., to use two RAP bins. This mix design was sampled by the UCPRC at the plant during construction and reheated at the UCPRC laboratories for specimen preparation and testing.

Two other mixes used in the I-40 project were also sampled at nearby plants for comparison of performance-related test results with HyRAP. A polymer-modified hot mix asphalt (HMA-M) meeting PG 64-28M specifications with 25% RAP aggregate replacement was sampled in December 2023, and a gap-graded rubberized asphalt hot mix asphalt (RHMA-G) with a PG 64-16 base binder was sampled in April 2024.

The three mixes (100% RAP, HMA-M, RHMA-G) used in construction of the I-40 project were placed on the dates and in the locations shown in Table 1.1.

Table 1.1: Summary of I-40 Test Sections and Sampling Dates for HyRAP 100% RAP Mix, Type A PG 64-28M Mix, and RHMA-G Mix

Pilot Project Test Sections						
Type	**Date**	**Begin Postmile**	**End Postmile**	**Lane Number**	**Direction**	**Tonnage**
100% RAP nSSP SL1	9/20/2023	26.00	approx. 26.30[1]	1	EB	754
100% RAP nSSP SL2	9/21/2023	26.00	26.75	1	EB	754
100% RAP nSSP SL3	9/25/2023	26.75	27.50	1	EB	754
100% RAP nSSP SL4[2]	9/26/2023	26.00	26.75	2	EB	739
100% RAP nSSP SL5[2]	9/27/2023	26.75	27.50	2	EB	739
1/2" Type A 64-28M SL1 and SL2	2023-2024	Various digout locations		All	EB/WB	No information available
3/4" RHMA-G 64-16 AR SL1 and SL2	2023-2024	20.00[3]	28.10[3]	All	EB/WB	No information available

Notes: EB = eastbound, WB = westbound, SL = sampling lot.

[1] SL1 material had a temperature problem during paving and was removed and replaced the next day with SL2 material by Manhole Adjusting Inc. at its own cost.

[2] Removed and replaced by Manhole Adjusting Inc. at its own cost on July 23, 2024, because of rutting.

[3] Except for Postmile 26.00 to Postmile 27.75 in both lanes where 100% RAP mix was placed.

The UCPRC also coordinated with the Caltrans South Region Laboratory, which performed deflection testing on the HyRAP test sections and the control RHMA-G sections on the I-40 project after the overlays were placed. The intent of the deflection testing was to provide an understanding of the pavement support to the HyRAP and control sections when reviewing cracking condition surveys in the future.

The summer after construction, rutting was observed in the lane carrying most of the truck traffic on eastbound I-40, requiring removal and replacement on July 23, 2024, of the SL4 and SL5 HyRAP materials in the Lane 2 test sections shown in Table 1.1. Manhole Adjusting Inc. removed and replaced those materials at its own cost. As of February 2025, the HyRAP that remains in the test sections is the material from SL2 and SL3 that was placed in Lane 1 between Postmiles 26.0 and 27.5.

This research report presents the results of the performance-related testing of the I-40 HyRAP, RHMA-G, and HMA-M materials that were sampled. The results reflect the materials at the locations sampled shown in Table 1.1. The deflection test results and a brief summary of the rutting observed in the summer of 2024 are also included in this report.

1.3 Problem Statement

The following research problems were addressed in this study:

- Comparison of performance-related test results for HyRAP mixes with currently used HMA, HMA-M, and RHMA-G mixes to assess the potential use of HyRAP in different applications to meet or exceed the engineering performance of the current HMA, HMA-M or RHMA-G alternatives.

- Comparison of performance-related test results with the observed performance between construction in late September 2023 and the removal and replacement of materials in Lane 2 in July 2024.
- Comparison of the deflection test results on the pavement throughout the project to determine whether the locations with HyRAP have the same underlying structural capacity as the rest of the project.
- The estimated greenhouse gas emissions for HyRAP mixes compared with those from currently used HMA, HMA-M, and RHMA-G mixes to assess the impact of HyRAP on global warming and to support decision-making by Caltrans regarding its use.

1.4 Goals and Research Questions

The goals of this research report are to measure and compare the performance-related properties of the binders and mixes used in the project through laboratory performance-related tests of plant-sampled mixes and extracted binders and to calculate the global warming impacts (GWIs) of the mixes used in the project and compare them with other typical mixes. The research and the report were designed to address the following questions:

1. **What are the results of performance-related testing of the extracted binder from the HyRAP mix sampled on I-40 project compared with the extracted binder from the HMA-M mix and the plant produced rubberized binder for the RHMA-G mix prior to mixing?**
    a. What are the performance grade (PG) high, intermediate, and low temperatures of the extracted binders?
    b. What is the aging of the binder, which controls its stiffness and viscoelastic response (phase angle) as measured by the carbonyl and sulfoxide contents, including after long-term aging using a pressure aging vessel (PAV)?
2. **What are the results of performance-related testing of the HyRAP mix sampled on the I-40 project compared with the RHMA-G and HMA-M mixes also used on the project and with the statewide median PG 64 and PG 70 HMA mixes?**
    a. Axial dynamic stiffness under different conditions of temperature and frequency of loading?
    b. Flexural dynamic stiffness under different conditions of temperature and frequency of loading?
    c. Flexural fatigue performance?
    d. IDEAL-CT strength related to stiffness and age-related cracking at intermediate temperatures after both reheating and medium-term oven aging (related to aging in the field) conditioning?

e. IDEAL-CT index value related to age-related cracking at intermediate temperatures after both reheating and medium-term oven aging (related to aging in the field) conditioning?
f. Repeated load triaxial permanent deformation (rutting) resistance under both confined and unconfined conditions?
g. IDEAL-RT index value related to rutting at high temperatures after both reheating and medium-term oven aging (related to aging in the field) conditioning?
h. IDEAL-CT strength results after moisture-induced stress tester (MiST) moisture conditioning?
i. Hamburg Wheel-Tracking testing related to permanent deformation and moisture damage resistance?

3. **What is the stiffness of the overall pavement and subgrade and the stiffness of the subgrade in the locations with HyRAP mix as measured by deflection testing compared with the stiffnesses (corresponding to structural capacity) where the control RHMA-G mix was placed the I-40 project?**
4. **How do the laboratory rutting test results for the different samples relate to the rutting performance of the sections where those materials were placed from construction in September 2023 to removal of Lane 2 mixes in July 2024?**
5. **What is the global warming impact calculated from modeling using known job mix formulas of the different mixes used on the I-40 project and how do they compare with each other and with other mixes used in California, assuming the same performance?**
   a. HyRAP mix considered with and without use of the natural gas-burning oxidizer used to reduce air pollution from the mixing plant and considering two sources of natural gas data?
   b. Compared with that of the I-40 PG 64-28M HMA with 24% RAP and RHMA-G mix designs?
   c. Compared with that of hypothetical default HMA mixes in the Caltrans life cycle assessment software *eLCAP* (*environmental Life Cycle Assessment for Pavement*) with HMA with no RAP, with 15% RAP, and with no RAP/polymer-modified binder, and with an RHMA-G mix with no RAP; compared with HMA and RHMA-G mixes with California EPDs; and compared with a 30% RAP mix from the National Asphalt Pavement Association (NAPA) life cycle assessment tool *(1)*?

1.5 Experimental Approach

The following are the experimental approaches used for this research project:

- The approach for measurement and comparison of the performance-related properties of the mixes was to sample the mixes in the field, transport them in cardboard boxes and metal buckets to the UCPRC laboratories in Davis and Richmond, reheat the buckets to split the samples and compact the test specimens, and test them, including testing after MTOA of the loose mix for IDEAL-CT testing. The approach for the measurement and comparison of the performance-related properties of the binders was to chemically extract the binders after reheating and splitting and test them, including after different conditions of long-term aging.

- The approach for comparison of laboratory test results with observed rutting performance was to identify where the different samples of materials were placed, where rutting was observed the next summer, and where the rutted materials were removed and replaced.
- The approach for the comparison of the structural capacity of the pavement in the project was to perform deflection testing throughout the project and analyze and compare the deflection data.
- The approach for the LCA GWI impact comparisons was to use the mix designs to identify quantities of mix components and energy used for manufacture per declared unit of mix (one metric tonne) and GWI emissions factors for each to calculate the total A1-A3 (per ISO 21930 definitions for material extraction, material transport to production plant, mix production) GWI for the mixes.

1.6 Asphalt Concrete Mixes Evaluated

It should be noted that, following Caltrans nomenclature, the term asphalt concrete in this report refers to two types of mixes:

- Hot mix asphalt – Type A, which has a dense aggregate gradation, denoted also as simply "hot mix asphalt" (HMA). Polymer-modified HMA (HMA-M) uses a polymer-modified binder meeting Caltrans PG specifications.
- Rubberized hot mix asphalt–gap-graded (RHMA-G), which has a gap gradation and includes a minimum of 7.5% asphalt rubber binder (by weight of mix) with a minimum content of 18% recycled tires crumb rubber.

1.7 Overview of the Report

Chapter 2 of this report documents the sampling and laboratory conditioning methods used for the mixes, the binder extraction method, and the testing methods for the binders and mixes. Chapter 3 presents construction observations. Chapter 4 presents the binder testing results, and Chapter 5 presents the mix testing results. Chapter 6 presents a discussion of the laboratory results for rutting and the observed rutting performance in the test sections. Chapter 7 presents the deflection testing results, and Chapter 8 presents the life cycle assessment results. Chapter 9 presents a brief summary of the research, answers to the study questions, and recommendations.

1.8 Measurement Units

In this report, both US and metric units (provided in parentheses after the US units) are provided in the general discussion. The performance grade of the asphalt binder is reported in metric units (°C) following AASHTO M 320. Similarly, some rheological aging indexes are reported in metric units in Chapter 2. A conversion table (US versus metric) is provided on page xv.

2 HyRAP PLANT, ASPHALT CONCRETE SAMPLING, LABORATORY CONDITIONING PROCEDURES, AND TEST METHODS

2.1 HyRAP Plant Description

The HyRAP mixing plant includes bins (Figure 2.1) for loading the RAP with different gradations onto the aggregate cold feed belt to the dryer drum (Figure 2.2), the pugmill where the dried and heated RAP is mixed with RA (Figure 2.3), and an oxidizer where the volatile emissions from the drying, heating, and mixing process are burned by a natural gas flame (Figure 2.4).

Figure 2.1: RAP bins for cold feed.

Figure 2.2: Dryer drum for drying and heating RAP.

Figure 2.3: Pug mill for mixing RAP and recycling agent.

Figure 2.4: Oxidizer for burning volatile emissions.

2.2 Job Mix Formulas for Three Mixes

The job mix formulas (JMF) for the three mixes tested in this study are shown in Table 2.1.

Table 2.1: Job Mix Formulas for 100% RAP (HyRAP), RHMA-G, and HMA-M (Digout) Mixes

Parameter		Mainline Mix (RHMA-G)		Digouts (HMA-M meeting PG64-28 specifications)		100% RAP (HyRAP)	
		¾" RHMA-G, R0, 64-16AR		½" SP Type A R25, 58-38M		5/16" nSSP, R100, 76-16	
		0% RAP		25% RAP		100% RAP	
		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
	3/4"	95	90-100	100	100-100	100	100-100
	1/2"	83	77-89	96	91-100	100	100-100
	3/8"	68	63-73	85	80-90	100	95-100
	#4	28	22-34	67	62-72	76	70-82
	#8	18	13-23	54	49-59	57	—
	#30	10	—	25	21-29	30	25-35
	#200	3.0	1.0-5.0	4.0	2.0-6.0	11.0	8.0-14.0
RAP content (% by weight of aggregate)		0	≤0	25	≤25	100	100
Base asphalt binder performance grade		64-16AR	—	58-34M	—	N/A	—
Additives used: Recycling agent (RA), warm mix additive (WMA), lime treatment		Lime	—	WMA	—	RA	—
Additive dosage (% by weight of binder or mix)		Lime: 1.0% of mix	Lime: 0.8-1.2% of mix	WMA: 0.6% of binder	—	RA: 27% of binder	—
Binder content (% by weight of mix)		7.5	7.1-8.0	5.2	4.9-5.7	6.33	5.83-6.83
Recycled binder content (% binder in mix)		0	—	1.08	—	4.63	—
Estimated binder replacement excluding additives (% of total binder)		0	—	20.8%	—	100%	—
Estimated binder replacement including additives (% of total binder)		0	—	26.8%	—	73.1%	—
Number of gyrations		50	50-150	85	85	Report only	85
Air-void content (%)		4	2.5-5.5	4	2.5-5.5	Report only	Report only
Voids in mineral aggregate (%)		18.4	18.0-23.0	14.5	12.5-15.5	N/A	N/A
Dust proportion		0.5	Report only	0.72	0.6-1.3	N/A	N/A
Hamburg (rut depth [in])		0.19 at 15,000 passes	0.5 at 15,000 passes	0.07 at 10,000 passes	0.5 at 10,000 passes	Not submitted	0.5 at 20,000 passes

Parameter	Mainline Mix (RHMA-G)		Digouts (HMA-M meeting PG 64-28 specifications)		100% RAP (HyRAP)	
	¾” RHMA-G, R0, 64-16AR		½” SP Type A R25, 58-38M		5/16” nSSP, R100, 76-16	
	0% RAP		25% RAP		100% RAP	
	JMF Design	JMF Limits	JMF Design	JMF Limits	JMF Design	JMF Limits
Moisture susceptibility, dry strength (psi)	100	100	250	100	Not submitted	100-300
Moisture susceptibility, wet strength (psi)	85	70	190	70	Not submitted	70
Indirect tensile strength from CT (psi)	N/A	N/A	N/A	N/A	Report only	Report only
Indirect tensile cracking tolerance (CT#)	N/A	N/A	N/A	N/A	Report only	Report only

2.3 Field Sampling

All mixes were sampled in cardboard boxes or metal buckets at the mixing plant after mixing with no storage time in the silo and were immediately shipped to the UCPRC laboratory. In the laboratory, the boxes and buckets were kept under shade to limit heating due to solar radiation and consequent aging. Storage temperatures varied from 50°F to 100°F (10°C to 38°C).

Sampling dates and samples are summarized for the three mixes used in the I-40 project as follows:

- 5/16” HyRAP sampled at the Manhole Adjusting Inc. mixing plant in Colton, California:
    - Sample 1 (SL1): September 20, 2023
    - Sample 2 (SL2): September 21, 2023
    - Sample 3 (SL3): September 25, 2023
    - Sample 4 (SL4): September 26, 2023
    - Sample 5 (SL5): September 27, 2023
- 1/2” Type A sampled at the Sully-Miller plant in Victorville, California:
    - Sample 1 (SL1): December 4, 2023
    - Sample 2 (SL2): December 5, 2023
- 3/4” RHMA-G sampled at the Sully-Miller plant in Victorville, California:
    - Sample 1 (SL1): April 4, 2024
    - Sample 2 (SL2): April 4, 2024

The testing that was completed for each lot is summarized in Table 2.2.

Table 2.2: Summary of Specifications, Mix Components, and Sampling Lots for 100% RAP (HyRAP), RHMA-G, and HMA-M (Digout) Mixes

Mix Label	Specifications	Type	Maximum Aggregate Size	RAP (%)	Virgin/Base Binder PG	Binder Source	Recycling Agent / Additives	# Lots
Experimental Data Set 1 (Full Standard Materials Mix Library, BMD Mix Testing, Extracted and/or Recovered Binder Testing)								
5/16” nSSP, R100, 76-16	nSSP	100% RAP HMA	5/16”	100	—	—	Petroleum-Based RA-1, Epolene EE-2	1 (SL1)
3/4” RHMA-G, R0, 64-16AR	Standard Section 39	RHMA-G	3/4”	0	64-16AR	LTR World Oil	LAS-Lime	1 (SL1)
1/2” SP Type A R25, 58-38M	Standard Section 39	HMA Type A	1/2”	25	58-34M	LTR World Oil	WMA-M1	1 (SL1)
Experimental Data Set 2 (BMD Mix Testing, Extracted and/or Recovered Binder Testing)								
5/16” nSSP, R100, 76-16	nSSP	100% RAP HMA	5/16”	100	—	—	Petroleum-Based RA-1, Epolene EE-2	1 (SL4)
1/2” SP Type A R25, 58-38M	Standard Section 39	HMA Type A	1/2”	25	58-34M	LTR World Oil	WMA-M1	1 (SL2)
Experimental Data Set 2 (BMD Mix Testing Only)								
5/16” nSSP, R100, 76-16	nSSP	100% RAP HMA	5/16”	100	—	—	Petroleum-Based RA-1, Epolene EE-2	3 (SL2, SL3, SL5)
3/4” RHMA-G, R0, 64-16AR	Standard Section 39	RHMA-G	3/4”	0	64-16AR	LTR World Oil	LAS-Lime	1 (SL2)

Figure 2.5 shows the loading of the trucks at the HyRAP mixing plant, the point at which mix was sampled (same procedure was used for the other two mixes). Figure 2.6 shows splitting of the mix for sampling following Caltrans procedures.

Figure 2.5: Truck load out at the HyRAP mixing plant (also the point of sampling).

Figure 2.6: Quartering and sampling of hot mix.

2.4 Reheating Conditioning for Mix Samples

The "reheating" conditioning procedure is intended to produce minimum aging on the mix. The procedure used by the UCPRC is an early version of the provisional method of test for laboratory conditioning of dense-graded asphalt mixtures developed by Caltrans, currently labeled as provisional Caltrans Test Method 320. The procedure is summarized as follows:

1. Heat the box or bucket in a preheated oven for two to three hours for boxes and for four hours for metal buckets with the lid on; the heating temperature must be 275°F (135°C) for HMA and 302°F (150°C) for RHMA-G.
2. Split the box or bucket content into pans. Spread the mix in a 2 in. (50 mm) lift.
3. Let the pans stand at room temperature for at least one hour and up to four hours.
4. Put the pans in the oven at 212°F (100°C) for 20 hours and then let stand at room temperature for one hour if mix is to be used for MTOA specimens (go to step 5 if not to be used for MTOA specimens). The MTOA sequence is summarized in Table 2.3.
5. Put the pans in an oven at the compaction temperature for 2 hours±15 minutes.
6. Proceed with compaction with either the gyratory (AASHTO T 312) or the rolling wheel (AASHTO PP3).

Table 2.3: Specimen Preparation Including Medium-Term Oven Aging

Activity	Time/Temperature
Bucket/box breakdown	4 hours inside bucket with lid on/2 hours in box HMA: 275°F (135°C) RMHA-G: 302°F (150°C)
Split	Spread mix in a 2 in. (50 mm) lift
Rest period	1 hour at room temperature
MTOA aging	20 hours at 212°F (100°C)
Rest period	1 hour at room temperature
Heat to compaction temperature	2 hours at compaction temperature
Compaction	Proceed with compaction with either the gyratory (AASHTO T 312) or the rolling wheel (AASHTO PP3)

2.5 Binder Extraction and Preparation for Binder Testing

2.5.1 Binder Extraction

To determine the PG grade and other parameters of the binder from each mix sample, binder was extracted following ASTM D8159 and ASTM D5404 procedures with the use of an automated asphalt extraction unit and rotary evaporator (Figure 2.7 and Figure 2.8).

Figure 2.7: Closed-loop binder extraction system.

Figure 2.8: Placing extraction cylinder with sample into extraction system.

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 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 like that caused by the rolling thin-film oven (RTFO) test (AASHTO T 240), and no further short-term aging was applied for PG grading. The 20-hour PAV aging and then 40-hour PAV aging and testing immediately followed.

2.5.2 Rubberized Binder Centrifuging to Remove Rubber Particles

As noted previously, the rubberized binder was not extracted from mix prepared in the plant but was instead sampled just before it was pumped into the mixing drum. The rubberized asphalt binder used in the control RHMA-G mix had the rubber extracted following the procedure summarized in the following discussion. The goal of the procedure is to test rubberized binder that has been modified by the digestion of rubber particles but after removal of the undigested particles that have been found to dominate PG testing if left in the binder.

Centrifuging was considered as an alternative to sieving as a means of improving efficiency, limiting the amount of binder reheating, minimizing wastage, and simplifying clean-up to produce rubberized asphalt without large particles. The draft procedure used by the UCPRC for this study used the same centrifuge that was used for the Caltrans Method of Test for Centrifuge Kerosene Equivalent and Approximate Bitumen Ratio (ABR) (CTM 303, now deleted, also ASTM D5148 Standard Test Method for Centrifuge Kerosine Equivalent). The sample cups required modification to incorporate a screen and a screw-on base below the screen to collect the processed binder. Screens were cut to size from standard laboratory sieve replacement screens. The modified cup setup is shown in Figure 2.9. The screen size used was 500 µm (#35 sieve) for testing in a dynamic shear rheometer (DSR) with 2 mm or 3 mm parallel plate gap geometries.

The bulk sample of rubberized binder was reduced into 450 g (16 oz.) sample tins. The 450 g samples were heated in a forced draft oven for 45 minutes at 190°C (374°F) or until a liquid state was achieved. Eight or more cups with the screen and base receptacle were assembled. Four centrifuge cups were heated in the same oven as the binder for the final 10 minutes of binder heating. The binder and cups were then removed from the oven, the binder was stirred to ensure that no phase separation had occurred, and then 20±5 g of binder was poured into each cup, shown in Figure 2.10. Each cup was put back into the oven while pouring the remaining cups. The four cups were then placed into the centrifuge and spun for one minute (Figure 2.11). The cups were then removed and unscrewed from their bases. Binder that had passed through the bottom of the screen was gently scraped into a clean sample receptacle (Figure 2.12). The cups and screens were inverted to drain out the binder and incompletely digested rubber particles on the screen (Figure 2.13). When all the receptacles were full, they were placed on a tray and heated to 190°C (374°F) for five minutes and then poured into a sample tin. The process was repeated until sufficient binder was collected for the required testing.

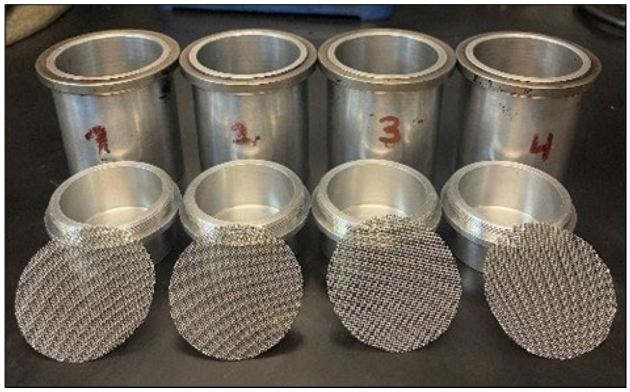


Figure 2.9: Modified centrifuge cups.

Figure 2.10: Pouring heated rubberized asphalt into centrifuge cup.

Figure 2.11: Cups with binder in centrifuge prior to centrifuging.

Figure 2.12: Removing the binder from the cup after centrifuging out the rubber particles.

Figure 2.13: Removing the residual rubber particles from the centrifuge cup.

The rubberized binder was then subjected to RTFO conditioning because it had not been mixed with aggregate at the plant and then extracted. Therefore, it had not undergone the additional aging that the extracted binders from the two other mixes had during plant mixing.

2.6 Laboratory Test Methods

Laboratory test methods include binder test methods and mix test methods.

2.6.1 Binder Test Methods

The binder testing performed by the UCPRC is as follows (details in Table 2.4):

- Performance grade (PG)
- Fourier transform infrared (FTIR) spectroscopy tests to track changes in binder chemistry after aging
- Linear amplitude sweep (LAS) testing to evaluate fatigue performance of binders

These tests were all performed on the plant-sampled binders and reheated as well as on the PAV-aged binders. Short-term aging of the extracted binders was not simulated in an RTFO because the binders were extracted from mixes that were plant produced. Long-term aging of the binders was simulated in a PAV for 20 hours following the AASHTO R 28 method, and additional PAV specimens were aged for 40 hours.

Table 2.4: Binder Testing Performed by UCPRC for HyRAP Project

Test Type	Test Method	Material Tested	Goal
Binder true grade	AASHTO R 29	Binder extracted from plant-sampled mix	Binder PG grade
Fourier transform infrared spectroscopy	ASTM E131, ASTM E168	Binder extracted from plant-sampled mix	Chemical component changes
Linear amplitude sweep	AASHTO T 391	Binder extracted from plant-sampled mix	Binder fatigue resistance

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

2.6.1.1 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 if the 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 40 hours. The low-temperature PGs were determined on PAV-aged binders using a bending beam rheometer (BBR), following AASHTO T 313.

2.6.1.2 Fourier Transform Infrared Spectroscopy

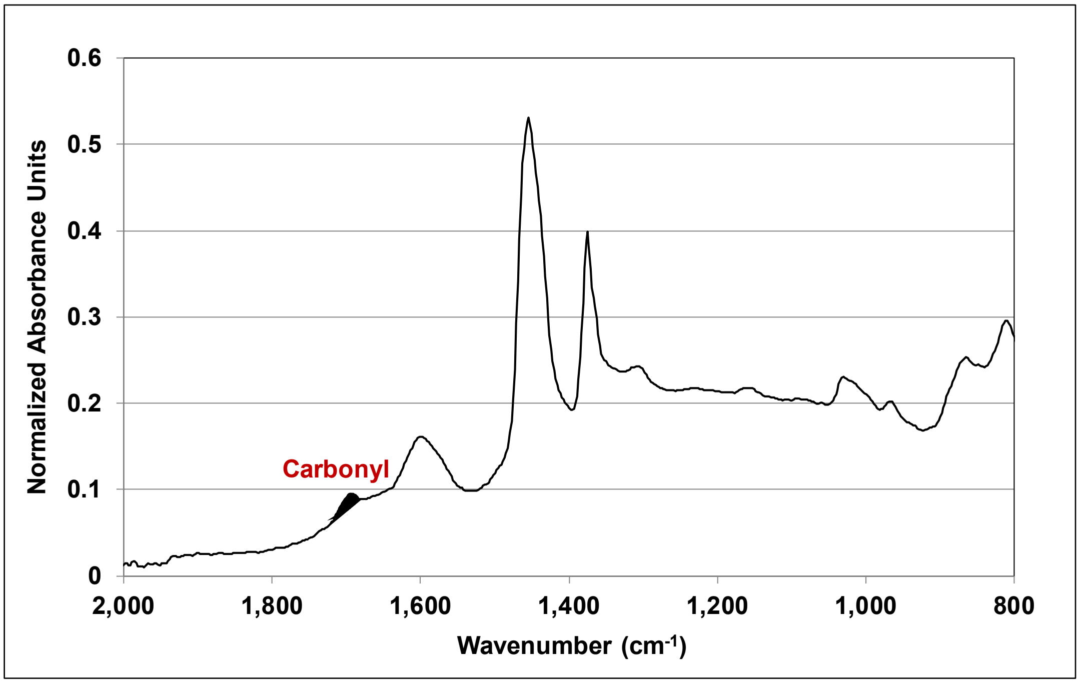
Chemical component changes in the extracted binders were evaluated using Fourier transform infrared spectroscopy with attenuated total reflection (FTIR-ATR). The spectra measured by the FTIR were recorded in a reflective mode, from 4,000 to 400 cm^{-1}, at a resolution of 4 cm^{-1}. Each measurement included 24 scans, and an average value was recorded. Nine replicate measurements were taken to ensure that representative measurements were collected for each binder sample. The carbonyl component was used to track oxidative aging, which is usually defined by the peak at 1,680 cm^{-1} *(3-6)*. The tangential integration of the component area index was calculated between the upper and lower wavenumbers (1,675 cm^{-1} and 1,750 cm^{-1}).

The spectra were normalized using the aliphatic band at 2,923 cm^{-1} to eliminate any variability introduced by the operator and any background impacts between repeat measurements. This aliphatic band structure is not affected by aging over time *(5,6)*. The chemical component area index was then integrated from the normalized spectra using Equation 2.1 *(6)*. Figure 2.14 shows an example of a spectrum and the respective component.

$$I_i = \int_{w_{l,i}}^{w_{u,i}} a(w)dw - \frac{a(w_{u,i})+a(w_{l,i})}{2} \times (w_{u,i} - w_{l,i}) \quad \textbf{(2.1)}$$

Where:

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



Note: Plot shows tangential integration with carbonyl areas.

Figure 2.14: Example of normalized FTIR absorbance spectrum.

2.6.2 Mix Test Methods

Mix testing included the following:

- Volumetrics (not performance-related tests):
  - Total binder content by extraction (virgin binder, RAP binder, recycling agent combined)
  - Air-voids under standard gyratory compaction (N_{design}, 85 gyrations)
- Aging conditioning for performance-related tests:
  - All mixes tested after reheating conditioning
  - IDEAL-CT and IDEAL-RT testing also performed after MTOA
- Stiffness:
  - Axial dynamic modulus (DM, AASHTO T 378; specimens prepared in a gyratory compactor)

    - Flexural dynamic modulus (FM, AASHTO T 321; specimens prepared using a rolling wheel compactor)
- Fatigue cracking:
    - Beam fatigue (FAT, AASHTO T 321; specimens prepared using a rolling wheel compactor)
- Age-related cracking:
    - IDEAL-CT indirect tensile strength test for peak strength and IDEAL-CT index value calculation (IDEAL-CT, ASTM D8225, specimens prepared in a gyratory compactor)
- Rutting:
    - Repeated load triaxial (RLT, flow number, AASHTO T 378 under both confined and unconfined conditions; specimens prepared in a gyratory compactor)
    - IDEAL-RT (ASTM D8360) specimens prepared in a gyratory compactor)
- Moisture sensitivity:
    - IDEAL-CT indirect tensile strength test after moisture-induced stress tester (MiST) moisture conditioning (ASTM D7870) for peak strength and IDEAL-CT index value calculation (IDEAL-CT, ASTM D8225, specimens prepared in a gyratory compactor)
- Rutting and moisture sensitivity:
    - Hamburg Wheel-Track test (Caltrans Test Method 378; specimens prepared in a gyratory compactor)

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

2.6.2.1 Test Specimen Air-Void Contents

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

2.6.2.2 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 the Williams-Landel-Ferry equation shift function *(8)* in Equation 2.2.

$$log(\alpha_T) = \frac{-C_1(T-T_r)}{C_2+(T-T_r)} \qquad \textbf{(2.2)}$$

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

2.6.2.3 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 sinewave 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. Flexural stiffnesses were used in *CalME* simulations (not included in this study).

2.6.2.4 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, low) at a frequency of 10 Hz and 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 2.3). Strain levels were selected, based on experience, to achieve fatigue lives between 10,000 and 100,000 load cycles at 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.

$$Ln(N) = A + B \, x \, Ln(\varepsilon) \quad \textbf{(2.3)}$$

Where:

N = fatigue life (number of cycles)
ε = strain level (μstrain)
A and B = model parameters

Test results can also be used to generate the material fatigue response for *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.

2.6.2.5 Indirect Tensile Cracking Resistance IDEAL-CT

The IDEAL-CT test uses a loading apparatus and specimen fixture shown in Figure 2.15. 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 illustrated in Figure 2.16.

Figure 2.15: Testing machine for IDEAL-CT test with a specimen.

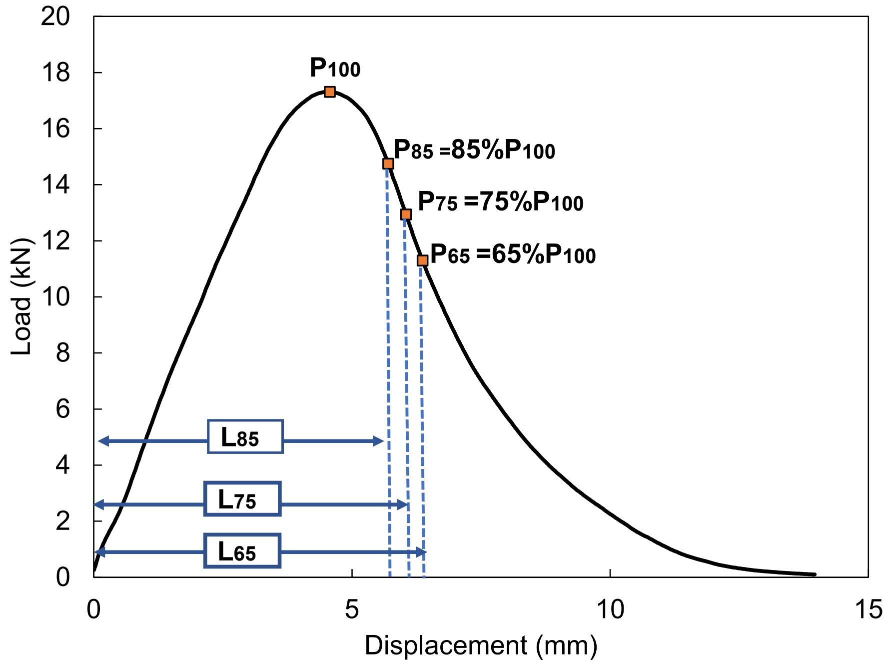


Figure 2.16: Example load-displacement curve from IDEAL-CT test.

Fracture parameters obtained from the IDEAL-CT test are shown in Table 2.5, along with definitions. The two parameters of primary interest are the CT_{Index} (referred 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 *Strength* parameter, which has also been found to have a strong correlation with flexural stiffness but half the test variability of the CT_{Index}.

Table 2.5: Fracture Parameters from IDEAL-CT Test

Parameters	Equations
$\lvert m_{75}\rvert$: post-peak slope (N/m)	$\lvert m_{75}\rvert = \left\lvert \frac{P_{85} - P_{65}}{l_{85} - l_{65}} \right\rvert$ Where: P_{85} = 85% of peak load P_{65} = 65% of peak load l_{85} = deformation at P_{85} l_{65} = deformation at P_{65}
l_{75} (mm)	Displacement at 75% of the peak load after the peak
G_f: failure energy (J/m^2)	$G_f = \frac{W_f}{D \times t} \times 10^6$ Where: W_f = area under load-displacement curve (J) $t = thickness\ (mm)$ $D = diameter\ (mm)$
CT_{Index}: cracking tolerance index (referred in this report as IDEAL-CT)	$CT_{Index} = \frac{t}{62} \times \frac{l_{75}}{D} \times \frac{G_f}{\lvert m_{75}\rvert} \times 10^6$
Strength	$Strength = \frac{Peak\ load}{2rt}$

2.6.2.6 Repeated Load Triaxial Permanent Deformation Resistance

Permanent deformation resistance under RLT testing was measured following 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) *(9,10,11)*.

2.6.2.7 IDEAL-RT Permanent Deformation Resistance

The ASTM D8360 test procedure, referred to as IDEAL-RT, was followed to determine the rutting tolerance index (RT_{Index}) of the mixes included in this study. The IDEAL-RT test uses an indirect tensile strength apparatus with a special platen for the shearing that occurs at the edges of the platen. The monotonic loading produces a relationship of deformation versus load from which the peak load can be taken to calculate the shear strength using an equation provided in the ASTM D8360 method. The shear strength is used with a constant to calculate the rutting tolerance index. The nominal maximum aggregate size (NMAS) of the mixes considered in this research was 19 mm or smaller. Therefore, specimens with a diameter of 6.00±0.08 in. (150±2 mm) and a thickness of 2.44±0.04 in. (62±1 mm) were prepared for testing. The testing temperature was 122°F (50°C), the same temperature as the Hamburg Wheel-Tracking (HWT) test. A constant displacement rate of 50.0±2.0 mm/min

(2±0.08 in./min) was applied during the test. The following equations were used to calculate the rutting tolerance index (RT_{Index}).

$$RT_{Index} = 6.618 * 10^{-5} * \frac{\tau_f}{1\,Pa} \quad \textbf{(2.4)}$$

Where:

τ_f = shear strength (Pa) [calculation shown in equation (2)], $6.618 * 10^{-5}$ is a scaling factor

$$\tau_f = 0.356 * \frac{P_{max}}{t * w} \quad \textbf{(2.5)}$$

Where:

P_{max} = maximum load (N), (see Figure 2.17)
t = specimen thickness (m), and
w = width of upper loading strip (=0.0191 m)
0.356 = a coefficient transferring maximum load to shear strength

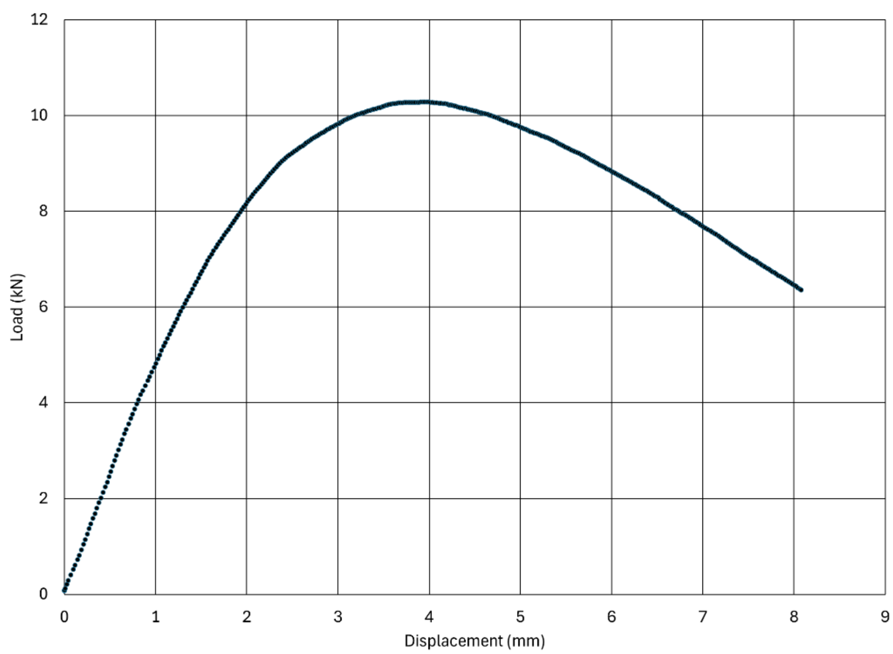


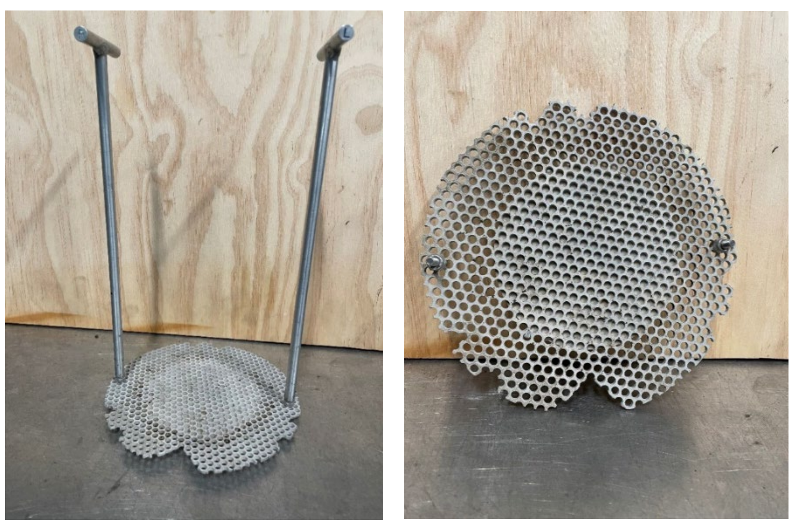
Figure 2.17: Load versus displacement diagram for IDEAL-RT test.

2.6.2.8 Moisture Resistance

To evaluate the moisture susceptibility of asphalt mixes, cylindrical samples were conditioned following the Standard Practice for Moisture Conditioning Compacted Asphalt Mixture Specimens by Using Hydrostatic Pore Pressure (ASTM D7870) procedure and then tested for IDEAL-CT indirect tensile strength. The results of the indirect tensile strength measurements were compared for the unconditioned (dry) and moisture conditioned (wet) specimens.

In this study, a MiST 2 device was used to condition the specimens following ASTM D7870. The MiST 2 system automatically heats the water and specimens to the target temperature and runs the conditioning procedure. The diameter and height of the prepared specimen were 6±0.08 in. (150±2 mm) and 2.44±0.04 in. (62±1 mm), respectively. Three specimens were placed in a hangar assembly inside the conditioning device (Figure 2.18) and conditioned at the same time. Separator spacers were placed between the specimens to separate one specimen from another (Figure 2.19). In total, three specimens were prepared for each mix type for the MiST conditioning. The target air-voids of the specimen range from 6.5% to 7.5%; however, all tested specimens did not deviate more than ±0.5% from each other. The conditioning temperature used in this study was 60°C. The specimens were subjected to 3,500 pressure cycles at 40 psi (276 kPa) to generate the effect of pore pressure generation inside the sample. This process requires approximately 4.33 hours at 4.46 seconds per cycle.

After completion of the final cycle, all the water was drained from the MiST 2 system into a 3.5-gallon bucket. This process usually takes about 20 minutes. Then sufficient tap water at 65°F to 80°F (18°C to 27°C) was poured in the chamber to cool down the specimens and to avoid specimen breakdown during the removal process. After 2 to 3 minutes, specimens were removed from the chamber and placed in a water bath at 77±1°F (25±1°C) for at least two hours. Then subsequent indirect tension tests were performed on the conditioned specimens following the appropriate test method, which for this study was IDEAL-CT indirect tensile strength but can also include other tests.



(a) (b)

Figure 2.18: (a) MiST hanger and baseplate assemblies and (b) separator spacer.

Figure 2.19: Specimens in the MiST 2 device.

2.6.2.9 Hamburg Wheel-Track Test Rutting and Moisture Resistance

HWT tests were also performed following AASHTO T 324. The HWT test provides information regarding both rutting resistance and moisture sensitivity by measuring the development of rutting in two gyratory compacted specimens under a steel wheel under water at 50°C (122°F). The rut depth in both specimens is tracked, and the average value is reported. Moisture sensitivity is indicated when an "inflection point" is seen in the rutting versus load repetitions relationship, shown in Figure 2.20.

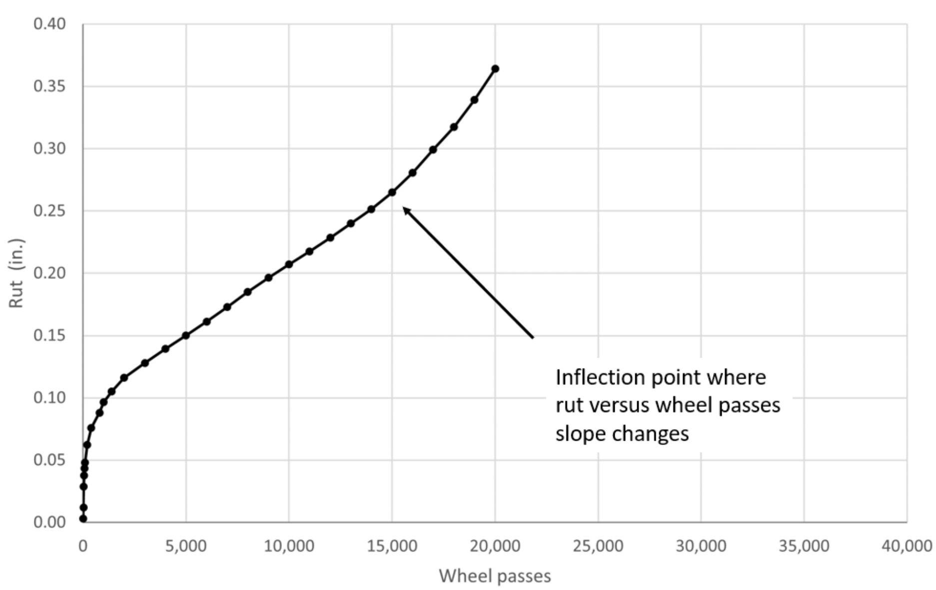


Figure 2.20: HWT test result showing inflection point attributed to moisture damage.

3 OBSERVATIONS FROM CONSTRUCTION

UCPRC engineers and technicians were on-site at the plant and at the I-40 construction site from September 19 to September 28, 2023. They collected four samples of the HyRAP 100% RAP mix, two samples of the Type A PG 64-28M mix, and two samples of the RHMA-G mix. Some samples were larger to provide enough material for a complete set of binder and mix testing in the laboratory. Some samples were smaller due to the availability of time and people, and only a limited amount of testing was possible on return to the laboratory. The following discussion includes observations by the UCPRC staff on-site during sampling and construction. The observations are limited to what the staff members observed, which was only a part of the total project.

3.1 Mix Production Observations

Observations of the production of the 5/16 in. HyRAP mix at the Manhole Adjusting Inc. plant in Colton, California, were as follows:

- During the first week of production, when UCPRC was on-site, (Sample 1 collected on September 20 and Sample 2 collected on September 21, 2023), relatively low binder contents were produced.
- Sample 1 was observed to have been produced at a very high temperature, though temperatures were not measured.
- Sample 2 was observed to have been produced at a lower temperature, though temperatures were not measured.
- During the second week of production during which UCPRC was on-site (Sample 3 collected on September 25, Sample 4 collected on September 26, and Sample 5 collected on September 27, 2023), the binder contents were increased and production continued at the lower temperatures than were used for Sample 1.

Observations of the production of the 1/2 in. HMA PG 64-28M with 25% RAP mix (used in the digouts) at the Sully-Miller plant in Victorville, California, were as follows:

- Sample 1 collected on December 3, 2023, had less than two hours of silo time.
- Sample 2 collected on December 4, 2023, had about 12 hours of silo time (it was produced at 5 am and sampled at about 4 pm).

Observations of the production of the ¾ in. RHMA-G mix (used as the overlay on most of the project) at the Sully-Miller plant in Victorville, California, were as follows:

- Sample 1 collected on April 4, 2024, had less than two hours of silo time.
- Sample 2 also collected on April 4, 2024, had about four hours of silo time.

3.2 Construction Observations

The HyRAP mix was observed to compact as expected for a dense-graded HMA. Figure 3.1 shows intermediate rolling with a pneumatic tired roller, Figure 3.2 shows final static steel rolling, and Figure 3.3 shows the completed mat.

The long haul time from the HyRAP production plant to the construction site resulted in some trucks arriving with cooler than anticipated temperatures on the first day of paving, despite the increased production temperatures. The high production temperature on the first day was likely at least partially attributable to concerns about the cooler temperature and long haul time. Adjustments were made during construction that day, and one section was placed too cold and was removed and repaved.

The UCPRC did not make any observations of the digout or RHMA-G paving. The Caltrans Office of Asphalt Pavement also had engineers on-site during part of the construction, and their observations are captured in a briefing document they produced, included as Appendix B.

Figure 3.1: Pneumatic tire rolling on HyRAP 100% RAP material.

Figure 3.2: Static steel rolling on HyRAP 100% RAP material.

Figure 3.3: Completed HyRAP 100% RAP material mat.

4 BINDER TEST RESULTS

This chapter discusses the binder testing results on the five total binder samples extracted from the three mixes used in the I-40 project. Binder was extracted from Sample 1 and Sample 4 (SL1 and SL4) of the plant-sampled HyRAP 100% RAP mix and Sample 1 and Sample 2 (SL1 and SL2) from the HMA-M mix with 25% RAP. Rubberized binder was sampled at the plant for the RHMA-G mix and the rubber was removed from the binder following the procedure described in Chapter 2. Sample 1 (SL1) of the binder from the RHMA-G mix was tested.

It should be noted that binder extracted from mixes results in complete blending of the materials contributing to the binders in the mix: the virgin binder, any RAP binder in RAP included in the mix, and the recycling agent if it is included in the mix. Complete blending, as occurs when binders are chemically stripped from the aggregate during extraction, may not have occurred in the mix at the time of sampling. Instead, the RAP may partially be considered to act as "black rock," meaning that part of the binder on the RAP aggregate may not have completely blended with the virgin binder and recycling agent. Binders extracted from plant mixtures and binders that have been blended in the laboratory and then RTFO-aged are considered to have the same aging condition. The three aging conditions of binders included in the report are Extracted/RTFO, PAV20, and PAV40.

4.1 PG Grading

The non-standard special provision[2] for HyRAP mix for the I-40 pilot project state that "the PG grade of recovered extracted binder must be between a PG 70-16 and PG 76 -16," which was interpreted for this research report to mean that it should meet either PG 70-16 or PG 76-16 specifications but not reach those of PG 82-16. Caltrans PG binder specifications do not include either PG 70-16 or PG 76-16, with the nearest being PG 64-16 for the low temperature and PG 70-10 for the high temperature.

Table 4.1 and Figure 4.1 show "true grade" performance grade (PG) temperatures for the binders tested, meaning the temperatures at which a virgin binder meets its specification limits for high, intermediate, and low-temperature grades. The table and figure show results for extracted binders from the HyRAP and HMA-M mixes and the plant-sampled RHMA-G mix binder taken prior to mixing. They also show the national AASHTO M 320 PG-specified true grade temperatures for PG 70-16 and PG 76-16 and the nearest Caltrans specification limits for virgin binders relevant to the I-40 project for comparison. The specification limits for virgin binders for PG 64-16 and PG 70-10 unmodified binders and PG 64-28M polymer-modified binders are only shown for comparison and evaluation of potential risks of rutting and cracking. The standard specifications are not applicable to extracted binders and are only shown for risk evaluation.

The high-temperature true grade provides an indication of performance risk at high temperatures for rutting. The intermediate temperatures are related to age-related cracking for all surface mixes and fatigue and reflective cracking in thin overlays. The low temperatures with 20 hours of PAV aging are

[2] nSSP, Section 39-2.15, 100% reclaimed asphalt pavement hot mix asphalt (100% RAP HMA).

related to age-related and low-temperature cracking. Also shown is the true grade PG at low temperature after 40 hours of PAV, a test that is not included in specifications but is an indicator of performance in particularly harsh environments for aging, such as the Mojave Desert where the I-40 project is located.

The factors that influence the PG true grades include the following (approximately in order of potential influence from highest to lowest):

- True grade values for the virgin binder (not applicable to the HyRAP mix)
- Quantity of RAP materials in the mix from one or multiple RAP sources, and the true grade value(s) of the RAP binder(s)
- Binder contents of the RAP source or sources
- Quantity and influence on true grade values of the RA, if used, and the warm mix additive, if used and if it has an influence
- Mixing temperature during production
- Time that the mix is kept hot in the silo and during transport to the construction site

The results show that the true grade temperatures were not consistent between the two QA samples of the HyRAP binder (Mix E) tested. HyRAP QA Sample 1 met the minimum high-temperature PG requirement of 70°C for the AASHTO PG 70-10 specification and for PG 70-10 virgin binders in the Desert climate region in California, while HyRAP QA Sample 4 did not meet the requirement, indicating inadequate rutting resistance. Both QA samples of the HyRAP mix met the specified low-temperature PG requirement (colder than the upper limit of -16°C) after 20 hours of PAV aging. HyRAP Sample 1 was close to the low-temperature limit even after 40 hours of PAV aging, and Sample 4 was still well below the limit after the additional aging. These results indicate good resistance to low-temperature cracking. The HyRAP results shown in Table 4.1 for low temperature show that for both Sample 1 and Sample 4 the low-temperature true grade temperature was controlled by the creep compliance (m-value) rather than the stiffness value (S-value). Both samples of the HyRAP met the intermediate-temperature limits after 20 hours of PAV aging for both PG 70-16 and PG 76-16 in the national specifications, indicating good resistance to age-related cracking.1

Table 4.1 and Figure 4.1 show that the two samples of the combined RAP and PG 58-34M binder intended to meet PG 64-28M binder specifications for the HMA-M mix used in the digouts also showed some variability in the low-temperature grade, with Sample 1 slightly missing the specified limit. Figure 4.1 also shows the high and intermediate-temperature true grades of the two RAP bins used to produce the HyRAP mixes. It can be seen that the 3/8 in. RAP bin had a significantly softer binder than the slurry sand RAP bin. The slurry sand-sized RAP had a very high-temperature PG of 108°C, one of the highest California RAP high-temperature PGs that has been measured at the UCPRC, while that of the 3/8 in. RAP was 11°C lower, in the mid-range to lower range of other RAP binder high-temperature PG values previously measured at the UCPRC. The difference between the intermediate-temperature grades was 12°C. The low-temperature PG of the RAP sources was not tested.

Table 4.1: Continuous Binder Grading Results for 100% RAP (HyRAP), RHMA-G, and HMA-M (Digout) Samples

Parameter	Mainline Mix (RHMA-G)		Digouts (Type A, M) (HMA-M meeting PG 64-28 specifications)			100% RAP (HyRAP)				
	3/4” RHMA-G, R0, 64-16AR		1/2” SP Type A R25, 58-38M			5/16” nSSP, R100				
	0% RAP		25% RAP			100% RAP				
	QA Sample 1 (SL1)	Caltrans PG 64-16 Specification Limits	QA Sample 1 (SL1)	QA Sample 2 (SL2)	Caltrans PG 64-28M Specification Limits	QA Sample 1 (SL1)	QA Sample 4 (SL4)	Caltrans PG 70-10 Specification Limits	AASHTO PG 70-16 Specification Limits	AASHTO PG 76-16 Specification Limits
High-temperature PG	80.8	64 min	69.8	71.0	64 min	72.1	66.7	70 min	70 min	76 min
Intermediate-temperature PG – PAV 20 hours	20.0	28 max	18.2	15.0	22 max	23.7	17.7	34 max	34 max	31 max
Intermediate-temperature PG – PAV 40 hours	—	—	21.9	19.4	—	—	—	—	—	—
Low-temperature PG – PAV 20 hours	-18.6	-16 max	-27.2	-34.0	-28 max	-21.3	-30.6	-10 max	-16 max	-16 max
PAV 20 hours m-value	—	—	—	—	—	-21.3	-30.6	—	—	—
PAV 20 hours S-value	—	—	—	—	—	-30.9	-37.4	—	—	—
Low-temperature PG – PAV 40 hours	—	—	-25.3	-28.4	—	-15.6	-24.9	—	—	—

Several reasons for the differences in results between Sample 1 and Sample 4 of the HyRAP mix are possible. Of the previously discussed influencing factors for PG true grades, the first possibility and a likely reason for the differences is the higher temperature used for mixing Sample 1. A second possible reason would be that a higher percentage of the very stiff slurry sand RAP was used in the mix compared with the softer 3/8 in. RAP. A possible third reason is shown in Figure 4.2 where the binder content of Mix E QA Sample 4 is 0.8% higher than that of Mix E QA Sample 1. The higher binder content in Sample 4 potentially resulted from a higher binder content in the 3/8 in. RAP for Sample 4, which had less aging than the slurry sand RAP, and the higher binder content might have also produced thicker binder films and therefore resulted in less aging during mixing and transportation. A fourth possible reason is that part of higher binder content might also have come from a higher RA content, which would result in softening. The reason for the differences could be any combination of these contributing factors.

Figure 4.1 shows that the control HMA-M (Mix J, 25% RP, 3.8% RA, polymer-modified) had low variability between QA samples tested at high and intermediate temperatures and more variability in the low-temperature value. The figure shows that HMA-M and control RHMA-G (Mix D, 0% RAP, rubberized) mix binders met all PG requirements for virgin binders in the Desert region (again noting that the comparison with that specification is for discussion purposes only).

For the Caltrans standard specifications for PG virgin binders, the results indicate that it is possible for the extracted HyRAP binder to meet the project specifications of PG 70-16 or PG 76-16 and it can potentially meet current Caltrans specifications. However, the data indicate that better quality control is needed to consistently meet the virgin binder specifications for a single climate region in the state. The variability of the results between Sample 1 and Sample 4 on the same project indicates that, for the Desert region, the material variability resulted in Sample 4 not meeting the PG 70-10 virgin binder requirements for high temperature and therefore having a potentially unacceptable risk of rutting.

The following is a summary of the PG specifications that were met by the samples tested from the three mixes:

- HyRAP Sample 1 and Sample 4 extracted binder results:
  - High-temperature PG: Sample 1 true grade = 72.1°C, meets PG 70 virgin binder specification; Sample 4 true grade = 66.7°C meets PG 64 virgin binder specifications but does not meet project specifications for a high temperature true grade above 70°C.
  - Intermediate-temperature PG with 20 hours of PAV aging: Sample 1 true grade = 23.7°C, meets PG 64-16 virgin binder specification; Sample 4 true grade = 17.7°C meets PG 64-28 virgin binder specifications. Both samples meet project specifications for PG 70-16 and PG 76-16 virgin binder.
  - Low-temperature PG with 20 hours of PAV aging: Sample 1 true grade = -21.3°C, meets PG-16 virgin binder specification; Sample 4 true grade = -30.6°C meets PG 28 virgin binder specifications. Both samples meet project specifications for PG 70-16 and PG 76-16 virgin binder.

    - Overall, the Sample 1 extracted binder meets PG 70-10, PG 70-16, and PG 76-16 virgin binder specifications, and Sample 4 meets PG 64-28 virgin binder specifications.
- HMA-M with 25% RAP and PG 58-34M binder Samples 1 and 2 extracted binder results:
    - High-temperature PG: Sample 1 true grade = 69.8°C, meets PG 64 virgin binder specification; Sample 2 true grade = 71.0°C meets PG 70 virgin binder specifications.
    - Intermediate-temperature PG with 20 hours of PAV aging: Sample 1 true grade = 18.2°C, meets PG 64-28M virgin polymer-modified binder specification; Sample 2 true grade = 15.0°C meets PG 58-34M virgin polymer-modified binder specifications.
    - Low-temperature PG with 20 hours of PAV aging: Sample 1 true grade = -27.2°C, meets PG 28M virgin polymer-modified binder specification; Sample 2 true grade = -34.0°C meets PG 34M virgin polymer-modified binder specifications.
    - Overall, Sample 1 and Sample 2 both meet PG 64-28M virgin polymer-modified binder specifications.
- RHMA-G and PG 64-16 virgin binder plant-sampled and RTFO-aged results, after removal by centrifuge of the undigested rubber particles:
    - High-temperature PG: Sample 1 true grade = 80.8°C, meets PG 70 virgin binder specification.
    - Intermediate-temperature PG with 20 hours of PAV aging: Sample 1 true grade = 20.0°C, meets PG 64-28 virgin binder specification.
    - Low-temperature PG with 20 hours of PAV aging: Sample 1 true grade = -18.6°C, meets PG 16 virgin binder specification.
    - Overall Sample 1 meets both PG 70-10 and PG 64-28 virgin binder specifications.

It must also be noted that this evaluation is based on extracted binders for the HyRAP and HMA-M mixes, which introduces some additional variability compared with the evaluation of virgin binders taken from the refinery without the varying effects of mixing temperatures, silo times, transport distances, and extraction and recovery. However, the results do indicate that construction variability of the binder properties in the HyRAP mix is subject to larger ranges of variability within those sources of variability than conventional mixes. Efforts should be made to reduce the variability of the HyRAP binder properties by reducing the effects of mixing temperatures, silo times, and transport distances. The additional sources of binder property variability in mixes that include RAP are variability of RAP binder contents and aging variability within the RAP pile, and variability of control of RAP and recycling agent contents during mixing. Some of the same issues (variability of RAP binder contents and aging, control of RAP and recycling agent during mixing) will arise as RAP contents are increased in all HMA mixes, with increases in variability proportional with the amount of RAP and recycling agent included in the mixes. They are accentuated in the HyRAP mix because it is 100% RAP.

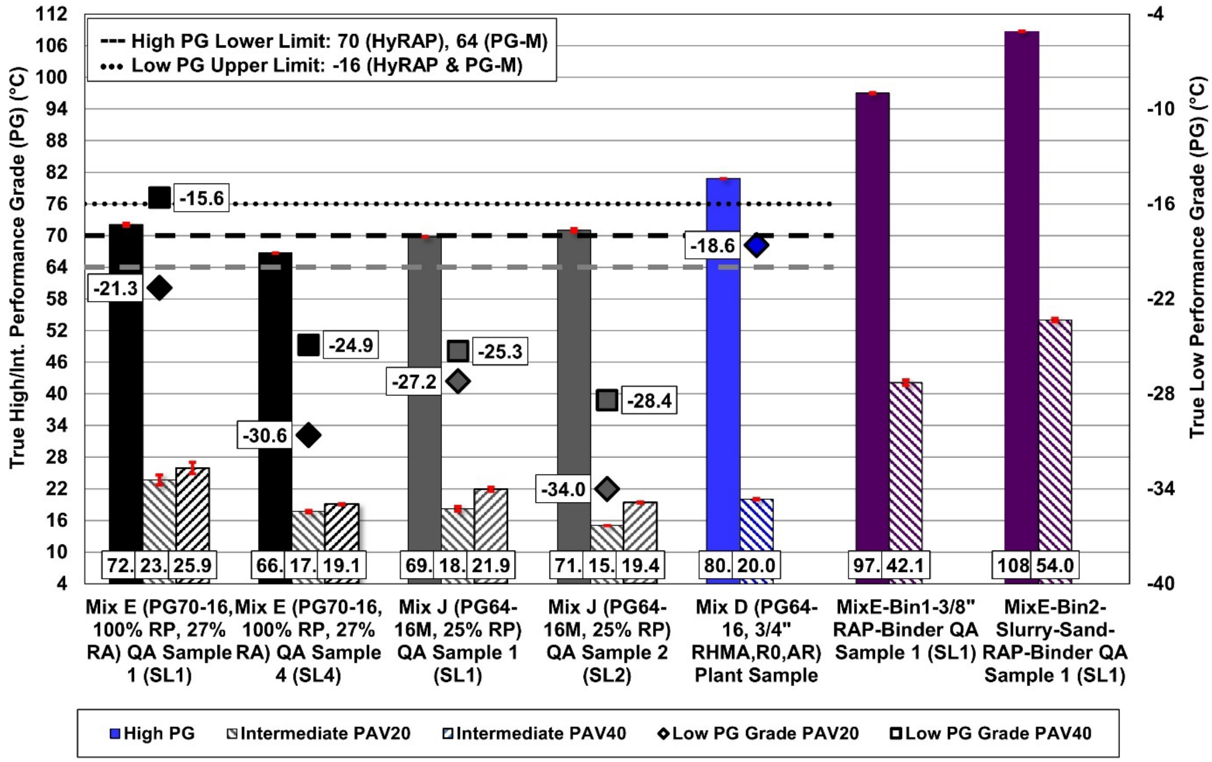


Figure 4.1: Continuous temperature binder grades for HyRAP binders and control binders.

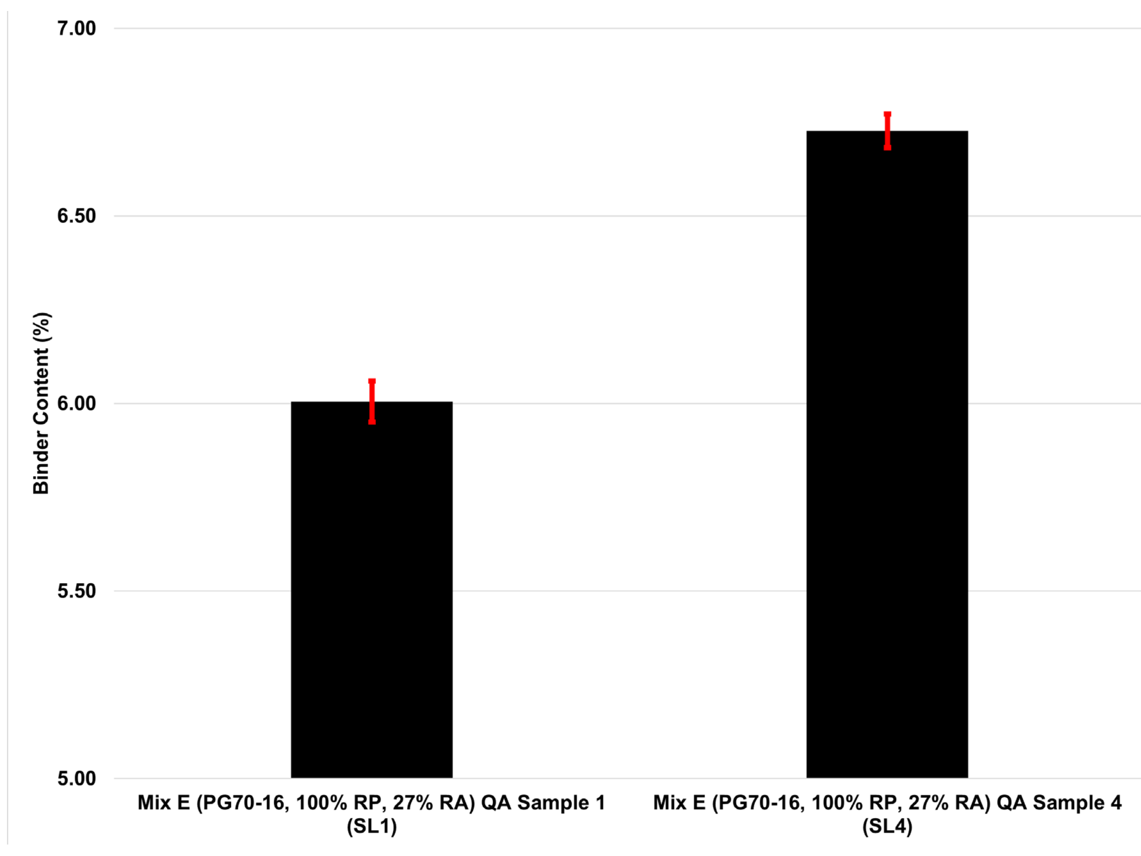


Figure 4.2: Binder contents for HyRAP binders from binder extractions.

4.2 Fourier Transform Infrared Spectroscopy

The quantities of aging chemical products carbonyl area (CA) index and sulfoxide (SULF) in the five binder samples (two each from the HyRAP and HMA-M extracted binders and one from the RHMA-G plant samples binder) and two RAP bin extracted binder samples (one from 3/8 in. RAP and one from slurry sand RAP) under three aging conditions were evaluated with the FTIR. The three aging conditions were the following:

- Extracted binder from mix with reheating (HyRAP and HMA-M), or RTFO-aged and reheated (RHMA-G binder sampled before mixing)
- PAV aged for 20 hours (PAV20)
- PAV aged for 40 hours (PAV40)

Figure 4.3 plots the CA index of the binders for these three conditions for all binder samples. Figure 4.4 shows the sulfoxide indexes for each of the binders extracted from the two QA samples. Figure 4.5 and Figure 4.6 show the CA index and the SULF, respectively, of the binder from each mix normalized to the Mix E QA Sample 1.

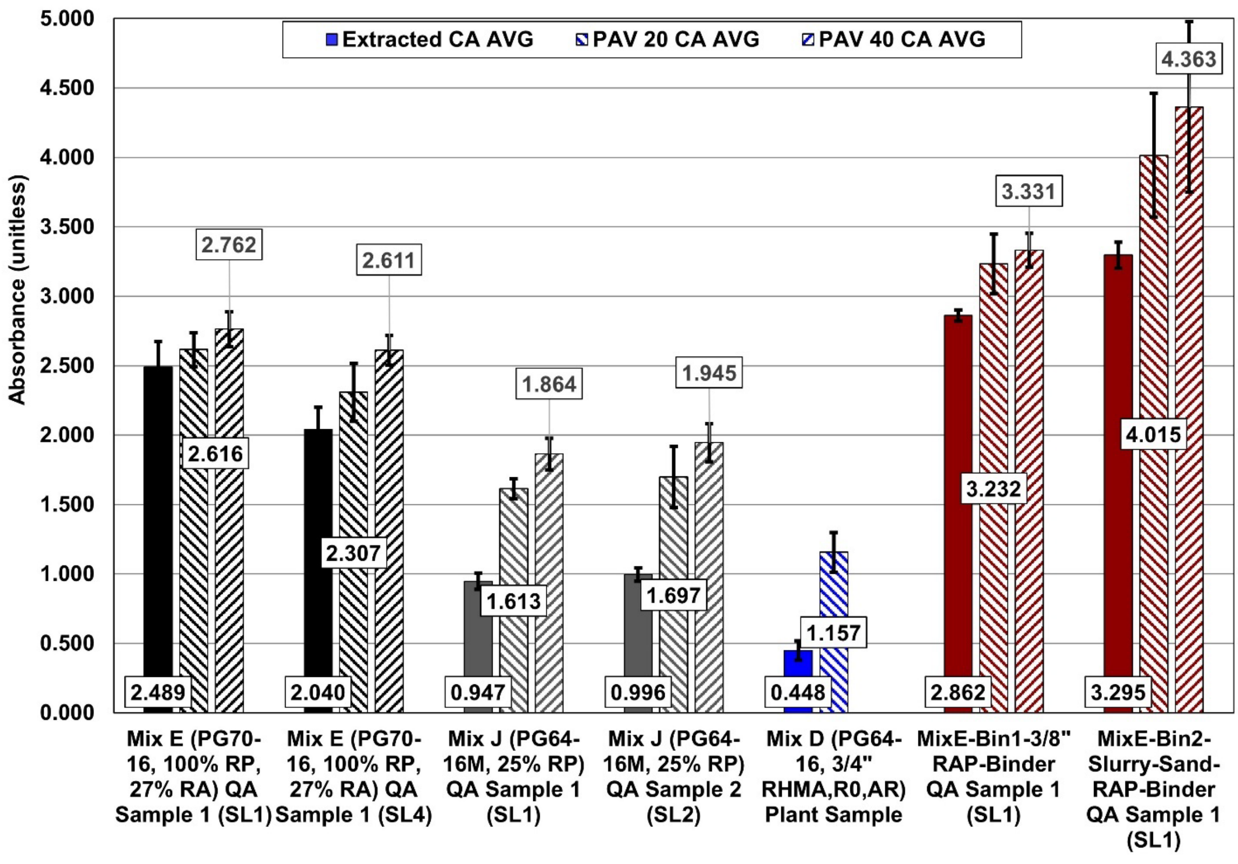
The differences in CA and SULF between samples of the same mix are shown in Figure 4.4 and Figure 4.5. The stiffer Sample 1 of the HyRAP mix (Mix E) has somewhat more CA than does the softer Sample 4 after extraction and after additional aging under PAV20 and PAV40 conditions. The differences between the two samples diminish as aging progresses, becoming statistically similar with advance aging (PAV40), indicating that potential locations in the binder for additional oxidation are finite. Higher CA is generally associated with greater stiffness of the binder.

The potential reasons for the higher CA content previously discussed include more aging from higher production temperatures, a greater percentage of the stiffer slurry sand RAP, and/or a lower content of recycling agent. The SULF contents for the HyRAP mix show a generally similar trend but with some inconsistency, such as a slight decrease in SULF for Sample 4 going from extraction to PAV20 aging. All other studies done by the UCPRC show that SULF is a compound that often increases with aging but can also decrease with additional aging, showing few completely consistent trends (unlike CA) *(12,13)*. This finding has been reported elsewhere in the literature, indicating that SULF is a "meta stable" aging compound. In general, the effects of SULF are considered to be much less important than the effects of CA.

The differences in the extracted binder CA contents for the HMA-M mix (Mix J) are similar between the two samples, indicating little variability in materials and materials processing. The SULF contents vary between samples and aging conditions. The general inconsistency of SULF is again noted.

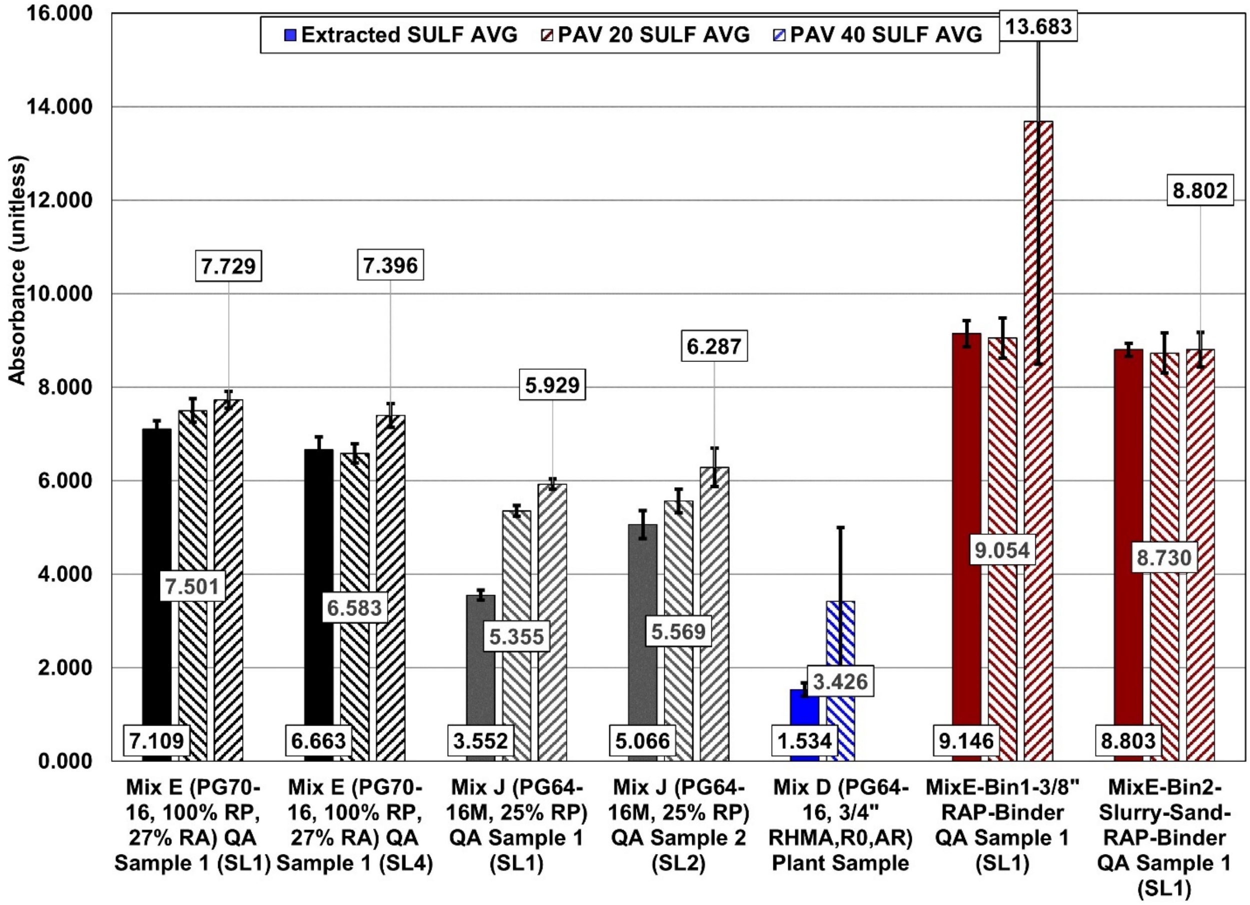
The differences in CA between the two RAP sources are consistent with their true PG grades, with the softer 3/8 in. RAP having a lower CA content than the stiffer slurry sand RAP. Greater percentages of slurry sand RAP in the HyRAP mix will increase the CA content and stiffness. Greater binder contents in the slurry sand RAP, within the variability of the RAP pile, will also increase the CA content and stiffness of the HyRAP mix when the proportions of slurry sand RAP and 3/8 in. RAP are constant. The variability of the HyRAP mix will vary as the relative proportions of the RAP sources changes and as the binder contents change in each pile.

The differences between the RAP sources and the three mixes for CA show that the RAP binders have the highest CA index and SULF. The two indexes then dropped with the addition of recycling agent to create the HyRAP mixes during production. The mixes with 100% RAP content had higher CA and SULF indices compared to the control RHMA-G and HMA-M with 25% RAP binders. The CA index increased with the aging condition of the binders. The aging, as measured by the CA index, increased more for the HMA-M and RHMA-G mixes than the HyRAP mix sample because aging asymptotes toward a high value as the available locations for oxidation become oxidized. Because the HyRAP mixes started with more aging, they aged less with conditioning. The rate of binder aging is also driven by original binder source. The SULF followed the same general trends as the CA but with the kinds of anomalies that are common for sulfoxides.



Note: Error bars indicate one standard deviation of results.

Figure 4.3: Carbonyl area index changes after aging for QA sampled binders.



Note: Error bars indicate one standard deviation of results.

Figure 4.4: Sulfoxide area index changes after aging for QA sampled binders.

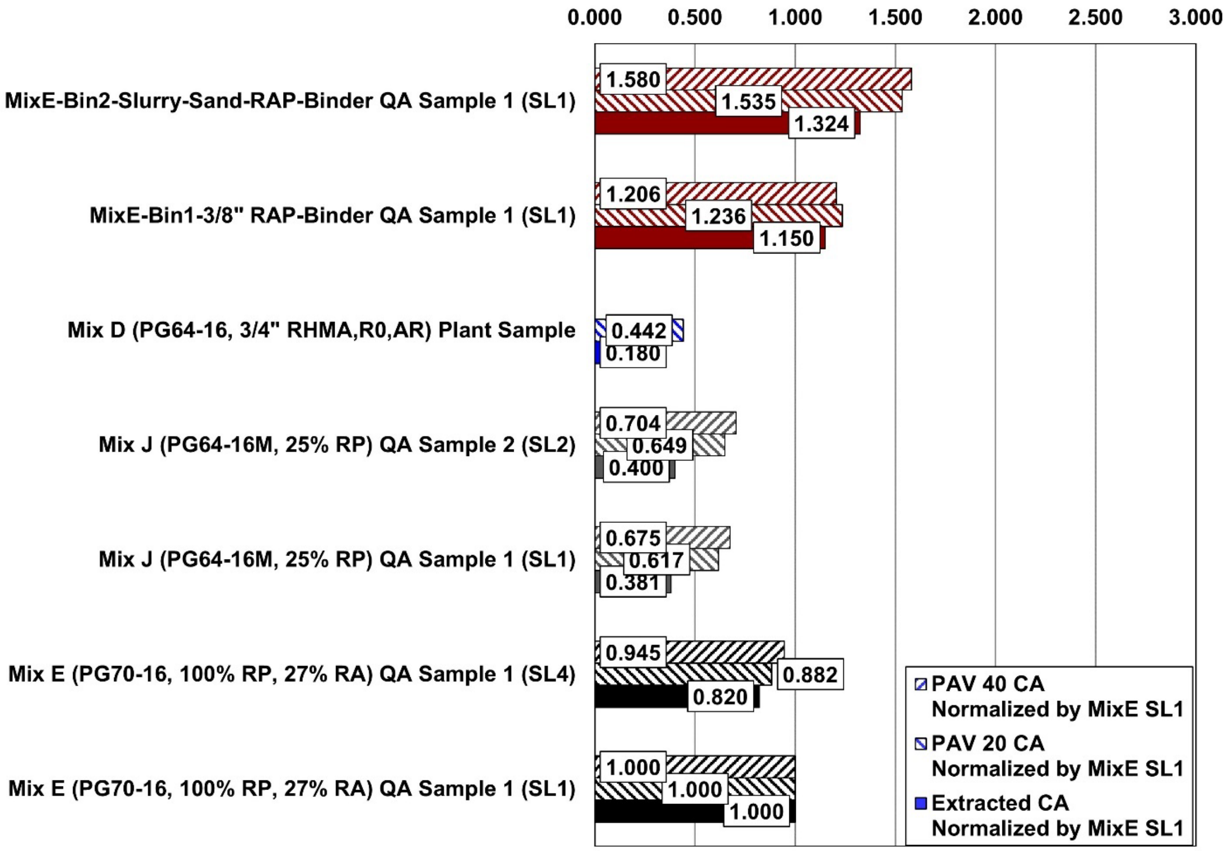


Figure 4.5: Binder carbonyl content for QA samples normalized to Mix E.

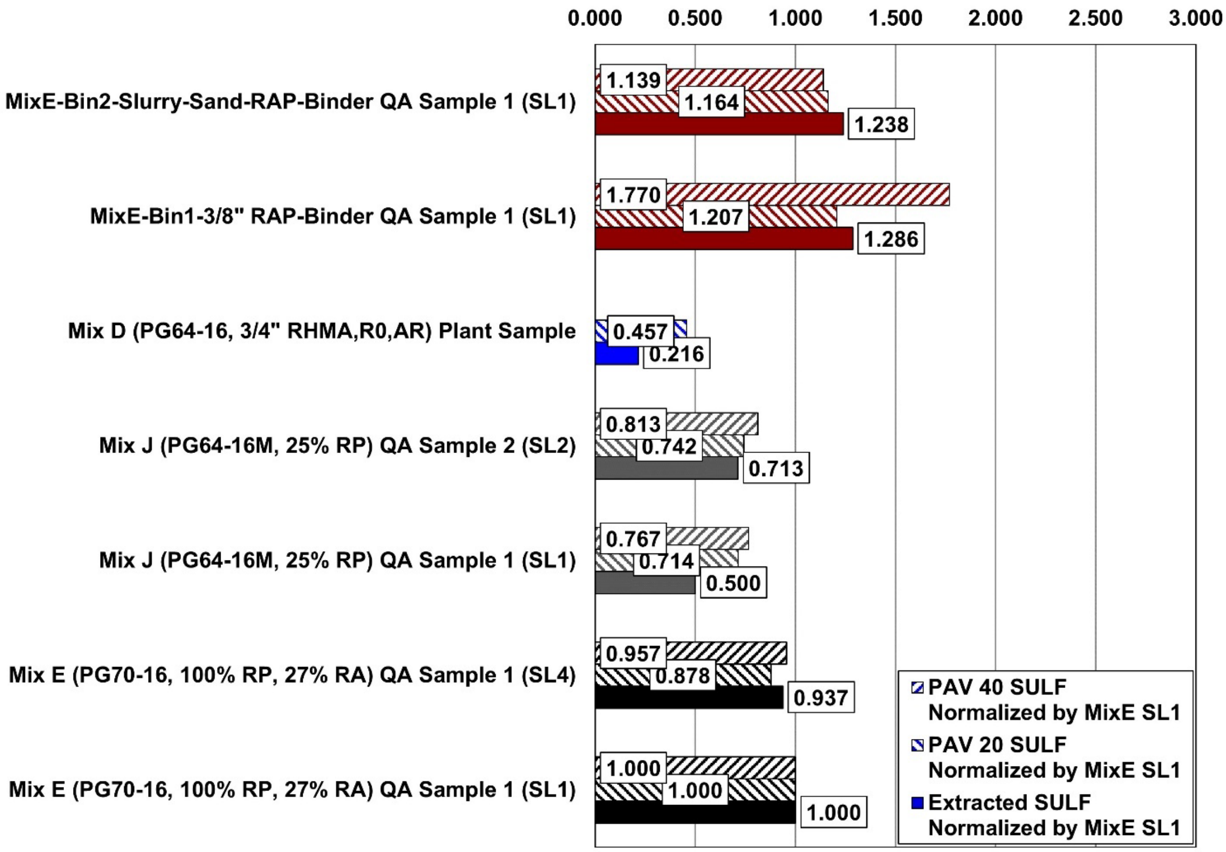


Figure 4.6: Binder sulfoxide content for QA samples normalized to Mix E.

5 MIX TEST RESULTS

This chapter discusses the mix testing results for the three mixes used in the I-40 project. Of the five samples taken for the HyRAP 100% RAP mix, sufficient material was collected only for Sample 1 to perform all mix tests. The other samples, Samples 2 through 5, were of smaller size due to available resources, and not all mix tests were performed on them. Of the two samples taken for the HMA-M and RHMA-G mixes, Sample 1 was a large sample and Sample 2 was smaller, and only Sample 1 was subjected to all mix tests. Most specimens of the HyRAP mix were compacted to 6% air-voids because the nSSP included that as a compaction specification. The other mixes were compacted to the standard 7% air-voids. The mix producer also requested some tests at 3% air-voids, which were conducted.

5.1 Volumetrics

Table 5.1 shows the extracted total asphalt contents from the mix samples from the Asphalt Paving and Recycling Technologies Inc. (APART) laboratory, the Manhole Adjusting Inc. laboratory, and the UCPRC laboratory. The APART and Manhole Adjusting Inc. laboratories used a different extraction process than the UCPRC laboratory. Also shown in the table are the air-voids at N_{design} under gyratory compaction for all mixes from the UCPRC laboratory.

As previously discussed in Chapter 4, the results show that first two samples of the HyRAP mix had lower binder contents than the design binder content of 6.33%. The third sample was at approximately the design binder content, and the last two samples were at higher binder content levels. Multiple extractions were made from the fourth mix sample, shown in Table 5.1. The binder contents of the two HMA-M samples were nearly identical. Binder contents cannot be determined for RHMA-G using extraction, and an insufficient amount of sampled mix was available to estimate binder contents using the ignition oven.

The gyratory compaction results shown in Table 5.1 and plotted in Figure 5.1 follow the binder contents, as expected, with low binder contents resulting in higher air-voids and high binder contents resulting in lower air-voids. In general, the gyratory compaction air-voids are much lower than the 3% air-void that is the typical target for conventional HMA mixes. The air-voids are also low for the one HMA-M with 25% RAP mix sample tested and the first of the two RHMA-G mix samples tested. There is considerable variability in the air-voids at N_{design} between the two RHMA-G mix samples.

The field compaction results from cores for the HyRAP mix test sections from Sequoia Consultants presented in Table 5.2 show that field compaction was uniform across the sublots and that the compaction resulted in low air-void contents, averaging 3.8% and with a standard deviation of 0.9%.

Table 5.1: Summary of Extracted Asphalt Contents from HyRAP 100% RAP Mixes and Laboratory Air-Voids at N_{design} for All Mixes

Sublot, Mix Type	Asphalt Content (ASTM D8159)			Laboratory Air-Void (%) at N_design	
	APART[1]	MAI[2]	UCPRC	MAI (Ndes = 50)	UCPRC (Ndes = 85)
SL1, 3/8" nSSP, R100, 76-16	5.79	5.75	6.00	3.1	1.8
SL2, 3/8" nSSP, R100, 76-16	5.76	5.67	5.99	1.7	1.2
SL3, 3/8" nSSP, R100, 76-16	6.43	6.02	6.19	2.3	1.2
SL4, 3/8" nSSP, R100, 76-16	7.09	6.84	6.73	1.0	1.0
SL4, 3/8" nSSP, R100, 76-16	6.59	6.42		1.2	
SL5, 3/8" nSSP, R100, 76-16	6.10	6.43	6.61	0.9	0.9
Average	6.29	6.19	6.30	1.7	1.2
Standard Deviation	0.51	0.45	0.35	0.9	0.3
Coefficient of Variation (COV)	0.08	0.07	0.05	0.5	0.3
SL1, 1/2" SP Type A R25, 58-38M	—	—	5.44	—	1.5
SL2, 1/2" SP Type A R25, 58-38M	—	—	5.28	—	—
Average	—	—	5.4	—	1.5
Standard Deviation	—	—	0.1	—	—
Coefficient of Variation (COV)	—	—	0.0	—	—
SL1, 3/4" RHMA-G, R0, 64-16AR	—	—	*	—	1.5
SL2, 3/4" RHMA-G, R0, 64-16AR	—	—	*	—	4.0
Average	—	—	—	—	2.8
Standard Deviation	—	—	—	—	1.7
Coefficient of Variation (COV)	—	—	—	—	0.6

[1] APART = Asphalt Paving and Recycling Technologies Inc.
[2] MAI = Manhole Adjusting Inc.
*UCPRC did not run D8159 for the RHMA-G mix.

Table 5.2: Field Compacted Air-Voids for HyRAP 100% RAP Mixes

Field Compacted Air-Voids of Asphalt Cores							
Sublot	**Core ID**	**Air-Voids (%)**	**Core ID**	**Air-Voids (%)**	**Core ID**	**Air-Voids (%)**	**Average Air-Voids (%)**
1	1A1	4.0	1B1	4.8	1C1	3.6	4.1
2	1A2	3.9	1B2	3.2	1C2	3.3	3.5
3	1A3	6.0	1B3	3.4	1C3	3.5	4.3
4	1A4	3.8	—	—	—	—	3.8
4	1A5	3.9	—	—	—	—	3.9
5	1A6	4.9	1B6	2.6	1C6	2.9	3.5
						Average	**3.8**
						Standard Deviation (all core)	**0.90**

Note: AASHTO T 275 from Sequoia Consultants.

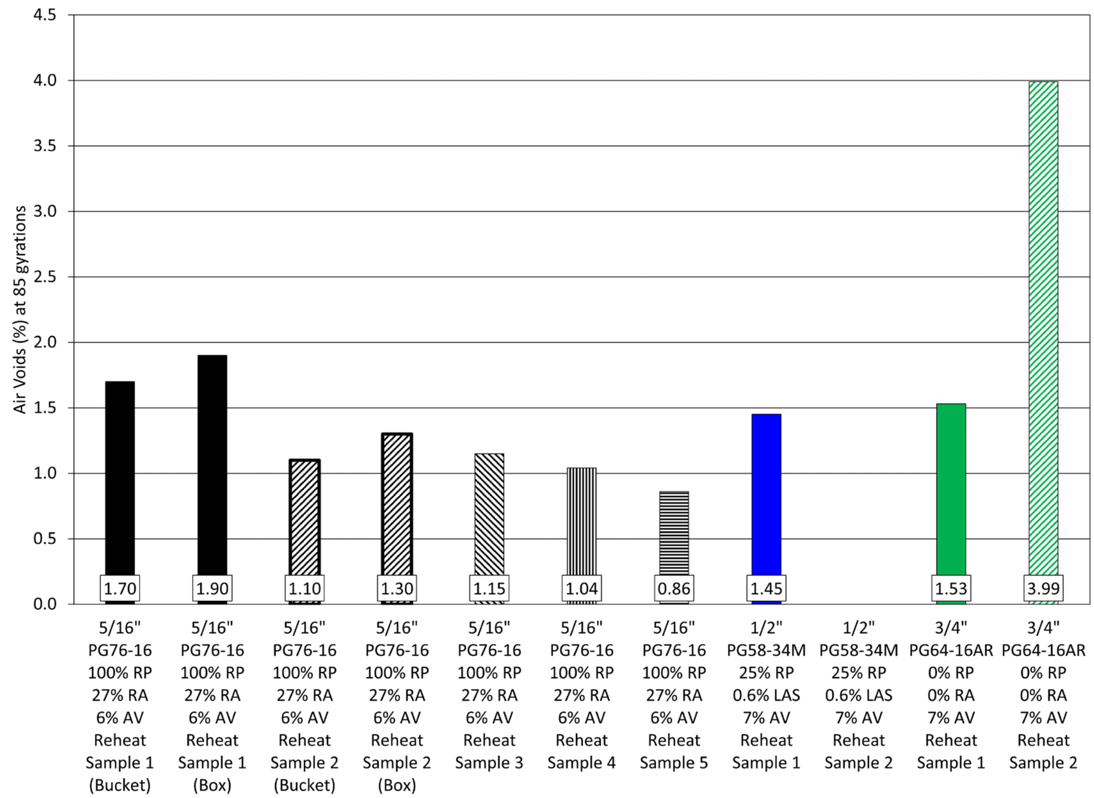


Figure 5.1: Air-voids for all samples of the three mixes from UCPRC testing (N_{design}, 85 gyrations).

5.2 Stiffness

Stiffness of the three mixes was measured using dynamic loading in both the axial and flexural modes. Axial stiffnesses are generally somewhat greater than flexural stiffnesses because mixes are stiffer in compression than they are in flexural, which is a combination of tension and compression. Flexural stiffnesses tend to be less reliable at very low frequencies combined with high temperatures when the stiffness is very low.

5.2.1 Axial Dynamic Modulus

The results of axial dynamic modulus testing (DM, AASHTO T 378; specimens prepared in a gyratory compactor) using a frequency sweep experiment design are shown in Figure 5.2 and normalized to the stiffness of the HyRAP mix in Figure 5.3. The results show that the HyRAP mix from Sample 1 is five times stiffer than the HMA-M with 25% RAP and RHMA-G mixes at low reduced frequencies, corresponding to slow truck traffic at high temperatures, while Sample 5 of the HyRAP mix has the approximately the same stiffnesses as Sample 1 of the RHMA-G and HMA-M mixes. At intermediate frequencies, corresponding to medium speed traffic at intermediate temperatures, the HyRAP Sample 1 mix is approximately twice as stiff as the other two mixes, while Sample 4 has approximately the same stiffness as the other two mixes. At high reduced frequencies, corresponding to fast traffic and cold temperatures, Sample 1 of the HyRAP mix is approximately 25% stiffer than the other two mixes, while Sample 4 is similar to the other two mixes.

The Black Space diagram, showing stiffnesses and phase angles across the combinations of temperature and loading frequency, is shown in Figure 5.4. The differences of stiffness and phase angle for Sample 1 of the HyRAP mix can be seen, with the curve shifted up and to the left from the other two mixes, indicating greater stiffness and more elastic behavior as compared to viscoelastic behavior (lower phase angles). In contrast, the Black Space diagram curve for Sample 4 of the HyRAP mix falls in between that of the HMA-M and the RHMA-G.

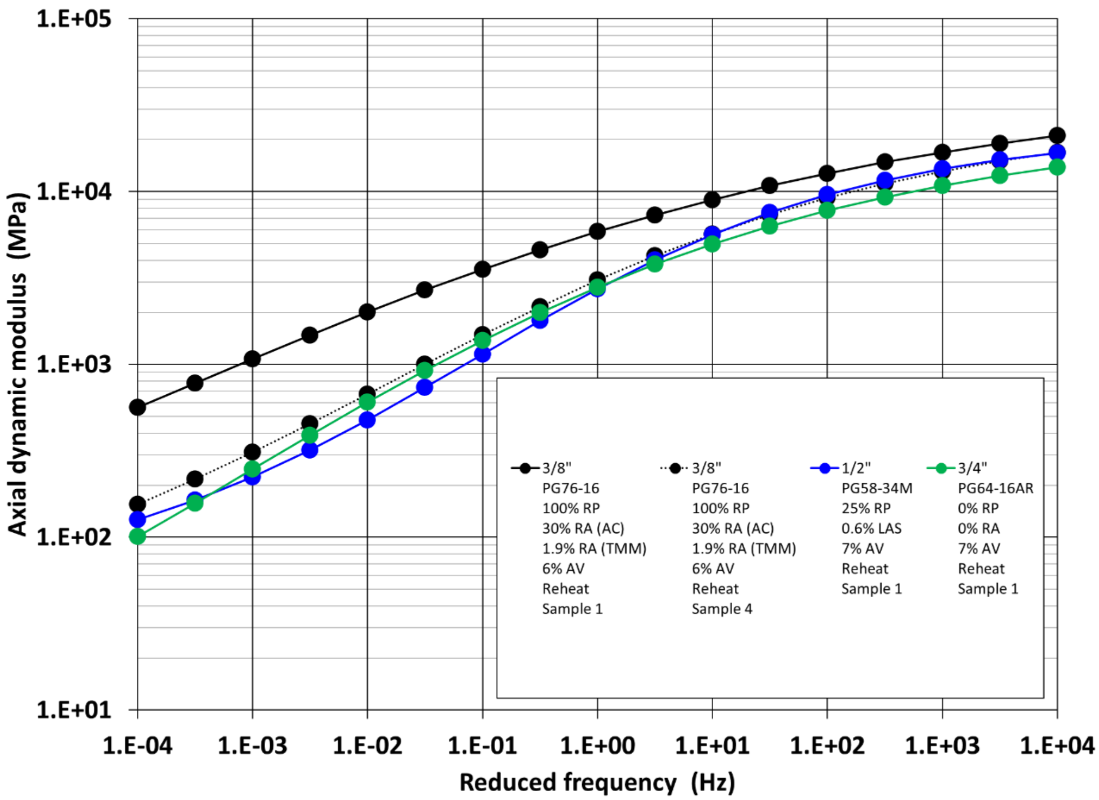


Figure 5.2: Axial dynamic modulus for Sample 1 of the three mixes and Sample 4 of the HyRAP 100% RAP mix.

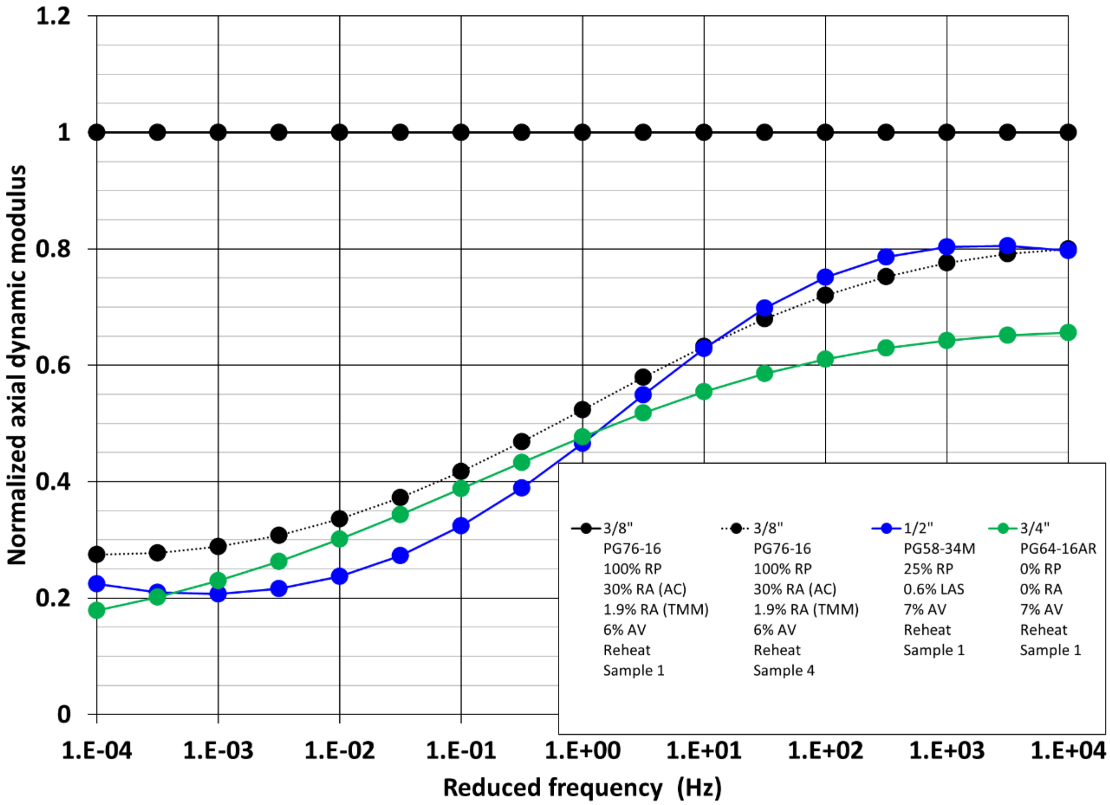


Figure 5.3: Axial dynamic modulus for Sample 1 of the three mixes normalized to Sample 1 of the HyRAP 100% RAP mix.

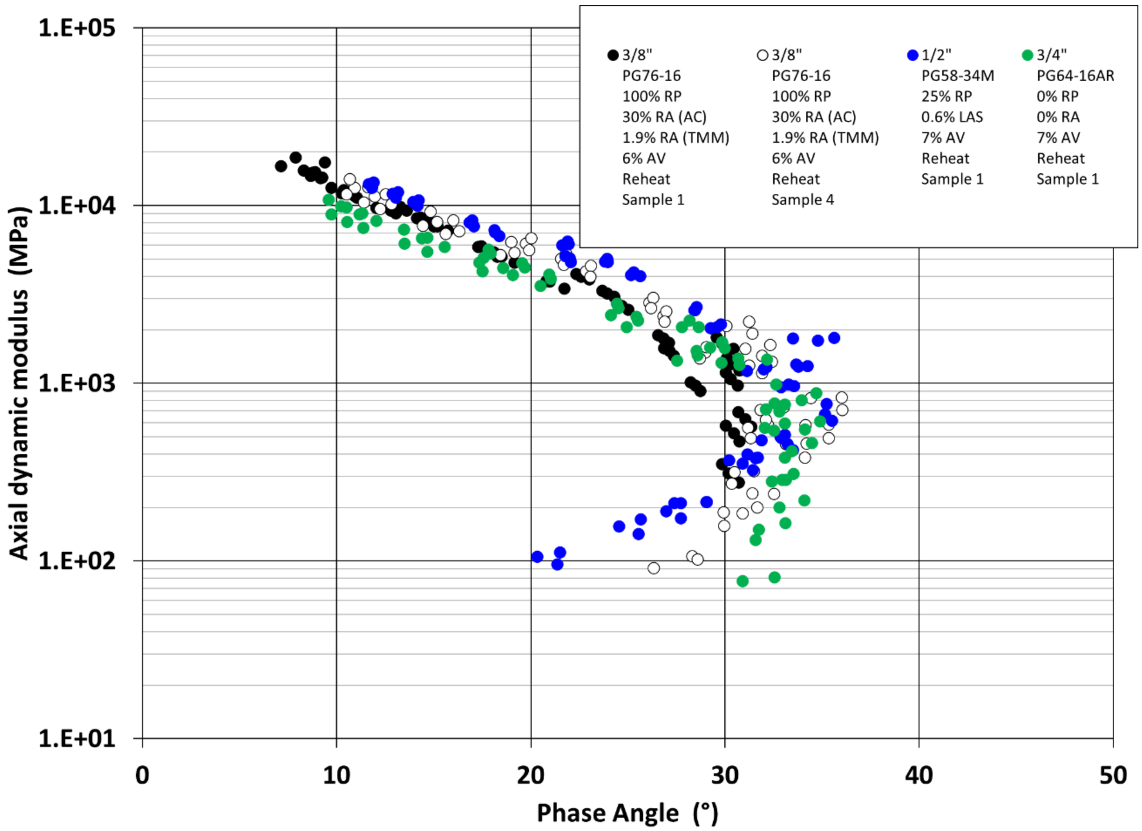


Figure 5.4: Black Space diagram for axial dynamic modulus for Sample 1 of the three mixes and Sample 4 of the HyRAP 100% RAP mix.

5.2.2 Flexural Dynamic Modulus

The results of flexural dynamic modulus testing (FM, AASHTO T 321; Specimens Prepared Using a Rolling Wheel Compactor) using a frequency sweep experiment design are shown in Figure 5.5 and normalized to the stiffness of Sample 1 of the HyRAP mix in Figure 5.6. The results of the flexural modulus testing are very similar to those of the axial dynamic modulus results. They show that the HyRAP mix from Sample 1 is five times stiffer than the HMA-M with 25% RAP and RHMA-G mixes at low reduced frequencies, corresponding to slow traffic at high temperatures. The stiffnesses of Sample 1 across the frequencies are generally close to those of the PG 70 statewide median mix. The stiffnesses of Sample 5 of the HyRAP mix are close to those of the RHMA-G mix across all but the slowest frequencies and softer than those of the PG 64 statewide median mix across all but the slowest frequencies. At intermediate frequencies, corresponding to medium speed traffic at intermediate temperatures, the HyRAP Sample 1 mix is approximately twice as stiff as the other two mixes. At high reduced frequencies, corresponding to fast traffic and cold temperatures, the HyRAP mix Sample 1 is approximately 30% stiffer than the other two mixes used in the project and HyRAP mix Sample 5 is 20% stiffer than Sample 1.

The Black Space diagram, showing stiffnesses and phase angles across the combinations of temperature and loading frequency for Sample 1 of the three mixes used in the project, is shown in Figure 5.7. The results for the flexural modulus are generally similar to those of the axial modulus.

The differences of stiffness and phase angle can be seen, with the HyRAP mix Sample 1 curve shifted up and to the left from the other two mixes, indicating greater stiffness and more elastic behavior as compared to viscoelastic behavior (lower phase angles). For both the axial and flexural stiffness tests, the results for low temperatures are at the upper left end of each curve. The fact that the HyRAP mixes sit farther up (stiffer) and to the left (less viscous behavior and ability to relax stresses) indicates less ability to relax stresses from thermal contraction that can contribute to age-related cracking.

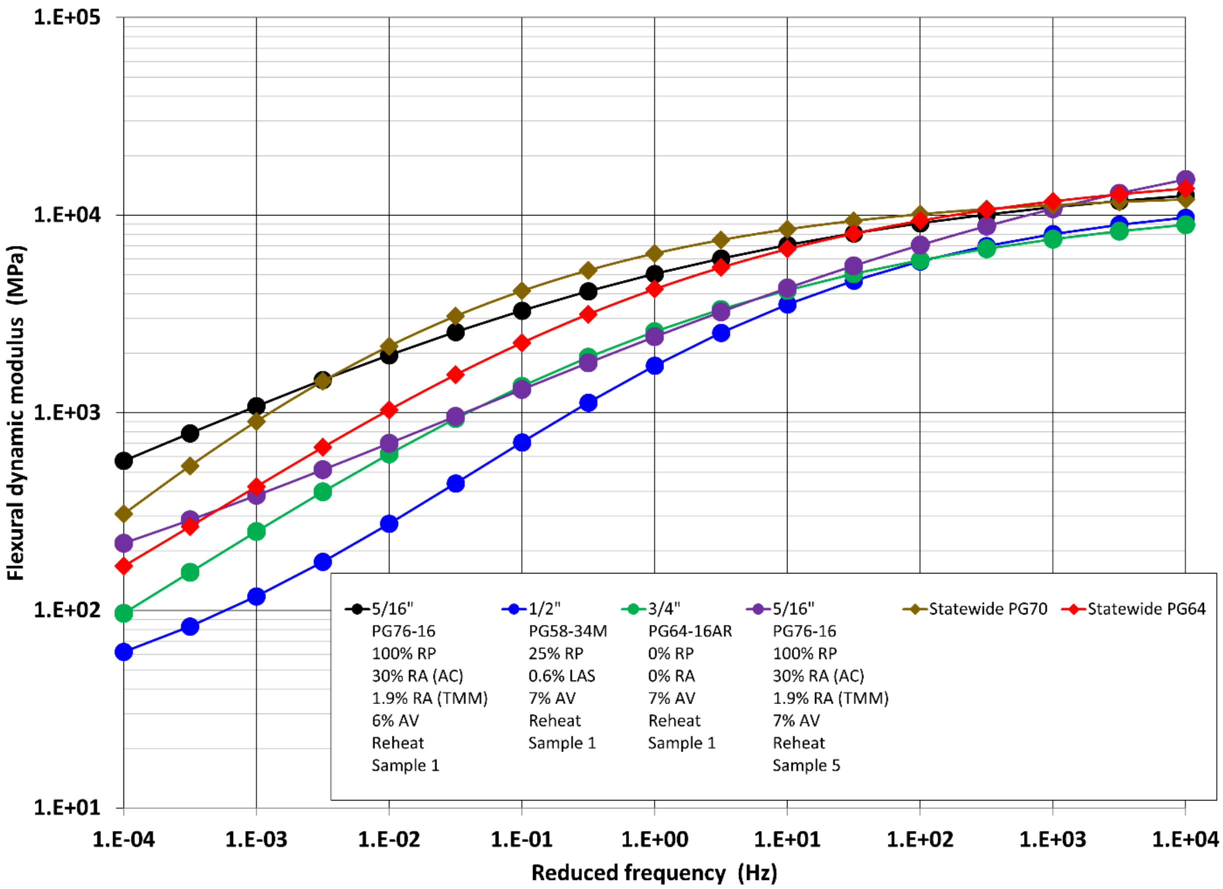


Figure 5.5: Flexural dynamic modulus for Sample 1 of the three mixes, Sample 5 of the HyRAP 100% RAP mix, and the statewide median PG 64 and PG 70 mixes.

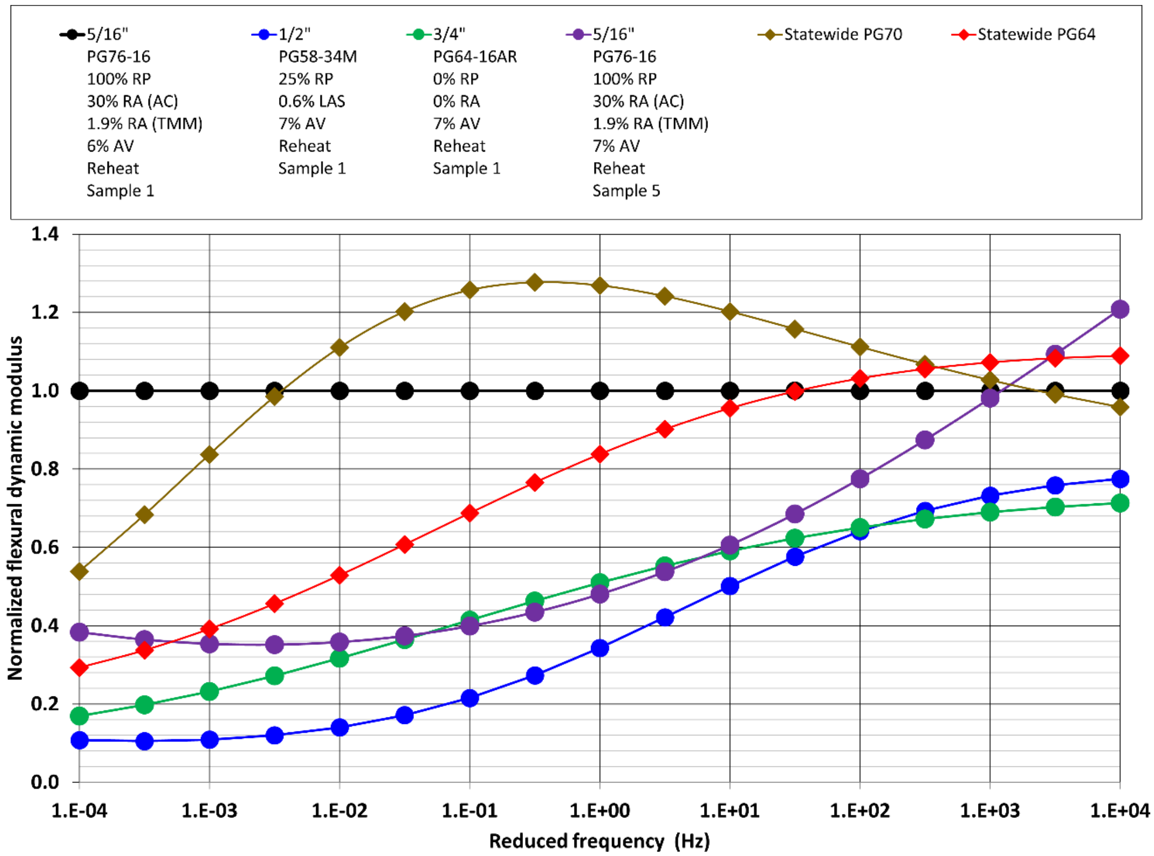


Figure 5.6: Flexural dynamic modulus for Sample 1 of the three mixes, Sample 5 of the HyRAP 100% RAP mix, and statewide median PG 64 and PG 70 mixes, normalized to Sample 1 of the HyRAP 100% RAP mix.

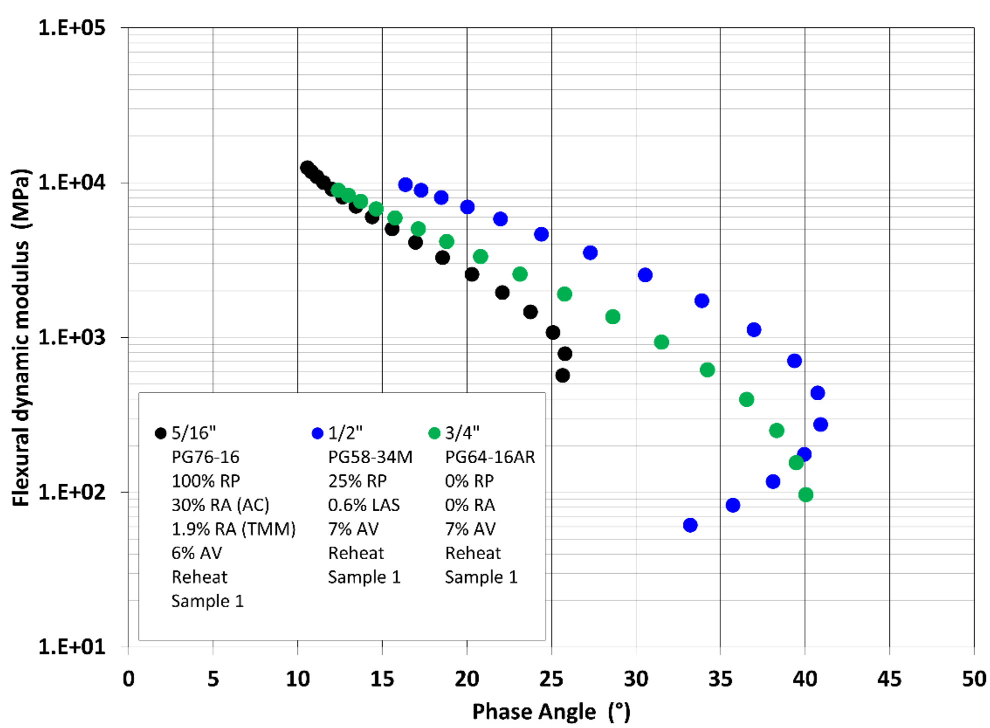


Figure 5.7: Black space diagram for Sample 1 of the three mixes used on the project.

5.3 Flexural Fatigue Cracking

The results of flexural fatigue cracking testing are shown in Figure 5.8. The results are shown for Sample 1 of each mix, Sample 5 of the HyRAP 100% RAP mix, and the statewide median PG 64 and PG 70 mixes. For Sample 1 of the HyRAP mix, the specimens were compacted to both 3% and 6% air-voids. For the HMA-M with 25% RAP mix, the RHMA-G mix, and the statewide median mixes, the specimens were compacted to 7% air-voids. For Sample 5 of the HyRAP mix, the specimens were compacted to 6% air-voids. Higher air-voids nearly always result in poorer flexural fatigue performance, which can be seen for results of the 3% air-void content HyRAP beams compared with those compacted to 6% air-voids.

The results indicate that the RHMA-G mix, by far, has the best fatigue performance. Sample 5 of the HyRAP mix as the second best performance at lower strains. Sample 5 has a very high strain sensitivity, doing better than most of the other strains at lower strains and worse than all but the PG 70 statewide median mix at the highest strains based on extrapolation of the fatigue curves. The HMA-M mix has the flattest strain sensitivity, with poorer fatigue performance than the HyRAP samples at lower strains and the best performance at higher strains, without discounting the beneficial effect of the better compaction given to the HyRAP laboratory beam specimens, which have either 1% or 4% better compaction. All of the three mixes used in the project, including both samples of the HyRAP mix, have better fatigue performance than both the PG 64 statewide median mix and especially better performance than the statewide median PG 70 mix.

It should be noted that Sample 1 of the HyRAP mix was the material that was produced at a high temperature, which will stiffen it and hurt fatigue performance, and with lower than design binder content, which will also hurt its fatigue performance. Sample 5 of the HyRAP mix, which is softer than Sample 1 at all but the lowest temperatures and highest frequencies due to a higher binder content and lower mixing temperature, showed better fatigue performance than Sample 1.

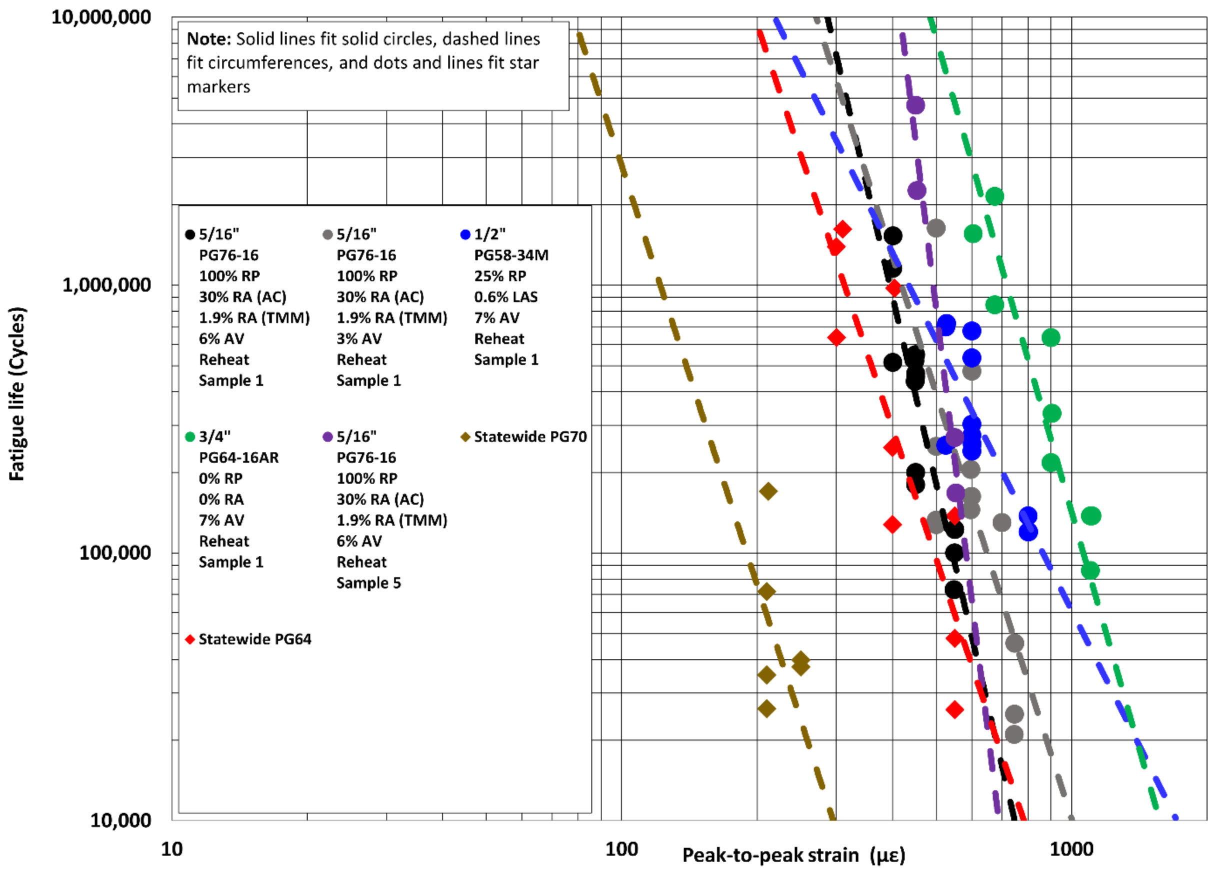


Figure 5.8: Flexural fatigue for Sample 1 of the three mixes, Sample 5 of the HyRAP 100% RAP mix, and the statewide median PG 64 and PG 70 mixes, including Sample 1 of the HyRAP 100% RAP mix at both 6% and 3% air-voids.

5.4 Age-Related Cracking

Age-related cracking was assessed using the IDEAL-CT test. Two parameters are taken from the test, indirect tensile strength and IDEAL-CT index value, and it was performed in the reheated condition after MTOA simulating additional aging in the field, MiST conditioning simulating the effects of moisture causing moisture damage, and both MTOA and MiST conditioning.

The indirect tensile strength (IDEAL-CT strength), peak value in the displacement versus load relationship from the test, is a very good indicator of dynamic stiffness. In general, stiffer mixes have less age-related cracking resistance, particularly after they have been further aged in the field as is at least partially simulated by the MTOA procedure. The IDEAL-CT index value has been related to age-related cracking and considers the post-peak slope of the displacement versus load curve, with flatter post-peak slopes supposed to indicate better ability to relax thermal contraction stresses that cause age-related cracking.

5.4.1 IDEAL-CT Indirect Tensile Strength Test

5.4.1.1 Reheated Mix

Figure 5.9 shows the load versus displacement relationship for the IDEAL-CT test on reheated plant mix for all three mixes, including all five samples of the HyRAP mix, both samples of the HMA-M with 25% RAP mix, and both samples of the RHMA-G mix. The HyRAP samples were compacted to 6% air-voids, reflecting the nSSP for the project. The HMA-M Sample 1 mix was compacted to both 6% air-voids and the typically specified 7% air-voids for comparison. The RHMA-G mix was compacted to the standard 7% air-voids.

Better compaction (lower air-voids) will result in higher strength and is generally considered to result in better age-related cracking resistance because better compaction results in less aging in the field. Better compaction is also generally considered to result in better age-related cracking resistance because fewer air-voids makes fracture paths more torturous. In general, it would be considered better to have a softer mix, indicated by a lower strength, except when the lower strength is caused by less compaction and higher air-voids. Therefore, it is typical to compare strengths (stiffnesses) of mixes between mixes and not for different compaction levels of the same mix, when assessing the potential for age-related cracking based on strength.

The tensile strengths are shown in Figure 5.10. The results show that Sample 1 of the HyRAP mix had the highest strength, which corresponds to higher stiffness as was seen in the dynamic modulus results. The HMA-M mix had higher strengths than the RHMA-G mix. Comparing Sample 1 of the three mixes, these results would indicate better age-related cracking resistance and likely also better fatigue cracking resistance when used in a thin overlay for the RHMA-G mix compared with the HMA-M mix and better age-related cracking and thin overlay fatigue cracking resistance for the HMA-M compared with the HyRAP. However, the other four samples of the HyRAP mix all had lower stiffnesses than Sample 1, influenced by lower production temperatures (all later samples) and higher binder contents (Samples 3, 4, and 5).

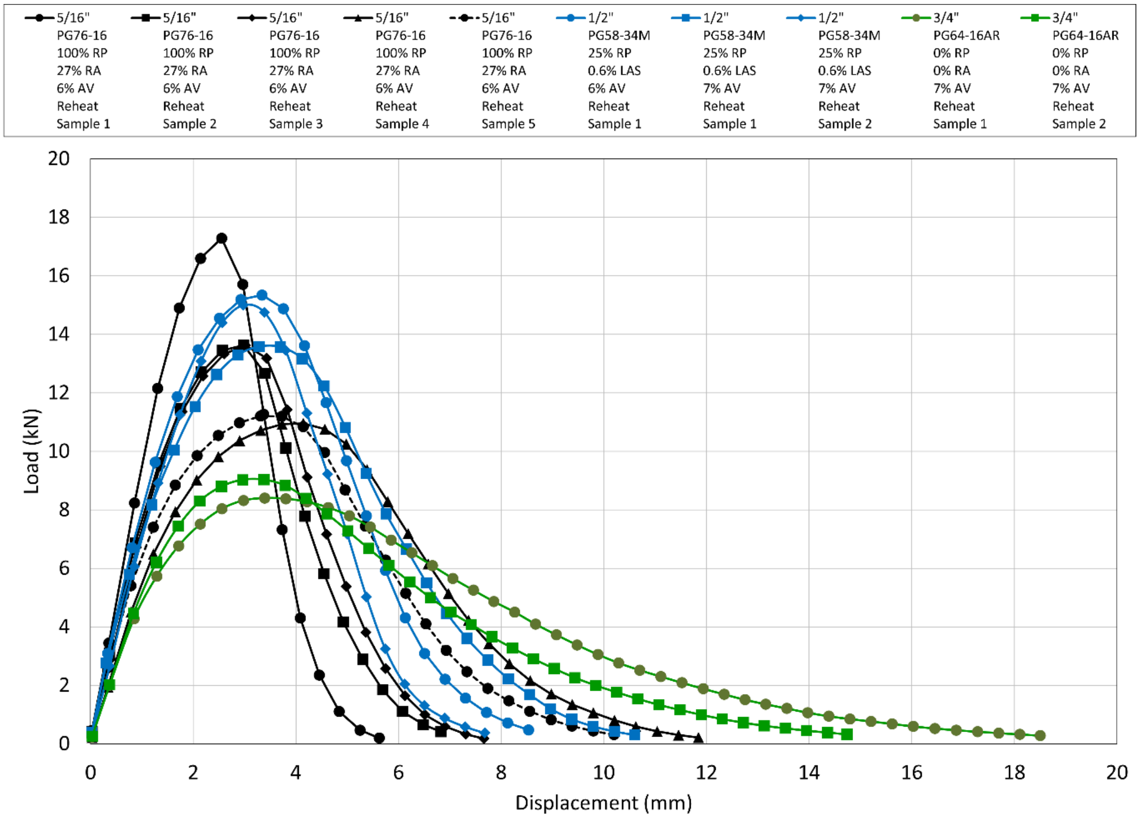


Figure 5.9: IDEAL-CT load versus displacement for all three mixes, including different samples and compacted air-voids.

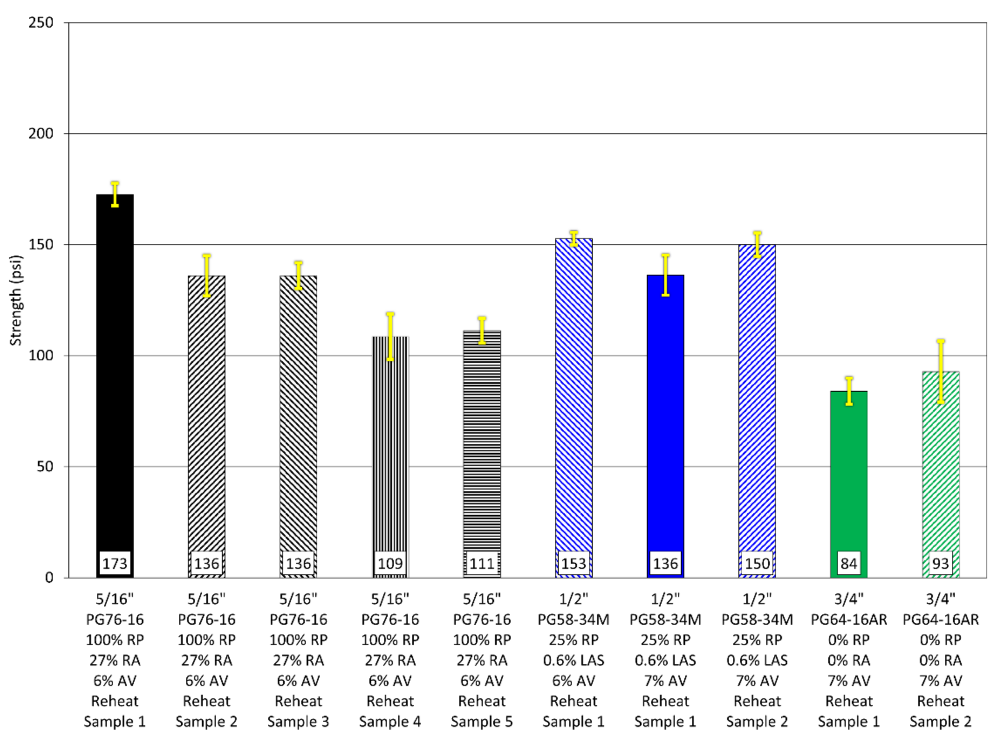


Figure 5.10: IDEAL-CT indirect tensile strength for all three mixes, including different samples and compacted air-voids.

5.4.1.2 Mix with Medium-Term Oven Aging Conditioning

Figure 5.11 shows the displacement versus load relationships for the three mixes and all samples after MTOA conditioning, with differing air-void contents, as previously noted. The strengths are shown in Figure 5.12. All of the strengths increased with aging as expected. The results show the same pattern of relative strengths as was seen for the reheated specimens, except that the RHMA-G mix had more relative aging effects on strength than did the other two mixes. This is likely due to the fact that the RHMA-G mix had no RAP in it and therefore potentially had more hydrocarbon location available for oxidation than did the other two mixes with 100% and 25% RAP. The MTOA results indicate that the RHMA-G mix had lower strength and therefore lower stiffness, generally better for age-related cracking, than did the other two mixes. However, Sample 4 of the HyRAP mix, which had a binder content that was approximately 0.7% greater than the design binder content, had strength comparable to the RHMA-G mix.

Table 5.3 shows the IDEAL-CT strength for the reheated and MTOA conditions for all mixes and samples and the percent change in stiffness after MTOA. As was previously noted, the RHMA-G mix had the greatest increase in strength, and therefore stiffness, with aging, although it remained the softest mix and therefore likely would have the best age-related cracking resistance and fatigue resistance in the thin overlay application on I-40. Overall, the IDEAL-CT strength results indicate that the HyRAP mix had high variability during construction, primarily binder content changes but also the high production temperature of Sample 1.

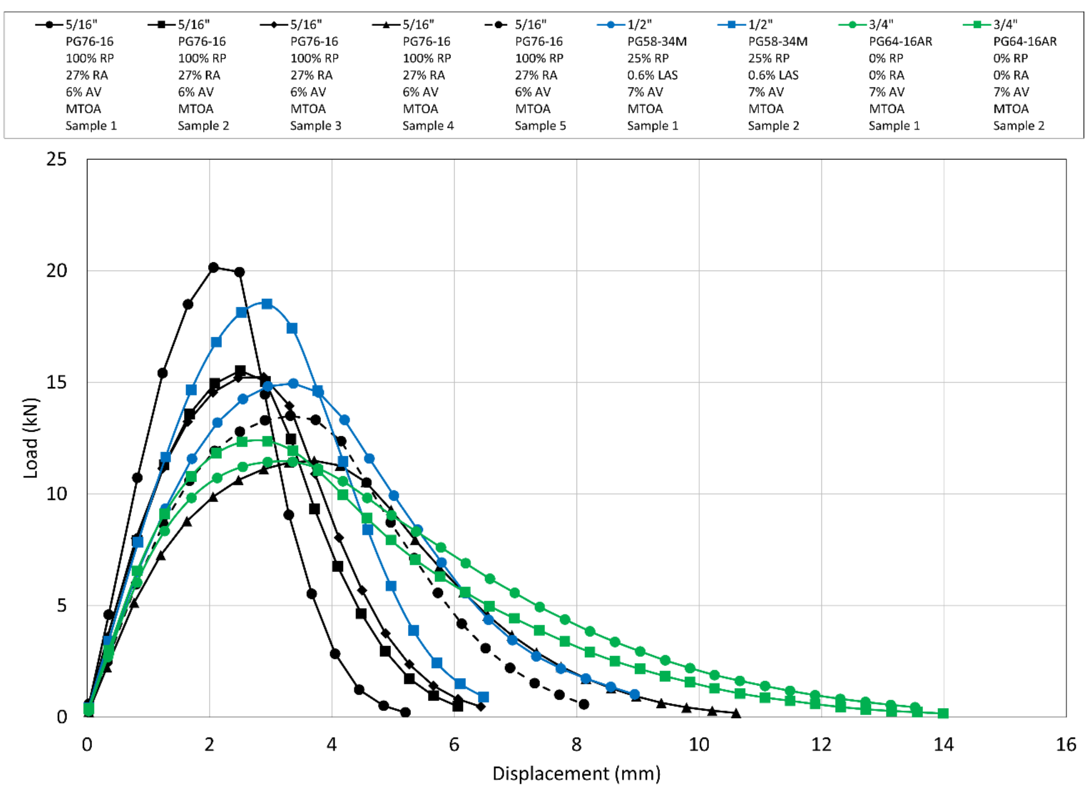


Figure 5.11: IDEAL-CT with MTOA conditioning load versus displacement for all three mixes, including different samples and compacted air-voids.

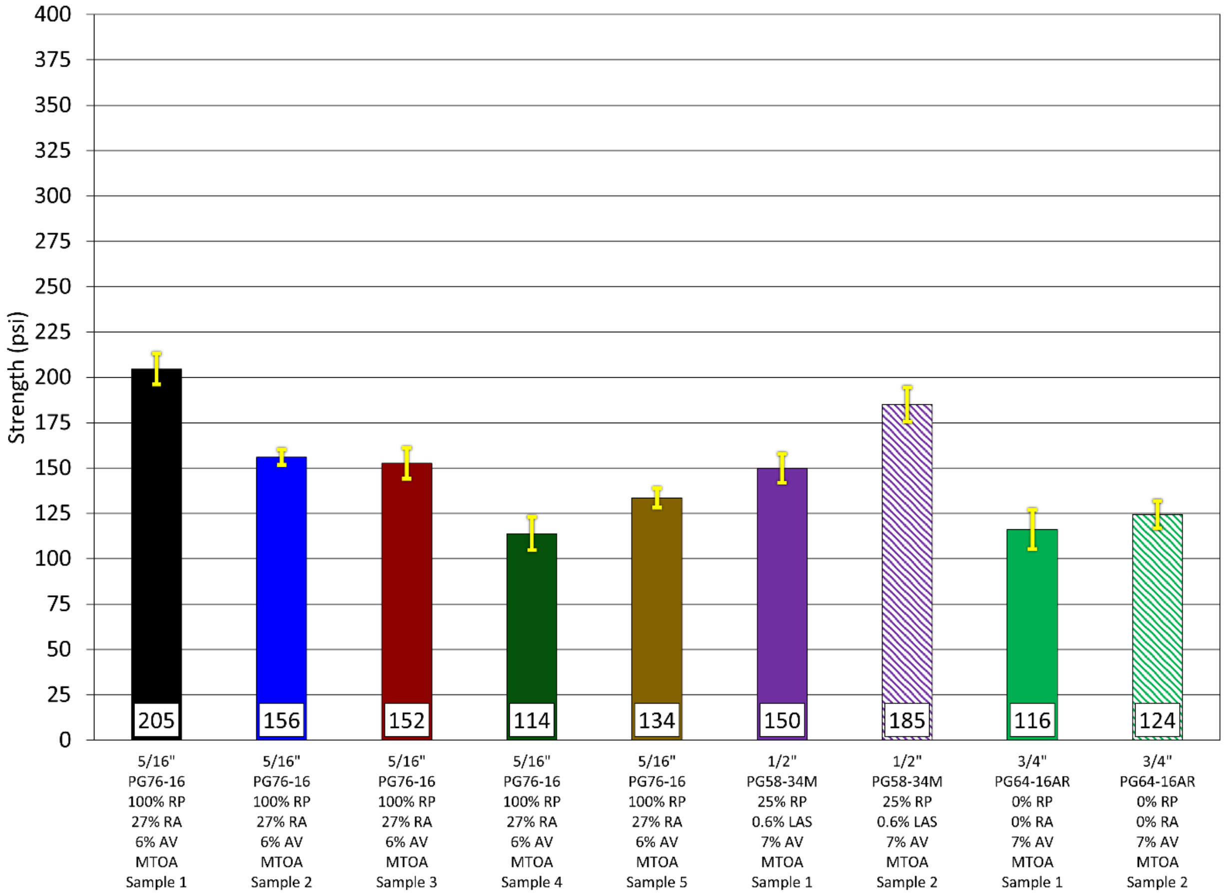


Figure 5.12: IDEAL-CT indirect tensile strength with MTOA conditioning for all three mixes, including different samples and compacted air-voids.

Table 5.3: Change of Strength Between Reheat and MTOA IDEAL-CT Strength Results

Sublot, Mix Type	Reheat	MTOA	Change (%)
SL1, 3/8" nSSP, R100, 76-16	173	205	18.5
SL2, 3/8" nSSP, R100, 76-16	136	156	14.7
SL3, 3/8" nSSP, R100, 76-16	136	152	11.8
SL4, 3/8" nSSP, R100, 76-16	109	114	4.6
SL5, 3/8" nSSP, R100, 76-16	111	134	20.7
SL1, 1/2" SP Type A R25, 58-38M (6%)	153	—	—
SL1, 1/2" SP Type A R25, 58-38M (7%)	136	150	10.3
SL2, 1/2" SP Type A R25, 58-38M	150	185	23.3
SL1, 3/4" RHMA-G, R0, 64-16AR	84	116	38.1
SL2, 3/4" RHMA-G, R0, 64-16AR	93	124	33.3

5.4.2 IDEAL-CT Index Value

As previously discussed, the IDEAL-CT index value test (also referred to as the cracking tolerance, IDEAL-CT Index, or the CT#) is proposed as a measure of age-related cracking for surface mixes and fatigue cracking for thin overlays. A higher IDEAL-CT index value is supposed to indicate better cracking resistance.

5.4.2.1 Reheated mix

The results of IDEAL-CT Index are shown in Figure 5.13 for the reheated condition. The results indicate that the RHMA-G mix should have the best cracking resistance, and the HyRAP mix samples with high production temperature and low binder content (Sample 1) or only lower binder contents (Sample 2) or the mix design binder content (Sample 3) would be expected to have the worst cracking performance. Less compaction for the same mix generally results in higher IDEAL-CT index values, even though the cracking resistance would be expected to be worse. The HyRAP samples have 1% lower air-voids, which would slightly reduce their index values. The results for HyRAP Sample 4 and Sample 5, with very high binder contents, had much better results, comparable to or better than the HMA-M with 25% RAP mixes and almost as high as Sample 2 of the RHMA-G mix.

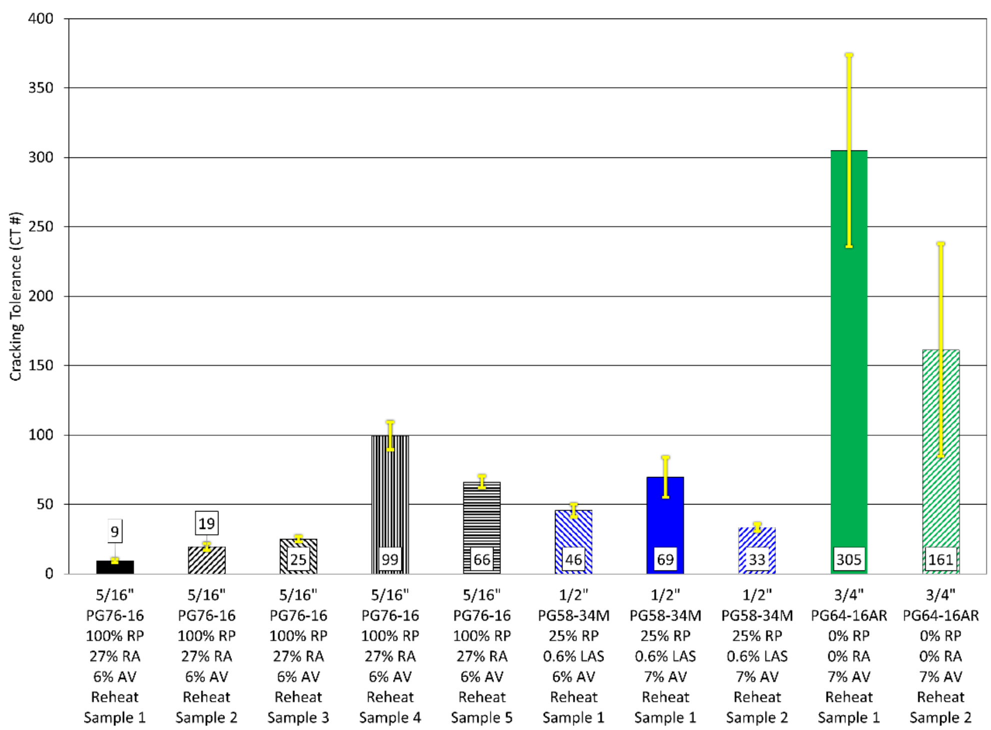


Figure 5.13: IDEAL-CT Index (cracking tolerance) for all three mixes, including different samples and compacted air-voids.

5.4.2.2 Mix with Medium-Term Oven Aging Conditioning

Figure 5.14 shows the IDEAL-CT index results for the five mixes and all samples after MTOA conditioning. The trends are similar to those for IDEAL-CT strength, except that the two HyRAP samples with high binder contents (Sample 4 and Sample 5) had results that were similar to or better than the two HMA-M with 25% RAP mixes. The RHMA-G mix results indicate better cracking resistance for the RHMA-G mix after MTOA conditioning. Table 5.4 shows the IDEAL-CT index value for the reheated and MTOA conditions and the percent change after MTOA aging. The results mirror those of the strength parameter, with the RHMA-G aging more than the other two mixes. There was high variability between samples for the two RHMA-G mixes in both conditions.

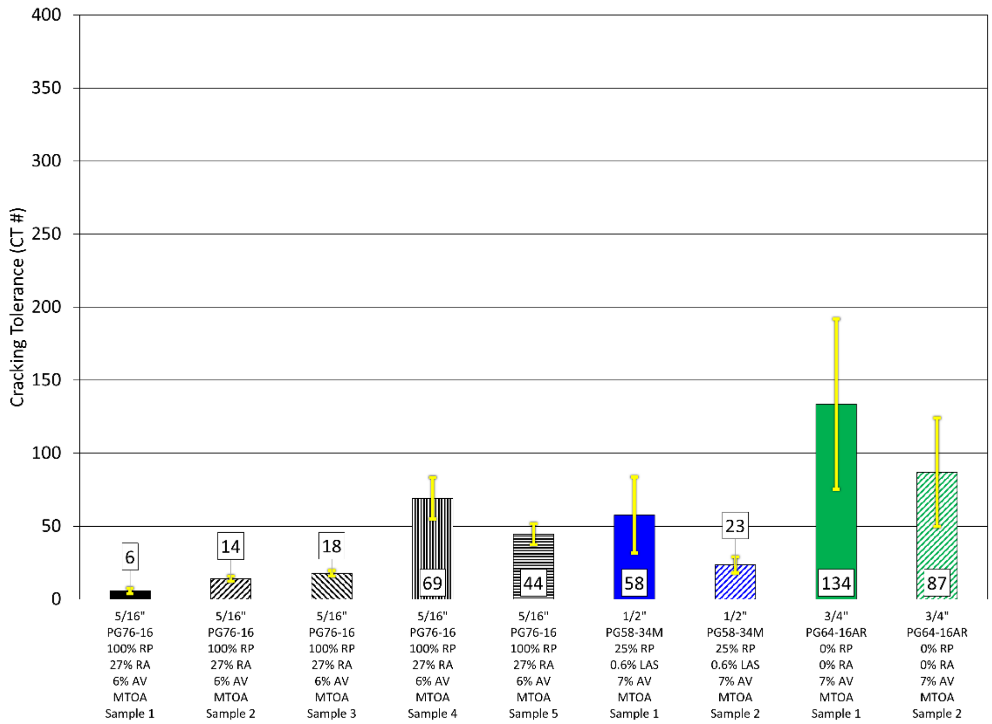


Figure 5.14: IDEAL-CT Index (cracking tolerance) for all three mixes after MTOA conditioning, including different samples and compacted air-voids.

Table 5.4: Change of IDEAL-CT Index (Cracking Tolerance) Between Reheat and MTOA Conditioning Results

Sublot, Mix Type	Reheat	MTOA	Change (%)
SL1, 3/8" nSSP, R100, 76-16	9	6	-33.3
SL2, 3/8" nSSP, R100, 76-16	19	14	-26.3
SL3, 3/8" nSSP, R100, 76-16	25	18	-28.0
SL4, 3/8" nSSP, R100, 76-16	99	69	-30.3
SL5, 3/8" nSSP, R100, 76-16	66	44	-33.3
SL1, 1/2" SP Type A R25, 58-38M (6%)	46	—	—
SL1, 1/2" SP Type A R25, 58-38M (7%)	69	58	-15.9
SL2, 1/2" SP Type A R25, 58-38M	33	23	-30.3
SL1, 3/4" RHMA-G, R0, 64-16AR	305	134	-56.1
SL2, 3/4" RHMA-G, R0, 64-16AR	161	87	-46.0

5.5 Rutting

5.5.1 Repeated Load Triaxial

Mixes with better rutting resistance are expected to have lower permanent deformation versus load cycles in the repeated load triaxial test (RLT, flow number, AASHTO T 378) under both confined and unconfined conditions; specimens prepared in a gyratory compactor). The confined results have generally been considered to be more representative of mixes that have better rutting resistance than the unconfined results *(13)*, while the unconfined test is easier to perform. The UCPRC typically performs the RLT at 45°C and 55°C. Those results are presented in this section. Additional tests were performed at 50°C for comparison with Hamburg Wheel-Track test results, which are also presented.

5.5.1.1 Confined Repeated Load Triaxial

Figure 5.15 shows the plot of axial permanent deformation strain versus load cycles for the confined tests at 45°C for Sample 1 of all three mixes. Figure 5.16 shows the same plot for the 50°C tests, which were conducted on Sample 1 and Sample 2 of each mix and on Sample 4 of the HyRAP mix. Figure 5.17 shows the same plots for the 55°C tests, which were only performed for Sample 1 of the mixes.

The results for Sample 1 of each mix for both 45°C and 55°C indicate that Sample 1 of the HyRAP mix has superior rutting resistance compared with the HMA-M and RHMA-G mixes, likely due to the high temperature at which it was mixed and the low binder content, which required that it be removed and replaced on the second day of paving. The results also show increased permanent deformation at the higher temperature, as expected.

The results for Sample 1 and Sample 2 of each mix and Sample 4 of the HyRAP mix at 50°C are shown in Figure 5.16. Reducing the production temperature and increasing the binder content of the HyRAP mix resulted in a much higher rate of permanent deformation accumulation for Sample 4 than for

Sample 1 and Sample 2. The permanent deformation resistance of Sample 4 is the worst of the mix samples tested, though the test results indicate that it is not that much worse than Sample 2 of the RHMA-G mix for the number of repetitions tested.

The results also showed that the second sample of both the HMA-M and RHMA-G mixes had better permanent deformation performance than did the first samples. Both Sample 1 and Sample 2 of the HyRAP mix had lower binder contents than the design binder content. Sample 4 and Sample 5 had much higher binder contents than the design binder content and would be expected to have much more permanent deformation. Unfortunately, the sample size that could be collected for Sample 5 did not provide enough material to perform RLT tests at 45°C and 55°C.

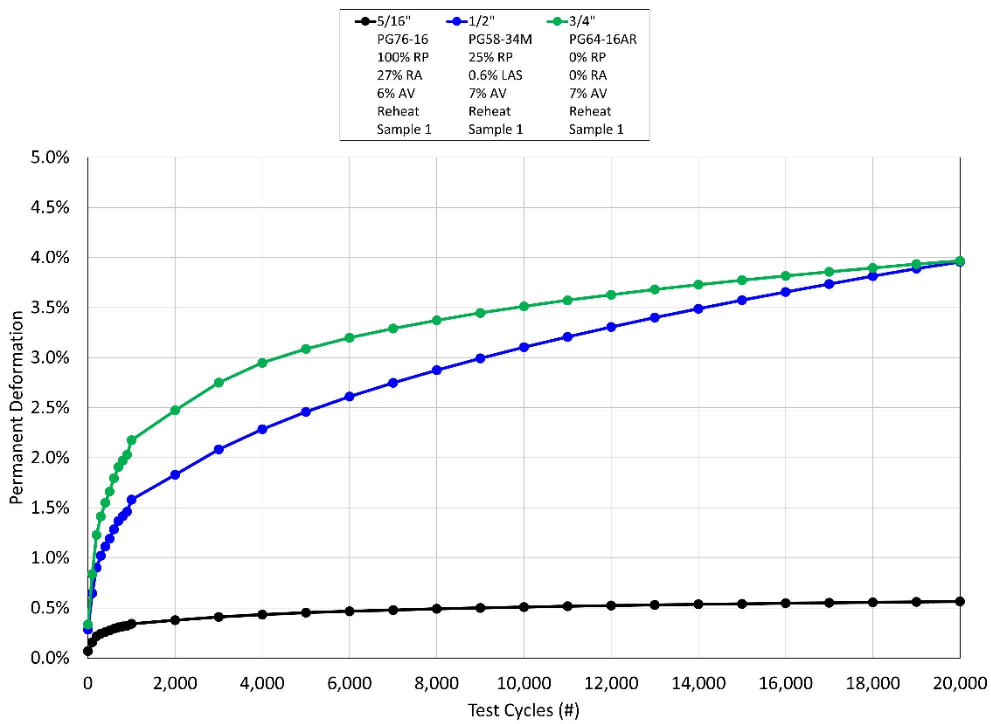


Figure 5.15: Confined repeated load triaxial permanent deformation versus load cycles for Sample 1 of all three mixes at 45°C.

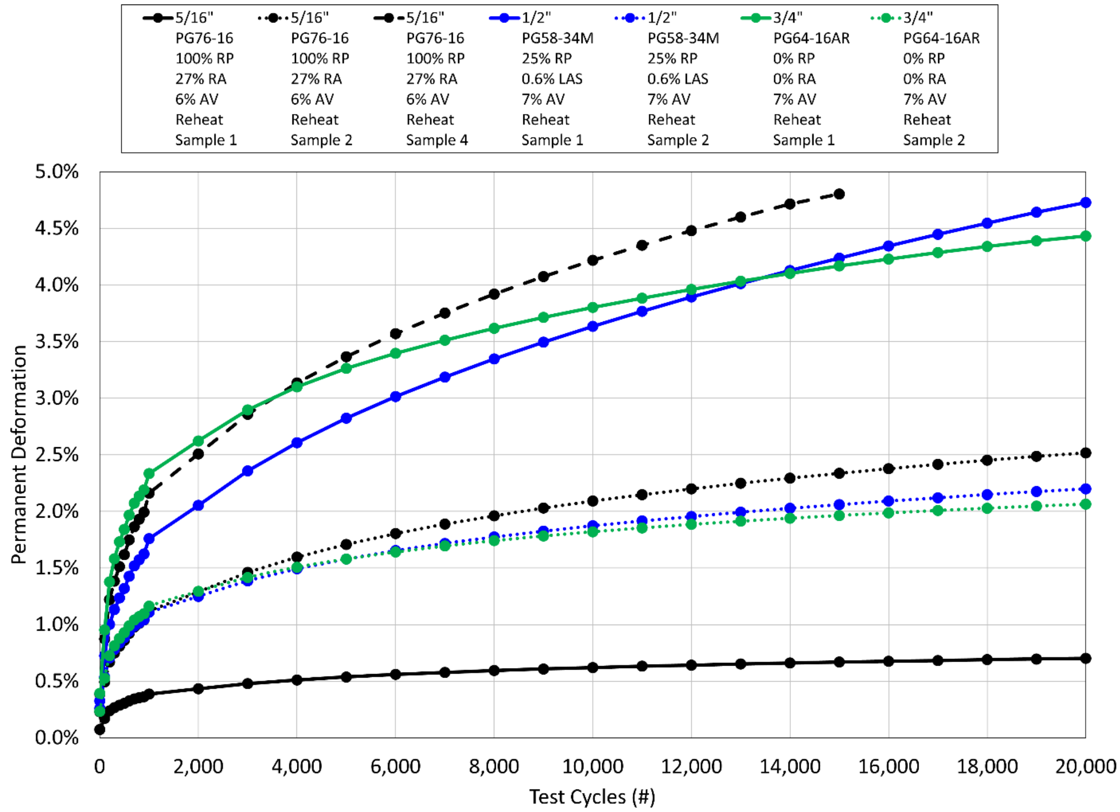


Figure 5.16: Confined repeated load triaxial permanent deformation versus load cycles for Sample 1 and Sample 2 of all three mixes, and Sample 4 of HyRAP, at 50°C.

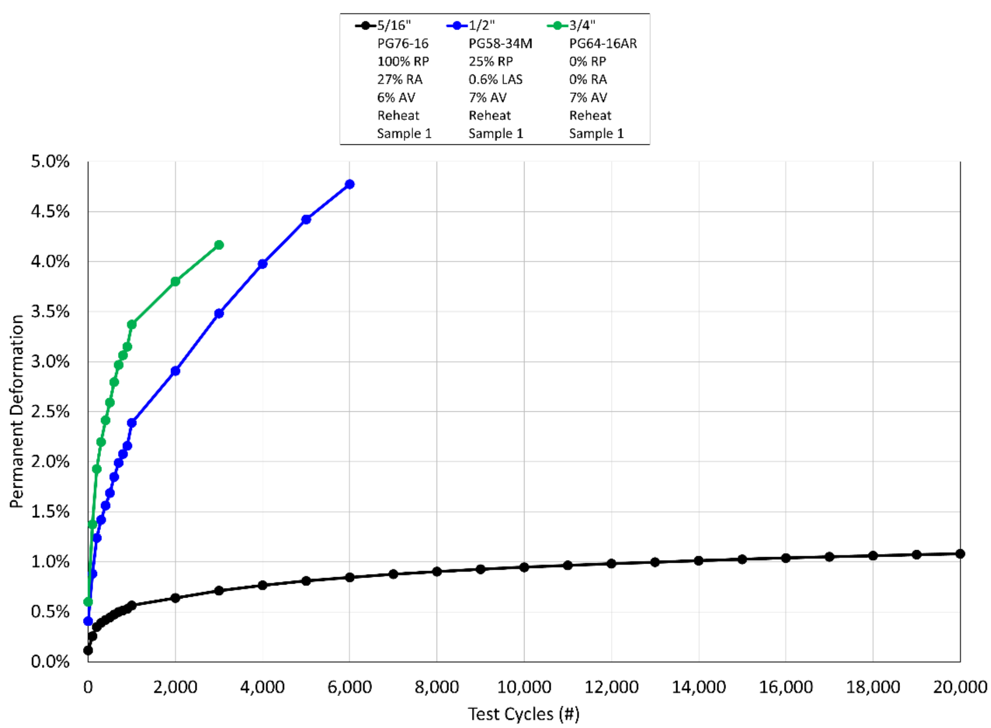


Figure 5.17: Confined repeated load triaxial permanent deformation versus load cycles for Sample 1 of all three mixes at 55°C.

5.5.1.2 Unconfined Repeated Load Triaxial

The unconfined RLT results showed similar trends to those of the confined tests, except the unconfined results for the HyRAP mix were all better than those of the HMA-M and RHMA-G mixes, shown in Figure 5.18, Figure 5.19 and Figure 5.20.

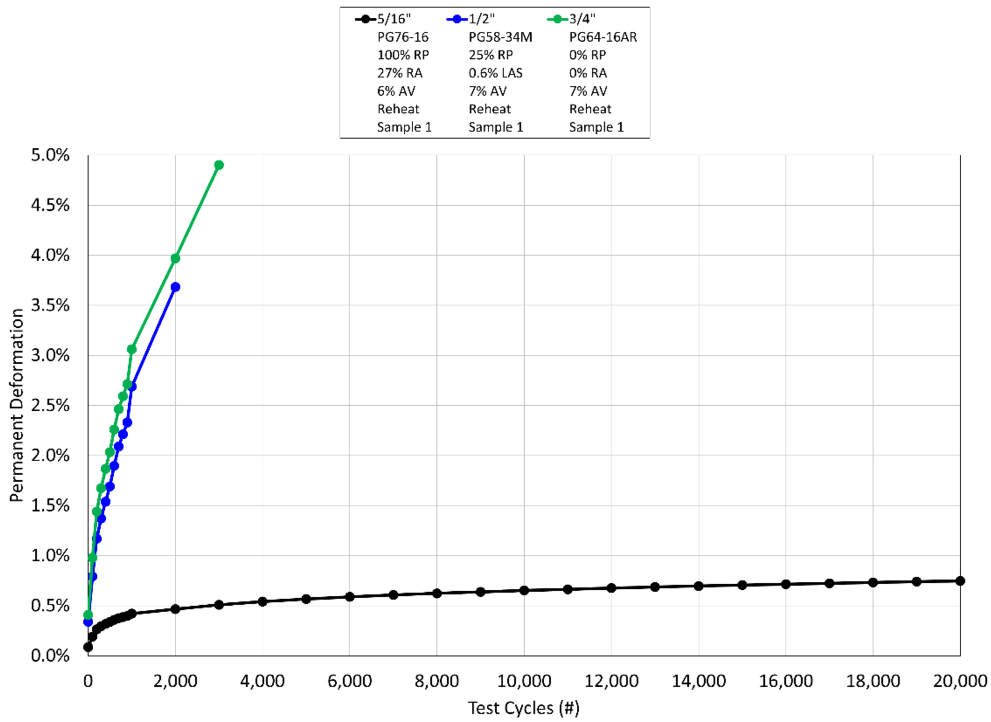


Figure 5.18: Unconfined repeated load triaxial permanent deformation versus load cycles at 45°C for Sample 1 of all three mixes.

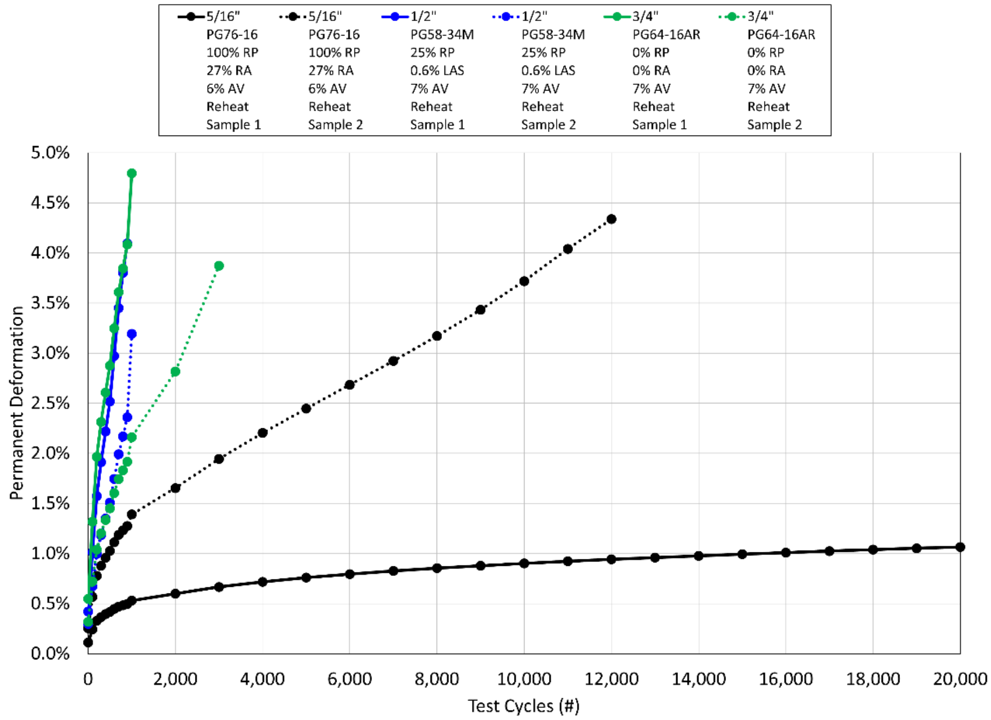


Figure 5.19: Unconfined repeated load triaxial permanent deformation versus load cycles at 50°C for Sample 1 and Sample 2 of all three mixes .

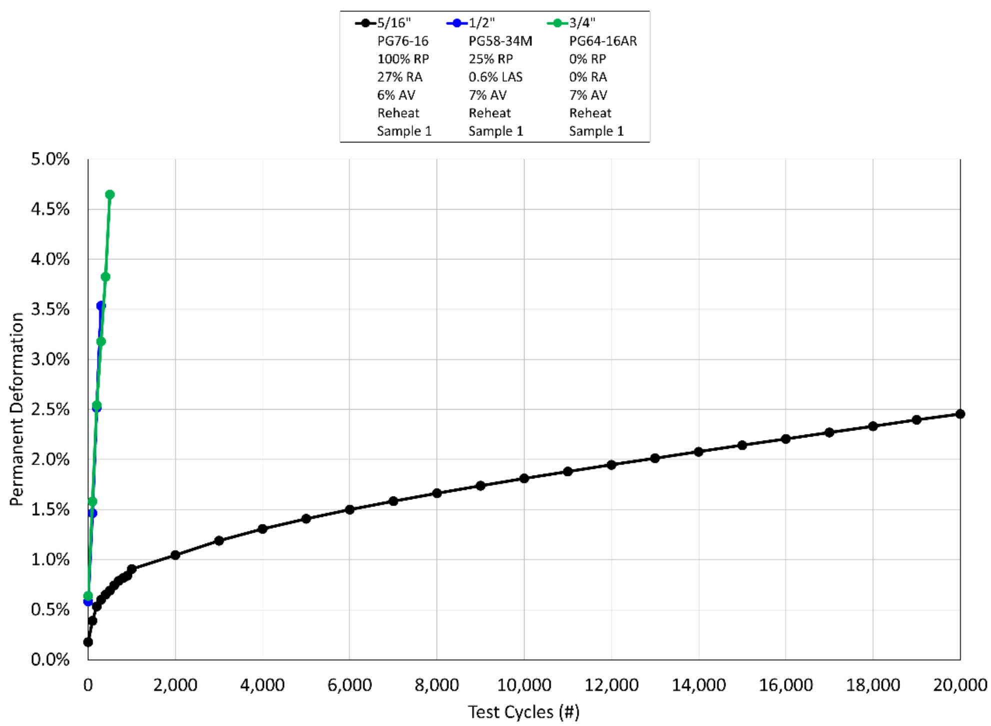


Figure 5.20: Unconfined repeated load triaxial permanent deformation at 20,000 load cycles at 55°C for Sample 1 of all three mixes .

5.5.2 IDEAL-RT Rutting Test

The IDEAL-RT test has been developed to correlate the shear stress at the edges of an indirect tensile test loading platen with pavement rutting performance. The test was performed on specimens made with both the reheated mix and MTOA-conditioned mix.

5.5.2.1 Reheated Mix

Figure 5.21 shows the IDEAL-RT value (RT#) for all specimens of all mixes. The standard is for the specimens to be compacted to 7% air-voids, which is the compaction used for the HMA-M with 25% RAP mix and the RHMA-G mix. The HyRAP mix was compacted to 6% air-voids to match the nSSP. It would be expected that the 1% reduction in air-voids would improve the shear strength and therefore the IDEAL-RT value. However, information was not found in the literature to confirm that expectation.

The Sample 1 results from each mix, the HyRAP mix, which was previously found to be stiffer at least partly due to a high production temperature and a low binder content, had much better results than the other two mixes, while the HMA-M mix had somewhat better results than the RHMA-G mix. These results match those of the confined RLT tests. The variability of the HyRAP mix across the five samples shows that reducing the production temperature for Sample 2 while keeping the same low binder content as Sample 1 resulted in considerably decreased rutting resistance compared with Sample 1 because the reduced production temperature made the binder softer. Increasing the binder content in Sample 3 while keeping the reduced production temperature of Sample 2 resulted in a small further decrease in the IDEAL-RT rutting test results, while the larger increase in binder content found in Sample 4 and Sample 5 resulted in further decreases in the rutting test results. The HMA-M mix also had variable results with Sample 2 having a much higher value than Sample 1. There was a smaller difference between Sample 1 and Sample 2 of the RHMA-G mix. Comparing the HyRAP samples, other than Sample 1, with the other mixes shows that the results of Sample 2, Sample 3, and Sample 5 from the HyRAP mix are similar to the results of the HMA-M mix, while the HyRAP mix Sample 4 results are similar to those of the RHMA-G mix.

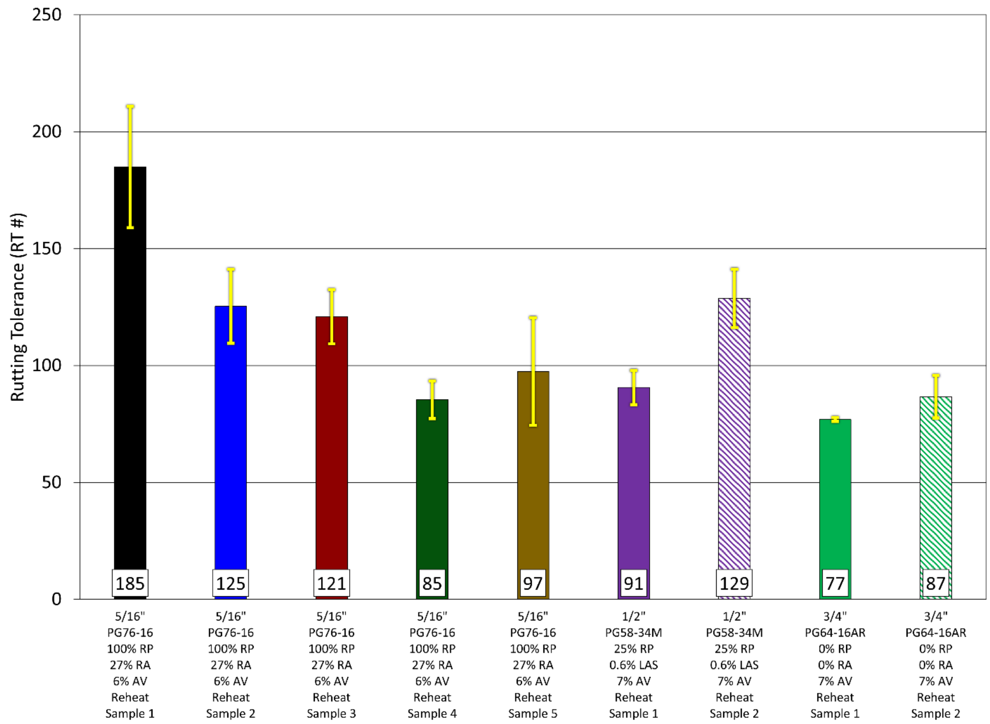


Figure 5.21: IDEAL-RT value (rutting tolerance) for all three mixes and samples.

5.5.2.2 Mix with Medium-Term Oven Aging Conditioning

IDEAL-RT test results on mix that was subjected to MTOA are shown in Figure 5.22 for the HyRAP and HMA-M mixes, and the amount of aging effect is summarized in Table 5.5. The HyRAP mixes showed different effects of the additional aging, with Sample 3 and Sample 5 showing much more aging than Sample 1, Sample 2, and Sample 4. The reasons are unknown, but they are certainly some combination of the factors influencing the mix, including the amounts of each RAP bin, the amount of recycling agent, and the binder contents of each bin. The HMA-M mix also showed considerable variability of response to the MTOA, with Sample 1 showing more effects of the aging than Sample 2. For the HyRAP mix, the effects of MTOA versus reheating for the IDEAL-RT are somewhat similar to the effects of MTOA versus reheating for the IDEAL-CT strength (Table 5.2) and IDEAL-CT values (Table 5.3). For the HMA-M mix, the effects of MTOA versus reheating on Sample 1 and Sample 2 are opposite for the IDEAL-CT strength and index value test results versus the test results for the IDEAL-RT value.

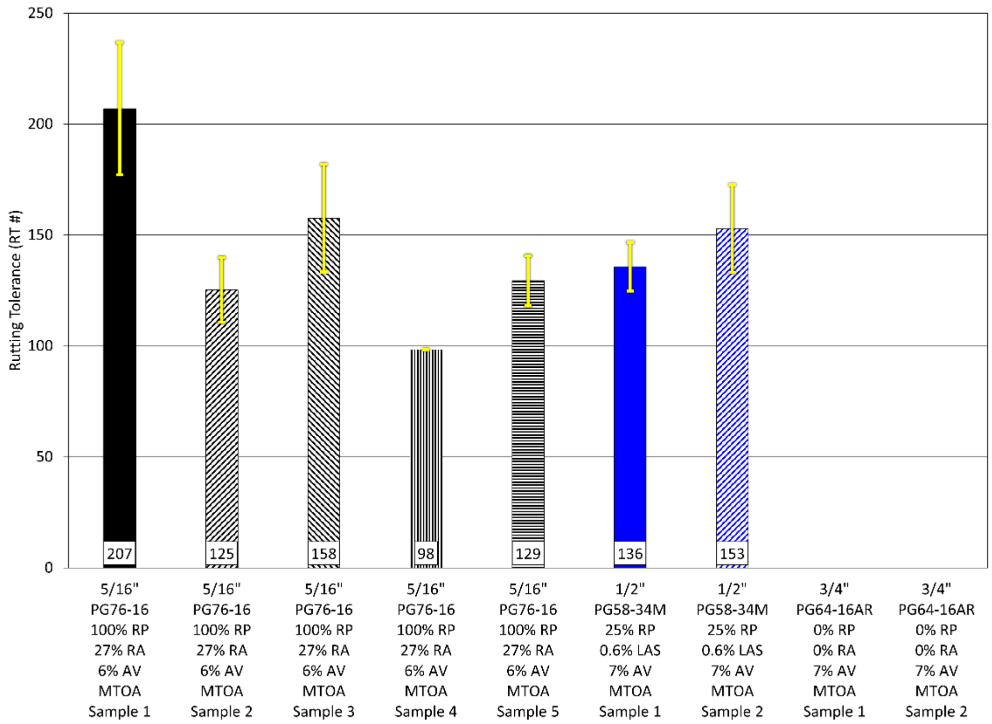


Figure 5.22: IDEAL-RT value (rutting tolerance) after MTOA conditioning for all three mixes and samples.

Table 5.5: Change of IDEAL-RT Value (Rutting Tolerance) Between Reheat and MTOA Conditioning Results

Sublot, Mix Type	Reheat	MTOA	Change (%)
SL1, 3/8" nSSP, R100, 76-16	185	207	11.9
SL2, 3/8" nSSP, R100, 76-16	125	125	0.0
SL3, 3/8" nSSP, R100, 76-16	121	158	30.6
SL4, 3/8" nSSP, R100, 76-16	85	98	15.3
SL5, 3/8" nSSP, R100, 76-16	97	129	33.0
SL1, 1/2" SP Type A R25, 58-38M	91	136	49.5
SL2, 1/2" SP Type A R25, 58-38M	129	153	18.6
SL1, 3" RHMA-G, R0, 64-16AR	—	—	—
SL2, 34" RHMA-G, R0, 64-16AR	—	—	—

5.6 Moisture Sensitivity: IDEAL-CT Indirect Tensile Strength Test After MiST Moisture Conditioning

The MiST conditioning is intended to simulate the effects of water inside the mix creating moisture damage. Only the IDEAL-CT strength test results are presented, for both reheated mix specimens and specimens made after both MTOA and MiST conditioning.

5.6.1 Reheated Mix

IDEAL-CT strength results after MiST conditioning are shown in Figure 5.23. The change in IDEAL-CT strength after MiST conditioning is shown in Table 5.6. The results show same rankings for strength after MiST conditioning seen for the reheated mix without moisture conditioning (Figure 5.10). The HyRAP mixes with lower binder contents (Sample 1 and Sample 2) had slightly less damaging effect on strength compared with the mixes with higher binder contents (Sample 3 and Sample 4), which is opposite of what would be expected. However, the changes in strength from MiST conditioning are small for all mixes and samples; therefore, the differences in the effects of the conditioning are not significant.

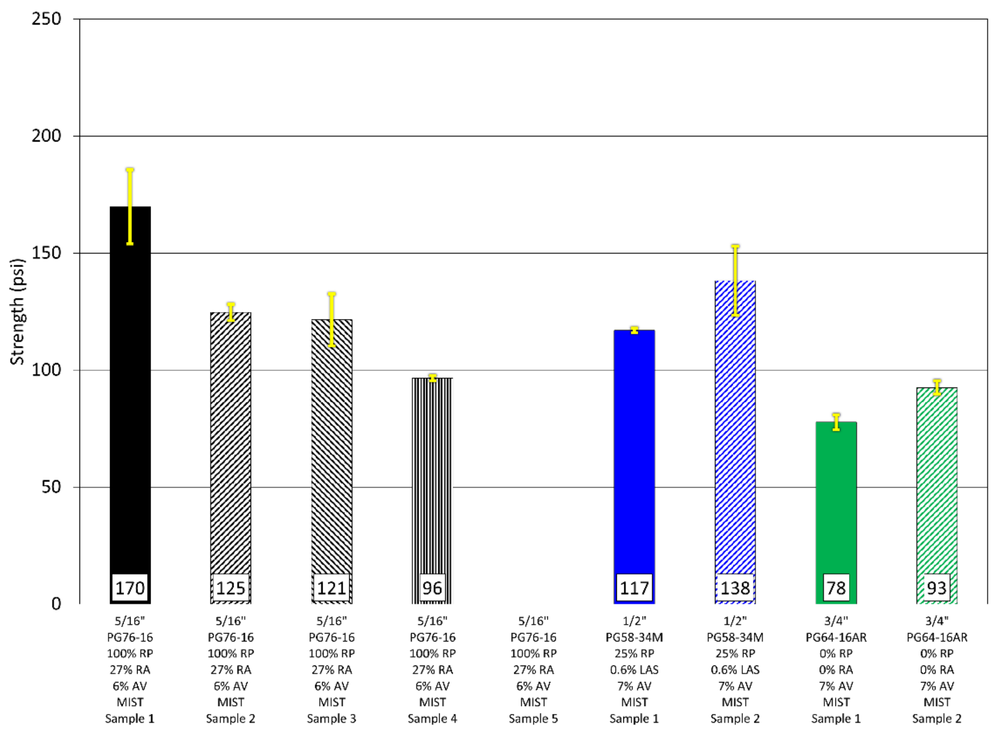


Figure 5.23: IDEAL-CT indirect tensile strength after MiST conditioning for all three mixes, including different samples and compacted air-voids.

Table 5.6: Change of IDEAL-CT Indirect Tensile Strength After MiST Conditioning

Sublot, Mix Type	Reheat	Reheat+MiST	Change from Reheat to Reheat+MiST (%)
SL1, 3/8" nSSP, R100, 76-16	173	170	-1.7
SL2, 3/8" nSSP, R100, 76-16	136	125	-8.1
SL3, 3/8" nSSP, R100, 76-16	136	121	-11.0
SL4, 3/8" nSSP, R100, 76-16	109	96	-11.9
SL5, 3/8" nSSP, R100, 76-16	111	—	—
SL1, 1/2" SP Type A R25, 58-38M (6%)	153	—	—
SL1, 1/2" SP Type A R25, 58-38M (7%)	136	117	-14.0
SL2, 1/2" SP Type A R25, 58-38M	150	138	-8.0
SL1, 3/4" RHMA-G, R0, 64-16AR	84	78	-7.1
SL2, 3/4" RHMA-G, R0, 64-16AR	93	93	0.0

5.6.2 Mix With Medium-Term Oven Aging (MTOA) and MiST Conditioning

IDEAL-CT strength results after MTOA of the loose mix followed by MiST conditioning of the compacted specimens are shown in Figure 5.24, where only HyRAP and HMA-M mixes were tested. The change in IDEAL-CT strength after MTOA and MiST conditioning is shown in Table 5.7. The results show generally the same rankings for strength after MTOA and MiST conditioning seen for the reheated mix without moisture conditioning (Figure 5.10), though the overall range of results across the HyRAP and HMA-M samples is less. The range of the change in strength from MTOA followed by MiST conditioning is small for all mixes and samples, less than 15%, except for Sample 2 of the HMA-M mix where the change was 22.2%. There does not appear to be better performance under the MiST conditioning for the HMA-M and RHMA-G mixes compared with the HyRAP mix samples.

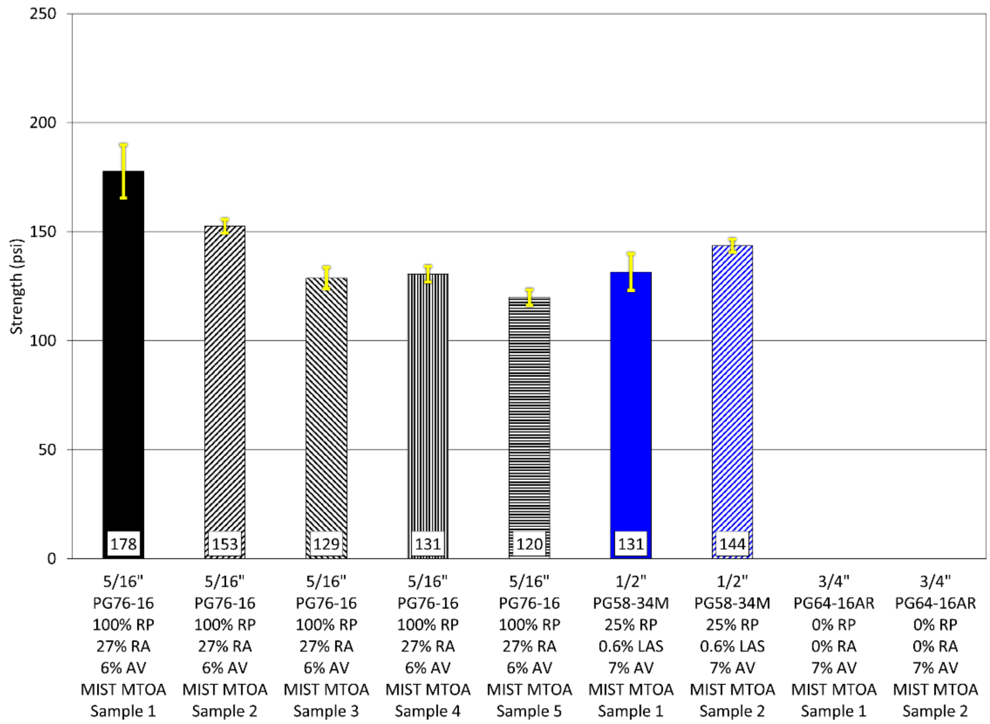


Figure 5.24: IDEAL-CT indirect tensile strength after MTOA and MiST conditioning for all three mixes, including different samples and compacted air-voids.

Table 5.7: Change of IDEAL-CT Indirect Tensile Strength After MTOA and MiST Conditioning

Sublot, Mix Type	MTOA	Reheat+MIST	Change from Reheat to Reheat+MiST (%)
SL1, 3/8" nSSP, R100, 76-16	205	178	-13.2
SL2, 3/8" nSSP, R100, 76-16	156	153	-1.9
SL3, 3/8" nSSP, R100, 76-16	152	129	-15.1
SL4, 3/8" nSSP, R100, 76-16	114	131	14.9
SL5, 3/8" nSSP, R100, 76-16	143	120	-10.4
SL1, 1/2" SP Type A R25, 58-38M (6%)	—	—	—
SL1, 1/2" SP Type A R25, 58-38M (7%)	150	131	-12.7
SL2, 1/2" SP Type A R25, 58-38M	185	144	-22.2
SL1, 3/4" RHMA-G, R0, 64-16AR	—	—	—
SL2, 3/4" RHMA-G, R0, 64-16AR	—	—	—

5.7 Rutting and Moisture Sensitivity: Hamburg Wheel-Track Test

The current test used for evaluating rutting in Caltrans mix design and quality assurance is the HWT test. Because the test is performed underwater, it can also be a test for moisture sensitivity. The relationship between the inflection point in the rut depth and wheel passes is generally considered to be an indicator of moisture sensitivity.

HWT test results plotted as average rut depth over the two HWT test specimens tested at the same time versus wheel passes are shown in Figure 5.25. Figure 5.26, Figure 5.27, and Figure 5.28 show bar charts for the rut depth at 10,000, 15,000 and 20,000 wheel passes, respectively. A 1/2 in. rut at 10,000 and 15,000 wheel passes are the specification limits shown for the HMA-M 25% RAP and RHMA-G mixes, respectively. The Caltrans specification limit for PG 70-10 mixes is 20,000 wheel passes, which was considered the applicable specification for the HyRAP mixes. In the three plots, a mix is not shown if it did not survive the commensurate wheel passes. It should be noted that the HyRAP specimens were all compacted to 3% air-voids, which was in the original version of the nSSP, while the HMA-M and RHMA-G mixes were compacted to the standard 7% air-voids. Lower air-void contents would be expected to produce better results because of the higher shear strength for the mix when better compacted and less water permeability.

The results show that the worst performance was for the HyRAP mix Sample 4, which had the highest binder content, followed by the HyRAP mix Sample 3, Sample 2, and then Sample 1. The HMA-M mix had highly variable performance as well, with Sample 1 showing much worse performance than Sample 2. The RHMA-G mix had consistently good performance.

The ranking of the HyRAP mixes samples among themselves is consistent with the RLT and IDEAL-RT results. However, the HWT test results are very different from the rutting test results from the RLT and the IDEAL-RT tests, which showed that HyRAP mix Sample 2, Sample 3, and Sample 4 had rutting performance in the range of the HMA-M mix samples. The RLT results at 50°C and the IDEAL-RT both showed the HyRAP mix Sample 4, HMA-M mix Sample 1 and RHMA-G mix Sample 1 having the worst rutting performance of all mix samples. In addition to mix rutting susceptibility, the HWT test results may be indicating the potential for moisture sensitivity for the HyRAP mixes because all the samples showed an inflection point after which the rut rate increased. The bar charts in Figure 5.26, Figure 5.27, and Figure 5.28 show the results from the plot in Figure 5.25 and also show the variability between the two HWT test specimens (Wheel 1 and Wheel 2) that are averaged in the plots in Figure 5.25.

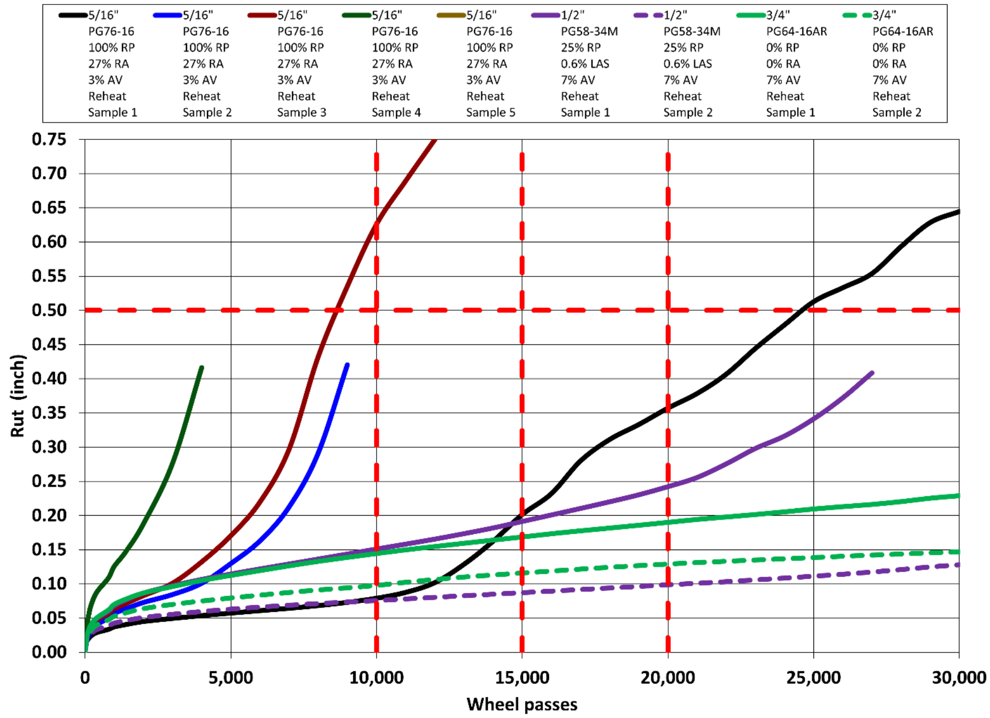


Figure 5.25: Hamburg Wheel-Track test rut depth versus load passes for all samples of all three mixes and different air-void contents.

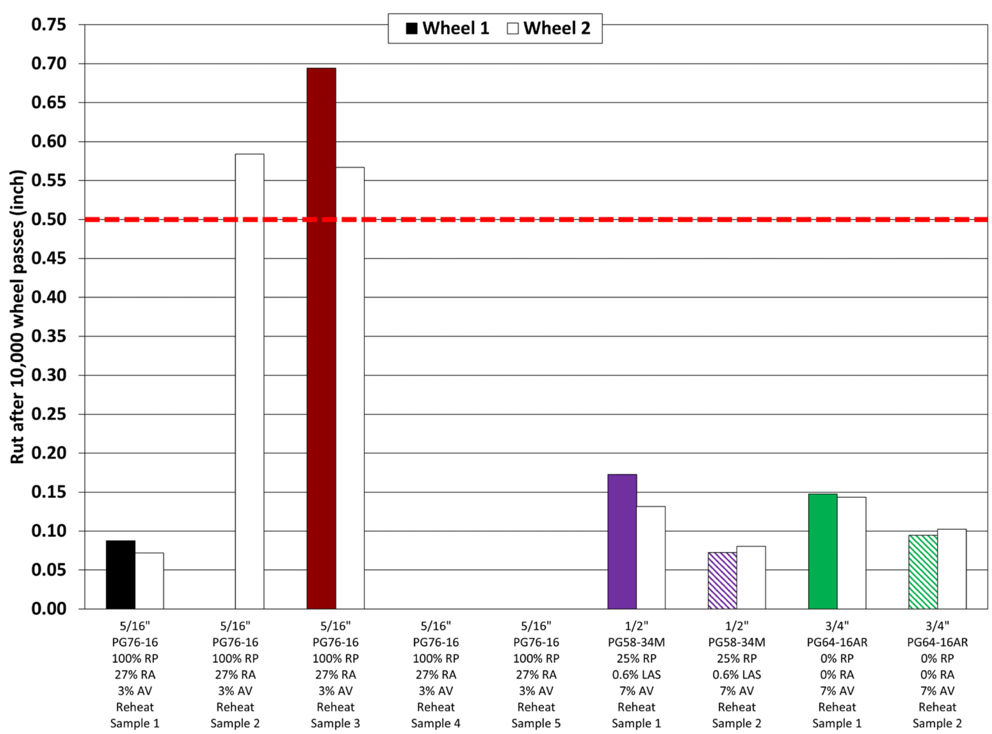


Figure 5.26: Hamburg Wheel-Track test rut depth at 10,000 passes (shown on JMF form 3513 as specification limit for HMA-M) for all three mixes and different air-void contents.

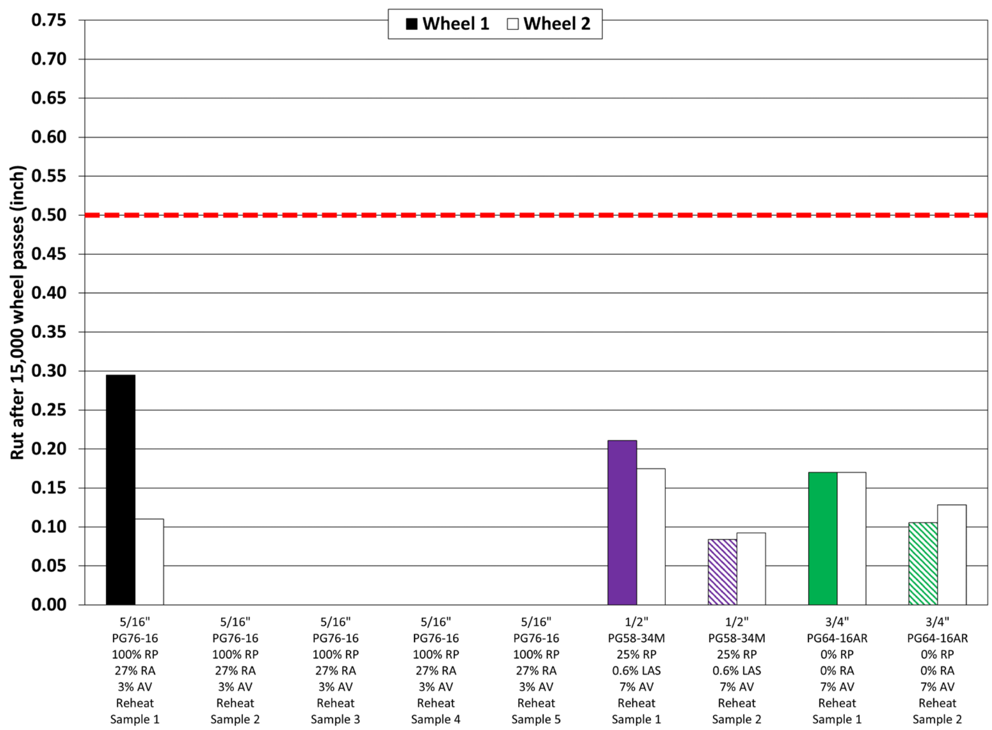


Figure 5.27: Hamburg Wheel-Track test rut depth at 15,000 passes (specification limit for RHMA-G) for all three mixes and different air-void contents.

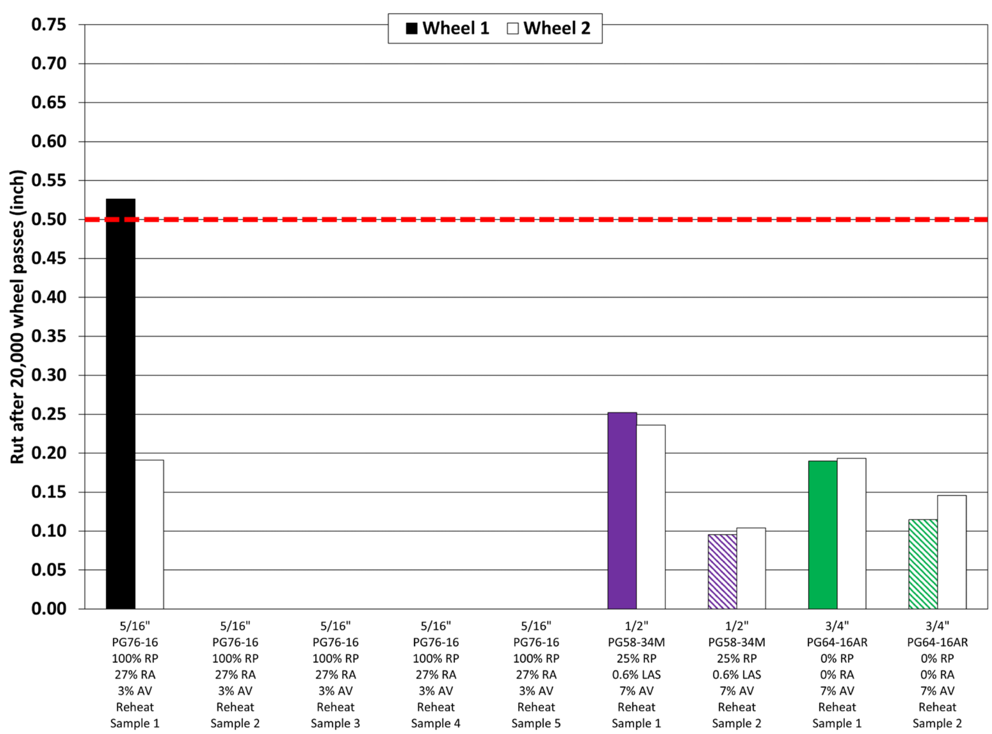


Figure 5.28: Hamburg Wheel-Track test rut depth at 20,000 passes (specification limit for PG 70 mixes, applicable to HyRAP mix) for all three mixes and different air-void contents.

6 DISCUSSION OF LABORATORY RESULTS AND OBSERVED RUTTING PERFORMANCE

Comparison of the confined RLT at 50°C, IDEAL-RT, and HWT laboratory testing results for the HyRAP samples shows a clear correspondence between increasing asphalt content and worse test results. For the UCPRC extracted binder contents shown in Table 5.1, Days 1, 2, and 3 of the HyRAP production (Sample 1, Sample 2, and Sample 3) had lower binder contents and were placed in Lane 1, which did not have heavy truck traffic. Sample 1 was removed and replaced with the Sample 2 mix because it had also been heated to a high temperature at the mixing plant in anticipation of cooling because of the long haul distance from Days 4 and 5, which resulted in significant stiffening. Days 4 and 5 of the HyRAP production (Sample 4 and Sample 5) had high binder contents and were placed in Lane 2. Lane 2 carries most of the heavy trucks while Lane 1 carries very few heavy trucks. Months after construction, during hot July weather, the high truck traffic and high pavement temperatures (the project site is in the hottest climate region in the state [Desert]) led to rutting in Lane 2 to an extent that required removal and replacement, shown in Figure 6.1.

The performance-related laboratory rutting test results generally identified the potential for rutting problems with the Day 4 (Sample 4) mix. However, the RLT (Figure 5.16) and IDEAL-RT (Figure 5.21) results for Sample 1 of both the RHMA-G mix and the HMA-M digout patching mix showed results that were only slightly better than the Day 4 HyRAP mix. The RHMA-G mix in Lane 2 had not rutted to an extent that it had had to be removed and replaced after the same trafficking and weather that resulted in rutting of the Days 4 and 5 HyRAP construction in Lane 2. Only the HWT test results (Figure 5.25) showed a clear distinction between the Day 4 HyRAP mix that rutted and the RHMA-G mix that did not rut. The HWT test results showed that the Day 3 HyRAP mix was also more vulnerable to rutting than the RHMA-G mix. However, it was placed in Lane 1 and not subjected to the heavy truck traffic.

Figure 6.1: Rutting in July 2024 in Lane 2 of HyRAP test section.

The tradeoff in the performance for the HyRAP mix between different days of production was that the higher binder contents on Days 4 and 5 showed better age-related cracking results in terms of lower IDEAL-CT strength (correlated with stiffness and, therefore, lower stiffness) both before and after MTOA (Figure 5.10 and Figure 5.12) and higher IDEAL-CT index values (Figure 5.13 and Figure 5.14). The Day 4 production also showed better fatigue resistance than the Day 1 mix and that fatigue performance was similar to that of the HMA-M mix (Figure 5.8), although still not as good as the RHMA-G mix.

It should be noted that in all of the laboratory testing results, the HyRAP mixes were compacted to 6% air-voids instead of the 7% air-voids for the other mixes routinely used in UCPRC testing for the tests included in this report (unless a higher level of compaction is required in the construction specifications). That greater compaction level was agreed upon by the Office of Asphalt Pavement and Manhole Adjusting Inc. to reflect the generally excellent compaction of the HyRAP mixes, which was observed on the I-40 test sections. The better compaction will generally improve both rutting and cracking resistance test results, except for the IDEAL-CT index value.

7 DEFLECTION TESTING AND STRUCTURAL CAPACITY ANALYSIS

Deflection testing with a falling weight deflectometer (FWD) was performed by the Caltrans South Region Laboratory on May 2, 2024. The results were sent to the UCPRC where they were plotted and analyzed. The deflections for the sixth sensor, which is the farthest from the FWD load, are shown in Figure 7.1 for the RHMA-G overlaid section between Postmiles 25 and 26 that was tested with the FWD and the HyRAP sections between Postmiles 26 and 28. The sixth sensor provides an indication of the stiffness of the subgrade. The results show that the subgrade stiffnesses are very similar between the two overlay types. The deflections range from similar to slightly higher in Lane 2 than in Lane 1, indicating that the subgrade stiffness is somewhat lower under Lane 2 than under Lane 1 in both the RHMA-G and HyRAP sections.

The deflections for the first sensor are shown in Figure 7.2. The first sensor is under the FWD load and provides an indication of the stiffness of the pavement structure combined with the subgrade, and it is therefore an indicator of structural capacity. The results show that the first sensor deflections are generally somewhat higher under the RHMA-G section than under the HyRAP section, indicating that it is somewhat less stiff, although the distributions are very similar.

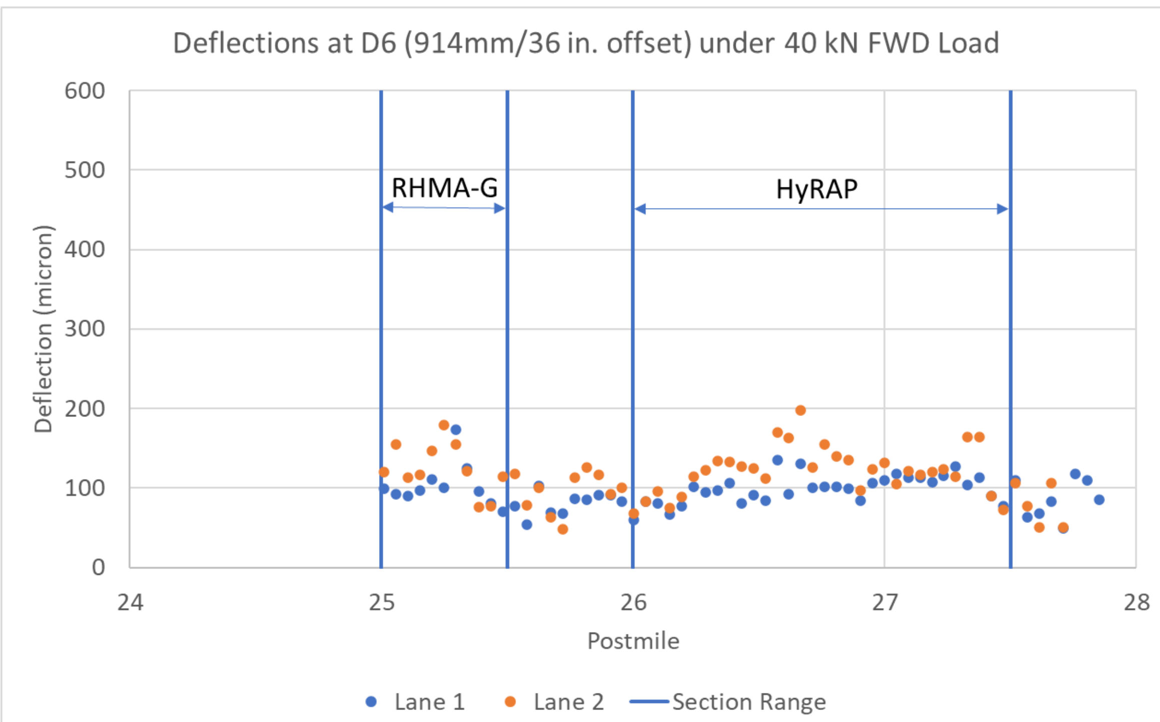


Figure 7.1: Falling weight deflectometer sensor 6 (at 914 mm from load) deflections measuring subgrade stiffness versus postmile with RHMA-G and HyRAP overlays locations marked.

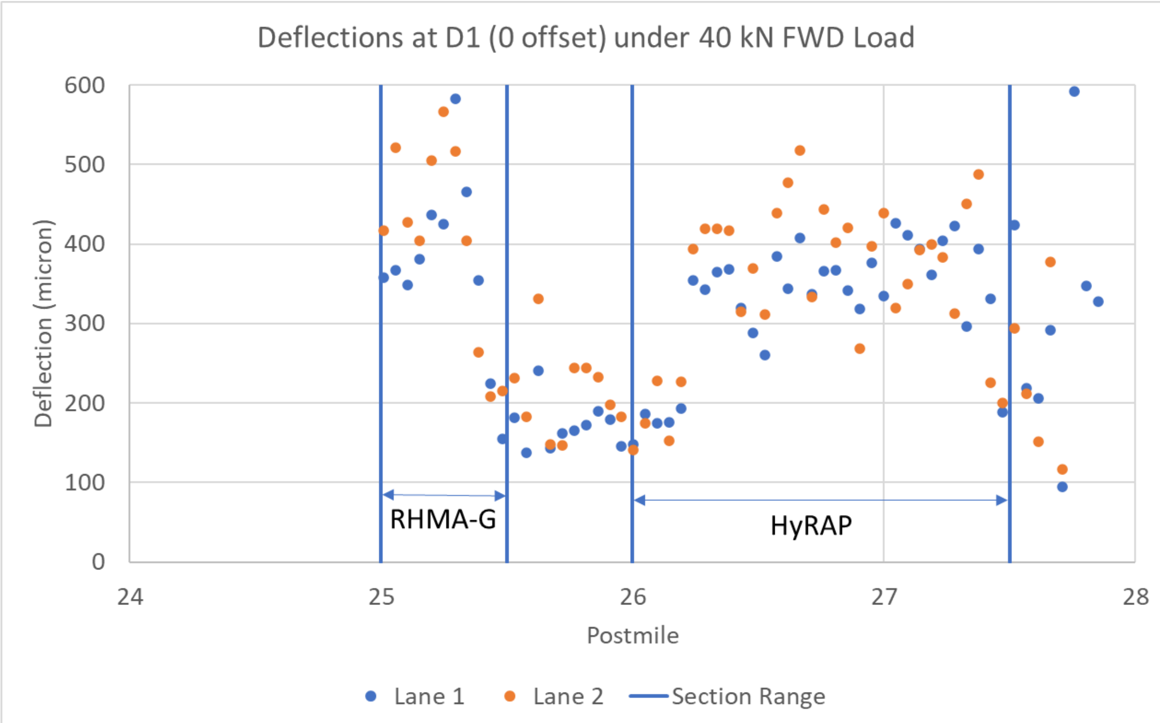


Figure 7.2: Falling weight deflectometer sensor 1 (under load) deflections measuring entire pavement structure stiffness versus postmile with RHMA-G and HyRAP overlays locations marked.

8 LIFE CYCLE ASSESSMENT RESULTS

8.1 Goal and Scope of the Life Cycle Assessment Study

The goal of this life cycle assessment (LCA) study is to quantify the life cycle environmental impacts of the HyRAP mix and compare them with the other mixes used in the I-40 project as well as several other mixes in the UCPRC library. The declared unit of this study is 1 kg of hot mix asphalt (HMA). A cradle-to-gate analysis was performed, which in ISO 21930 terms means it includes the extraction of raw materials (A1), their transport to the manufacturing/production plant (A2), and product manufacturing (A3). Additionally, a sensitivity analysis was also performed by using the different HMA plant natural gas consumption numbers. Lastly, comparison of the global warming impact (GWI) from the unit mass of HyRAP with other HMA mixes was performed. The impacts calculated using the US Environmental Protection Agency's (US EPA) *Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts* (*TRACI*) *(14)* and the primary energy demand that is not part of the TRACI impacts were quantified for the HyRAP. For the purposes of sensitivity analysis and comparing to other mixes purposes, only GWI is discussed.

8.2 Life Cycle Inventory Assumptions, Data, and Sources

In this study, the HyRAP job mix formula (JMF) and plant energy data were provided by Manhole Adjusting Inc., shown in Table 8.1. The electricity consumption to produce 3,209 metric tons of HyRAP was 673 kWh. The natural gas was used for two purposes in the plant: drying and heating RAP in the drum mixer and in the thermal oxidizer. The thermal oxidizer is a combustion system that breaks down hazardous air pollutants, volatile organic compounds (VOC), and odorous emissions at an asphalt plant to control air pollution. VOC emissions that escape into the air at the plant and cause air pollution were not included in modeling because no data were available. The oxidizer technology is not widely used in HMA production and requires combustion fuel. Thus, it was decided to evaluate the HyRAP mix with and without using the oxidizer natural gas fuel consumption data. Additionally, a reduction of 70% natural gas usage for the thermal oxidizer was proposed by Manhole Adjusting Inc. as being possible in the future based on the use of a heat exchanger from the drum to help heat the thermal oxidizer. No virgin binder, crumb rubber, extender oil, diesel fuel, or other materials/fuels were used to produce the HyRAP mixes at the plant.

It should be noted that the energy numbers previously discussed are for five days of HyRAP production. Furthermore, it should be clarified that the quantification of impacts in this study are indirect emissions, which includes emissions from the production and combustion of fuels to run the unit processes in the life cycle of material production. The direct emissions at an asphalt plant from the materials are not included in the analysis.

Table 8.1: HyRAP Mix Design and HMA Plant Energy Data for 1 kg of HyRAP Mix

Energy and Materials (at Plant)	HyRAP with Oxidizer (1kg)	HyRAP without Oxidizer (1kg)	HyRAP with Oxidizer (natural gas adjusted for heat exchanger) (1kg)
RAP, slurry sand, fractionated (%)	58.95	58.95	58.95
RAP, 3/8 in., fractionated (%)	39.32	39.32	39.32
Epolene: oxidized polyethylene (%)	0.2	0.2	0.2
Viplex 50: paraffinic solvent (%)	1.5	1.5	1.5
CA: 2023 electricity (MJ)	7.5E-04	7.5E-04	7.5E-04
Natural gas combusted in industrial equipment[1] (m^3)	2.0E-02	8.1E-03	1.1E-02

[1] 1 therm = 100 ft^3 = 2.83 m^3

The 3/8 in. and slurry sand RAP inventories were obtained from *eLCAP* fractionated RAP data. It was assumed that RAP was at the asphalt plant located in Colton, California, and transport of the RAP to the plant was not included because that transport was considered to be part of other projects. Thus, no transportation impacts are associated with this material. However, electricity energy of 2.2E-04 MJ and 3.6E-07 hours of front loader operations were needed for handling and moving 1 kg of RAP to the conveyor belt and the fractionation process at the plant *(15)*. The Caltrans *eLCAP* tool (version 1.0) was used to determine the life cycle materials and construction GWIs for each activity *(16)*. Models and GWIs for asphalt binder, hydrated lime, styrene-butadiene-styrene (SBS) polymer, crumb rubber, extender oil, rail transport, truck transport, natural gas combustion, and diesel combustion are reviewed in a previous UCPRC technical memorandum *(15)*.

Epolene is an oxidized polyethylene used as a polymer modifier in the HyRAP mix, and Viplex 50 is a paraffinic solvent used as a recycling agent/additive. This information about the additives was extracted from their relevant material safety datasheets. No EPDs exist for these materials currently. Therefore, life cycle impact assessment data for these materials were acquired from Sphera's *LCA for Experts* software, a commercial database. It was assumed epolene was produced using the same process and materials as low-density granulate polyethylene and Viplex 50 had the same inventory as petroleum paraffin wax. The inventory data for these materials cannot be shared in this report due to proprietary data terms from Sphera.

The production and transportation impacts for these additives were included in the analysis. Epolene is imported from Houston, Texas, a distance of 1,497 miles, and Viplex 50 is imported from Oklahoma City, Oklahoma, a distance of 1,279 miles. Both additives are transported by rail. It was assumed that the rail transports other commodities when returning to the origin locations where the additives were acquired. Therefore, only one-way rail impacts were allocated to the additives. It was assumed that truck transport of 31 miles is needed on each end at the rail station to transport additives from the manufacturing facility to the rail station and then from the rail station to the asphalt plant.

The diesel fuel powered rail and truck transport impacts were acquired from the US LCI database available in the Federal LCA Commons Repositories.[3] The California electricity mix was modeled in *eLCAP* using the 2023 grid mix data acquired from the US Energy Information Administration, shown in Table 8.2, and grid losses of 5%.

Table 8.2: Electricity Grid Mix for California in 2023

Sources	Quantity of Total (%)
Biogas	0.567
Biomass	1.996
Geothermal	4.485
Hard Coal	0.086
Heavy Fuel Oil	0.031
Hydro-Power	12.757
Natural Gas	38.579
Nuclear	7.249
Photovoltaics and Solar Thermal	28.155
Wind	6.095

Source: US Energy Information Administration, n.d. *(17)*.

8.3 HyRAP Life Cycle Assessment Results

The cradle-to-gate impacts for 1 kg of HyRAP are shown in Table 8.3. The differences in the impacts shown for HyRAP are mainly due to the natural gas usage for the three scenarios of HyRAP production assumed and previously described. The results indicate that even though the oxidizer is being used for avoiding air pollutant emissions in the plant, there are additional natural gas combustion impacts that are associated with the process. If the CO_2 emissions could be avoided or some other cleaner fuel could be used in the oxidizer process, the total emissions could be reduced. A heat exchanger process can also significantly reduce the total impacts, which was modeled to produce approximately a 33% reduction in global warming impact, 48% reduction of particulate matter, and 19% reduction in total energy (renewable and nonrenewable energy).

[3] Federal LCA Commons: https://www.lcacommons.gov/.

Table 8.3: Cradle-to-Gate Impacts of 1 kg of HyRAP Mix

Selected Impact Categories and Inventories	Unit	HyRAP with Oxidizer (1kg)	HyRAP without Oxidizer (1kg)	HyRAP with Oxidizer (natural gas adjusted for heat exchanger) (1 kg)
Acidification	kg $SO_{2\text{-eq}}$	4.51E-04	2.14E-04	2.45E-04
Ecotoxicity	$CTU_{\text{-eq}}$	6.83E-02	3.28E-02	3.70E-02
Eutrophication	kg $N_{\text{-eq}}$	7.63E-06	5.31E-06	5.67E-06
Global warming air, excluding biogenic carbon	kg $CO_{2\text{-eq}}$	7.04E-02	4.28E-02	4.69E-02
Human health particulate air	kg $PM_{2.5\text{-eq}}$	2.71E-05	1.23E-05	1.40E-05
Human toxicity, cancer	CTU_h	3.39E-11	2.75E-11	2.85E-11
Human toxicity, non-cancer	CTU_h	4.59E-09	3.14E-09	3.33E-09
Ozone depletion	kg CFC $_{11\text{-eq}}$	7.03E-14	5.40E-14	5.88E-14
Smog air	kg $O_{3\text{-eq}}$	2.20E-03	1.59E-03	1.69E-03
Primary energy demand from renewable and nonrenewable resources (net calorific value)	MJ	1.76E+00	1.32E+00	1.42E+00
Primary energy from nonrenewable resources (net calorific value)	MJ	1.75E+00	1.31E+00	1.38E+00
Primary energy from renewable resources (net calorific value)	MJ	1.63E-02	1.63E-02	4.62E-02

8.4 HyRAP Global Warming Impact Compared with Other Hot Mix Asphalt Mixes

8.4.1 Mixes Compared with HyRAP

It was assumed for the purposes of this LCA study that the performance of all the mixes was the same and, therefore, the A1 to A3 GWI can be compared without considering the complete life cycle effects of different performances. GWIs for different HMA mix types (mix designs and other information shown in Table 8.4) were identified to compare with the GWI for HyRAP shown in Table 8.3. The list includes the following:

- The other two mixes being used on the I-40 project were also modeled in *eLCAP*: the I-40 Type A HMA-M mix and the I-40 RHMA-G mix. Ingevity's Evotherm[4] M1 environmental product declaration (EPD) liquid anti-strip data were included in the analysis for the I-40 HMA-M mix design. Lime was included in the I-40 RHMA-G mix design. These are shown in Table 8.4.
- Four library mixes from *eLCAP* are also shown in Table 8.4.: HMA without RAP (HMA w/o RAP), gap-graded rubberized HMA (RHMA-G) without RAP, polymer-modified (styrene-butadiene-styrene) asphalt without RAP (HMA-M), and HMA with 15% RAP (HMA-15% RAP).

[4] Evotherm: https://www.ingevity.com/featured-products/evotherm/.

- GWIs for two mixes were acquired from EPDs for California mixes from the National Asphalt Pavement Association website: Type A HMA with 30% RAP (Type A HMA-30% RAP) (NAPA 2021)[5] and RHMA with 15% RAP (RHMA-15% RAP) (EPD 2024).[6]
- Transportation of virgin aggregates can be very energy and emission intensive. Five HMA mixes were modeled in *eLCAP* where 95.5% of an HMA mix was aggregates (4.5% virgin binder and no RAP) and that were transported from a quarry site 0, 50, 100, 200 and 500 miles away. It was assumed that the trucks were fully loaded when leaving the quarry and returning empty.
- The natural gas combustion data for HyRAP mixes, shown Table 8.3, and for RHMA production from *eLCAP*, shown in Table 8.4, are higher than those for the HMA mixes, shown in Table 8.4, because RHMA and HyRAP mixes are mixed at higher temperatures than HMA.

The resulting GWI comparison is shown in Figure 8.1. The figure includes comparison of the HyRAP mix without the oxidizer using natural gas consumption data taken during production and using *eLCAP* estimated consumption.

8.4.2 Comparison of Results

Figure 8.1 shows a sensitivity analysis comparing the HyRAP with the use of the oxidizer, HyRAP without the oxidizer, and HyRAP with the oxidizer but with the heat exchanger, using *eLCAP* plant fuel data. These three versions of the HyRAP mix production were found to have the lowest GWIs among all the HMA mix types. On the other hand, production of the HyRAP mix with the oxidizer and without the heat exchanger had GWIs that were almost as high as a typical RHMA-G and HMA-M used in the I-40 project. The main reason the HyRAP GWIs without the oxidizer are lower than most other mixes is due to the absence of virgin aggregate transport, as the two RAP stockpiles are available at the plant, and no virgin binder usage. In typical LCA emissions, accounting for emissions from a material that is already available is counted as part of the previous project that produced it. The major impacts for the HyRAP primarily came from natural gas usage and the two additives that were used (Viplex 50 and Epolene).

Use of recycled materials such as RAP also helps in GWI reduction in all mixes with RAP (HMA-15% RAP, and I-40 Type A HMA-M, which has 25% RAP). Chemical additives that are sometimes added to RAP mixes, such as recycling agents, or additives that can be used in all mixes, such as warm mix additives, liquid anti-strip additives, and lime treatment, come with their own life cycle GWI impacts. EPDs or other LCA information for most additives are not available. Additive manufacturers should publish EPDs for the chemical additives so that real benefits of modified asphalt mixtures can be determined. EPDs are expected to be required in future asphalt mixture product category rules.

The polymer-modified HMAs had increased GWI impacts because of the high polymer modifier production impacts. The I-40 RHMA-G mix showed the highest GWI of all the mixes other than those with long hauling distances for virgin aggregate, mainly due to use of hydrated lime, which has almost twice the production GWI (0.937 kg CO_{2e} per kg) of asphalt binder production (0.475 kgCO_{2e} per kg) *(15)*.

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[5] Environmental Product Declaration (EPD): https://asphaltepd.org/epd/d/mYUPap/.
[6] Environmental Product Declaration (EPD): https://asphaltepd.org/epd/d/o8UkBl/.

Table 8.4: Different HMA Mix Types and Plant Fuel Consumption to Produce 1 kg of HMA Mix

Energy and Materials (at Plant)	HMA w/o RAP (eLCAP)	RHMA-G (eLCAP)	HMA-M (eLCAP)	HMA-15% RAP (eLCAP)	I-40 Type A HMA-M	I-40 RHMA-G	HMA-30% RAP (NAPA 2021)	RHMA-15% RAP (EPD 2024)
Crushed aggregate (%)	95.5	92.5	95.5	80.33	71.92	91.58	67.5	81
Unmodified virgin asphalt binder (%)	4.5	5.81	4.21	4	3.97	5.85	3.5	>3.5
Crumb rubber (%)	0	1.5	0	0	0	1.5	0	0.5
Extender oil (%)	0	0.19	0	0	0	0.15	0	<1
Hydrated lime (%)	0	0	0	0	0	0.92	0	<1
Polymer modifier (%)	0	0	0.29	0	0.12	0	0	0
RAP, fractionated (%)	0	0	0	15.67	23.96	0	29	14
Evotherm M1 (%)	0	0	0	0	0.03	0	0	0
CA: 2023 electricity (MJ)	1.30E-02	1.30E-02	1.30E-02	1.30E-02	1.30E-02	1.30E-02	1.10E-02	N/A
Natural gas combusted in industrial equipment (m^3)	8.80E-03	9.40E-03	8.80E-03	8.80E-03	8.80E-03	9.40E-03	8.30E-03	N/A
Diesel combusted in industrial equipment (m^3)	0	0	0	0	0	0	1.80E-07	N/A

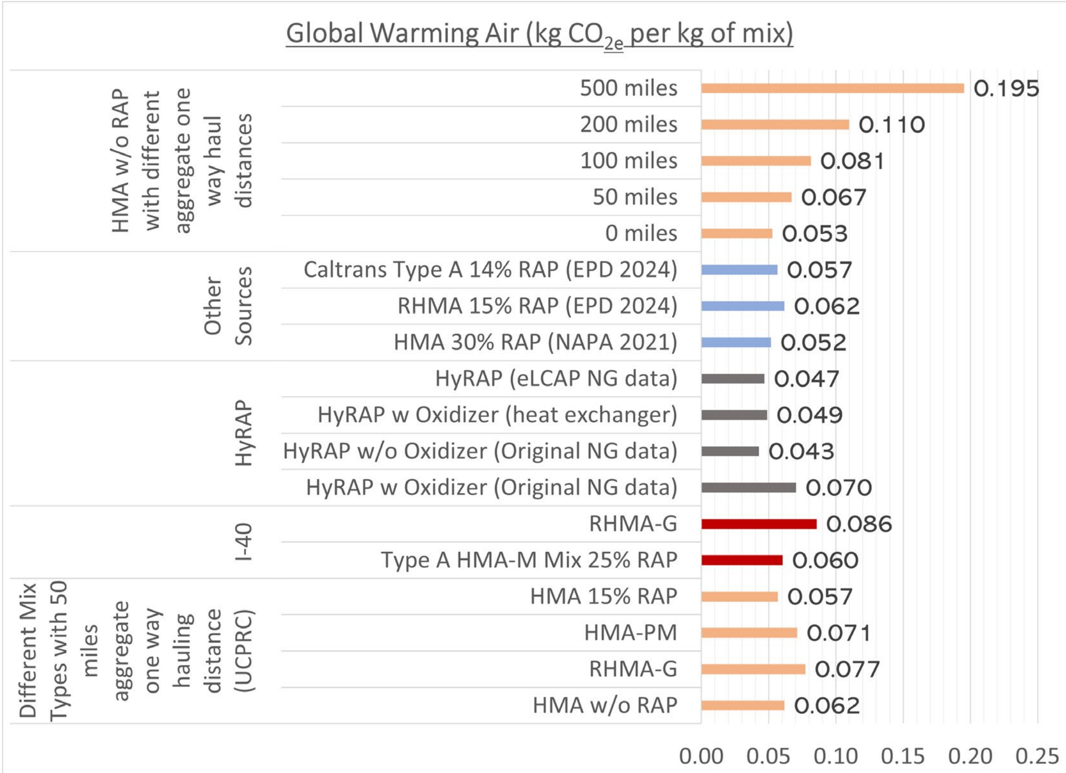

Figure 8.1: Global warming impact in kg CO_{2e} per kg of different HMA mixes.

Figure 8.1 indicates that aggregate or RAP transport by truck results in higher GWIs, confirming that transporting materials long distances should be avoided where possible. The HMA without RAP from *eLCAP* with an assumed hauling distance of 40 miles (bottom of Figure 8.1) and the HMA without RAP and 50 miles of hauling distance (in the group at the top of the figure) had almost the same GWI. Increasing the truck hauling distance for the aggregate to 100 miles increases the GWI by 21%.

Figure 8.1 also indicates that if the HyRAP mix performance is similar to that of other mixes shown in the figure, then HyRAP with the oxidizer and heat exchanger or HyRAP without the oxidizer could be favorable materials to use in areas where aggregate transportation is required for virgin materials, based on the GWIs. The results in the figure indicate approximately a 10% to 20% reduction in GWI for HyRAP for those two options compared with HMA with 15% RAP and a 40-mile aggregate hauling distance. However, if the oxidizer is used without the heat exchanger, then there is about a 25% increase in GWI for the HyRAP compared to that HMA with 15% RAP mix. Considering that virgin aggregate resources are dwindling in much of Southern California while there are large supplies of RAP at the quarries, the HyRAP mix, if it can be run without the oxidizer or with the heat exchanger operating on the oxidizer, becomes more attractive from the GWI perspective.

To determine the benefits or disbenefits of the use of HyRAP mixes, it is essential to determine their performance through laboratory testing and in the field through pilot projects. It is also recommended that full pavement life cycle LCA considering performance be conducted once a better picture of the complete environmental benefits or disbenefits of the use of HyRAP is determined.

9 SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

9.1 Summary of the Study

This report presents the results of a large sampling, testing and analysis project regarding an asphalt mix type containing 100% RAP and no virgin asphalt binder or aggregate, known as HyRAP®. A version of the HyRAP mix was used in a thin overlay as part of an emergency repair on a Caltrans freeway connector in San Diego County in June 2022. That mix was sampled by G3 Quality and subjected to performance-related tests for fatigue resistance, flexural and axial dynamic stiffness, age-related cracking resistance, and permanent deformation resistance as well as permanent deformation resistance combined with moisture damage resistance. The results of that testing were reported to G3 Quality in an informal technical memorandum, which is included as Appendix A in this research report.

In September 2023, HyRAP was used in short test sections on a pilot project on I-40 in the Mojave Desert in San Bernardino County. The HyRAP mix was sampled by the UCPRC on five days over two weeks along with two other mixes that were used on the project. The mixes were sampled at the production plants and brought to the UCPRC laboratories in Davis and Richmond for testing. The HyRAP mix was subjected to a range of mix tests used on the 2022 samples as well as extracted binder tests, and the results were compared with those of the gap-graded rubberized hot mix asphalt (RHMA-G) with no RAP used as a thin overlay in most of the I-40 project and a polymer-modified hot mix asphalt (HMA-M) with 25% RAP used in the digouts on the I-40 project but representative of HMA-M mixes being used by Caltrans. Some comparisons of fatigue performance and stiffness were also made with the statewide median PG 64 and PG 70 mixes.

Cursory observations were made at the construction location on I-40 when the UCPRC sampling crew visited the site. The Caltrans Office of Asphalt Pavement did a more comprehensive construction observation during a site visit, the results of which are included as Appendix B in this research report. Regarding the production of the 5/16 in. HyRAP 100% RAP mix, the UCPRC observations at the Manhole Adjusting Inc. plant in Colton, California, were as follows:

- During the first week of production, during which UCPRC was on-site (Sample 1 collected on September 20, 2023, and Sample 2 collected on September 21, 2023), relatively low binder contents were produced.
- Sample 1 was produced at a very high temperature.
- Sample 2 was produced at a lower temperature.
- During the second week of production, during which UCPRC was on-site (Sample 3 collected on September 23, 2023, Sample 4 collected on September 26, 2023, and Sample 5 collected on September 27, 2023), the binder contents were increased and production continued at lower temperatures than were used for Sample 1.

Regarding the production of the 1/2in. HMA PG 64-28M with 25% RAP mix used in the digouts, the observations at the Sully-Miller plant in Victorville, California, were as follows:

- Sample 1 collected on December 3, 2023, had less than two hours of silo time.
- Sample 2 collected on December 4, 2023, had about 12 hours of silo time (it was produced at 5 am and sampled at about 4 pm).

Regarding the production of the 3/4 in. RHMA-G mix used as the overlay on most of the project, the observations at the Sully-Miller plant in Victorville, California, were as follows:

- Sample 1 collected on April 4, 2024, had less than two hours of silo time.
- Sample 2 also collected on April 4, 2024, had about four hours of silo time

Deflection tests were performed by the Caltrans South Regional Laboratory and analyzed by the UCPRC to determine whether the locations where the RHMA-G and HyRAP mixes were placed had similar subgrade stiffness and similar overall pavement structural capacity. An environmental LCA was performed for the ISO 21930 A1 to A3 life cycle stages (material extraction, material transportation in the supply chain, and material production), also known as "cradle to gate." The LCA primarily focused on global warming impact (GWI).

Comparisons were made between the performance-related laboratory rutting test results and the observed field rutting performance between construction in September 2023 and July 2024 when the Lane 2 HyRAP mixes were removed because of rutting. The Lane 2 mixes removed were Sample 4 and Sample 5, which had the highest binder contents and did not have high mixing temperatures.

A set of questions was developed as part of the problem statement for the study. They are answered in the following discussion, along with summary conclusions.

9.2 Conclusions

9.2.1 Research Question Answers

The conclusions, presented below, have been grouped around the main questions that this research intended to answer.

1. **What are the results of performance-related testing of the extracted binder from the HyRAP mix sampled on I-40 project compared with the extracted binder from the HMA-M mix and the plant produced rubberized binder for the RHMA-G mix prior to mixing?**
    a. What are the performance grade (PG) high, intermediate, and low temperatures of the extracted binders?
        - HyRAP mix: Sample 1, which had a high production temperature and low binder content, meets PG 70-10 virgin binder specifications. Sample 4, which had a lower production temperature and high binder content, meets PG 64-28 virgin binder specifications.

- HyRAP RAP sources: The 3/8 in. RAP stockpile had a high-temperature true grade of 97°C and intermediate-temperature true grade of 42°C. The slurry sand RAP stockpile was much more aged with a high-temperature true grade of 108°C and intermediate-temperature true grade of 54°C.
- HMA-M with 25% RAP: Overall, Sample 1 and Sample 2 both meet PG 64-28M virgin polymer-modified binder specifications.
- RHMA-G: Overall, Sample 1 meets both PG 70-10 and PG 64-28 virgin binder specifications.
- It must also be noted that this evaluation is based on extracted binders for the HyRAP and HMA-M mixes, which introduces some additional variability compared with evaluation of virgin binders taken from the refinery without the varying effects of mixing temperatures, silo times, transport distances, and extraction and recovery. However, the results indicate that construction variability of the binder properties in the HyRAP mix is subject to larger ranges of variability within the sources of variability than conventional mixes and that efforts should be made to reduce those.
- Extended silo storage time for Sample 1 of the HMA-M mix also introduced high variability of the binder true grade temperatures compared with Sample 2, which had a short amount of time in the silo.
- Some of the same issues (variability of RAP binder contents and aging, control of RAP and recycling agent during mixing) will arise as RAP contents are increased in all HMA mixes, proportional with the amount of RAP and recycling agent included in the mixes.

b. What is the aging of the binder, which controls its stiffness and viscoelastic response (phase angle), as measured by the carbonyl and sulfoxide contents, including after long-term aging using a pressure aging vessel (PAV)?
   - The carbonyl content (CA) of HyRAP Sample 1, which had a higher production temperature and low binder content, was significantly higher than that of Sample 4, which had a lower production temperature and a high binder content.
   - Sample 1 of the HyRAP had more aging during production because of higher production temperatures (Sample 1 HyRAP) had less effect of PAV aging in the laboratory than Sample 4.
   - Carbonyl contents of the HMA-M mix were comparable between the two samples tested and were significantly less than those of the HyRAP mixes. The CA content of the RHMA-G mix, which had no RAP, was the lowest of the three mixes.
   - The CA content of the slurry sand RAP was much higher than that of the 3/8 in. RAP, indicating more aging. Changes in mix design or variability of construction production that change the percentages of these RAP sources in the HyRAP mix will change the

stiffness of the mix, measured by the CA content of the total mix, as will variation in the binder contents in each of the stockpiles during construction production.

2. **What are the results of performance-related testing of the HyRAP mix sampled on I-40 project compared with the RHMA-G and HMA-M mixes also used on the project and with the statewide median PG 64 and PG 70 HMA mixes?**

   (Note: To match the air-void content for specimen preparation in the non-standard special provisions (nSSP) for the I-40 project, the HyRAP laboratory specimens were tested at 6% air-voids instead of the standard 7% air-voids used for the other two mixes. Several additional specimens for the HyRAP mix were also tested at 3% air-voids for comparison at the request of the mix producer. The reduction in compacted air-void content should increase stiffnesses, increase fatigue resistance, increase indirect tensile strength, increase rutting resistance, and reduce the effects of moisture conditioning.)

   a. Axial dynamic stiffness under different conditions of temperature and frequency of loading?

      - The axial dynamic stiffness (modulus) of the HyRAP Sample 1 mix, which had a low binder content and high production temperature, was approximately five times stiffer than the HMA-M and RHMA-G mixes at high temperatures and slow speeds, twice as stiff at intermediate temperatures and speeds, and 25% stiffer at low temperatures and fast speeds. The axial dynamic stiffness (modulus) of the HyRAP Sample 4 mix, which had a high binder content and lower production temperature, was similar to the stiffnesses of the HMA-M and RHMA-G mixes, closer to the RHMA-G mix at high temperatures and slow speeds, and closer to the HMA-M mix at low temperatures and fast speeds. The stiffnesses of the HMA-M and RHMA-G mixes were similar across the temperature and speed spectrum. The results for HyRAP Sample 1 indicate better rutting resistance, worse fatigue cracking performance as a thin overlay, and worse age-related cracking resistance.
      - The HyRAP mix Sample 1 had somewhat lower phase angles at low temperatures and fast speeds, indicating more elastic and less viscous behavior, which will reduce the ability to relax low and intermediate-temperature contraction stresses that cause age-related cracking. The HyRAP mix Sample 4 had phase angles in between those of the RHMA-G and the HMA-M mixes.
      - There was insufficient mix available from the other samples of HyRAP taken to test them.

   b. Flexural dynamic stiffness under different conditions of temperature and frequency of loading?

      - The flexural stiffness results were very similar to the axial stiffness results with regard to differences between Sample 1 of the three mixes, except that the RHMA-G mix was approximately 15% stiffer than the HMA-M mix at higher temperatures and slower speeds. The HyRAP mix Sample 4 flexural stiffness test results also followed the same patterns as the axial stiffnesses. The HyRAP Sample 1 mix generally matched the stiffnesses of the statewide median PG 70 mix, although it was stiffer than the PG 70 at high temperatures and slow speeds. The HyRAP Sample 4 mix stiffness was similar to the PG 64 mix at the highest temperatures and slowest speeds and at the lowest temperatures and fastest speeds, and softer than the PG 64 mix at intermediate temperatures and speeds.

- There was insufficient mix available from the other samples of the HyRAP mix taken to test them.

c. Flexural fatigue performance?

- Flexural fatigue results for the three mixes, compacted to 7% air-voids for the RHMA-G and HMA-M Sample 1 mixes, 3% and 6% for the HyRAP Sample 1 mix, and 6% for the HyRAP Sample 4 mix, showed that the RHMA-G mix had by far the best fatigue performance, followed by the HMA-M mix at lower strains and the HyRAP Sample 4 mix at higher strains. All of the mixes used on the project had better fatigue performance than the statewide median PG 64 mix and considerably better performance than the statewide median PG 70 mix.
- Projection of the trends for the HyRAP Sample 4 mix indicated that it had very good fatigue performance at low strains. Projection of the trends for the HMA-M and HyRAP Sample 1 mixes indicated that they had similar performance at lower tensile strains (approximately 400 microstrain).
- The HyRAP mix had better performance at 3% air-voids than at 6% air-voids.
- There was insufficient mix available from the other samples of HyRAP taken to test them.

d. IDEAL-CT strength related to stiffness and age-related cracking at intermediate temperatures after both reheating and medium-term oven aging (related to aging in the field) conditioning?

- The HyRAP mix had high variability across the five samples tested. The variability of strength of the HyRAP samples compared to those of the HMA-M and RHMA-G mix samples ranged from Sample 1 being the stiffest of all to Sample 4 being less than the HMA-M and only somewhat stiffer than the RHMA-G mix in the reheated condition. HyRAP Sample 1, which was produced at a high temperature and with low binder content, had the highest strength, while later samples had reduced strength as the binder content was increased to the design binder content and then to approximately 0.8% higher than the design binder content across Sample 2 to Sample 5 and after the high production was reduced after Sample 1. Strength is highly correlated with stiffness at intermediate temperatures and speeds.

- The effects of medium-term oven aging (MTOA) on the IDEAL-CT strengths and, therefore, stiffnesses of the three mixes were variable for the HyRAP mix but overall less than the effects on the HMA-M mix, which had 25% RAP, and much less than the effects on the RHMA-G mix, which had no RAP. Mixes that are already more aged, whether from production or RAP content, are generally expected to be less affected by additional aging, although the two HMA-M samples had the opposite of the expected trend.
- The effects of higher stiffness as measured by the IDEAL-CT strength are the same as those previously discussed for the axial stiffness.
- There was some variability for the HMA-M and RHMA-G mix samples, with the variability between the two HMA-M samples likely attributable to the differences in silo time.

e. IDEAL-CT index value related to age-related cracking at intermediate temperatures after both reheating and medium-term oven aging (related to aging in the field) conditioning?

  - IDEAL-CT index values generally, but not completely, work in opposite directions to the IDEAL-CT strength, which was observed in this study.
  - The HyRAP mix had high variability across the five samples tested. Sample 1, produced at a high temperature and with low binder content, had an extremely low IDEAL-CT index value, which is supposed to represent greater risk of age-related cracking and greater risk of fatigue cracking when used as a thin overlay. The results for HyRAP Sample 2 and Sample 3, with lower production temperatures and less aging than Sample 1, were somewhat greater, with 19 for Sample 2, which also had a low binder content, and 25 for Sample 3, which had close to the design binder content.
  - The IDEAL-CT index values for Sample 4 and Sample 5 of the HyRAP mix were comparable to or higher (better for cracking) than the two samples of HMA-M. The IDEAL-CT index values for the RHMA-G mix samples were considerably higher than those of the other two mixes, although they also showed high variability between the two mixes.
  - The rankings of IDEAL-CT index values did not change after MTOA conditioning. The HyRAP and HMA-M mixes showed similar ranges of change in index values after MTOA conditioning compared to before it. The RHMA-G mix samples, which had no RAP, showed a greater effect of the conditioning, and the difference between their index values and those of the other mixes were reduced, although the RHMA-G mix remained the mix with the best values.

f. Repeated load triaxial permanent deformation (rutting) resistance under both confined and unconfined conditions?

- The confined and unconfined repeated load triaxial (RLT) test results both showed far superior rutting resistance for Sample 1 of the HyRAP mix compared to Sample 1 of the other two mixes at 45°C and especially at 55°C.
- Sample 1 and Sample 2 of the HyRAP mix were tested at 50°C. The results showed that the reduction in production temperature for Sample 2, although still at a lower than design binder content, decreased the rutting resistance so that it was almost the same as Sample 2 of the HMA-M and RHMA-G mixes. The additional aging from extended silo storage of HMA-M mix Sample 2 resulted in a large increase in rutting resistance. The results for HyRAP mix Sample 4 showed the worst rutting resistance, although it was not much worse than Sample 1 of the RHMA-G and HMA-M mixes.

g. IDEAL-RT index value related to rutting at high temperatures after both reheating and medium-term oven aging (related to aging in the field) conditioning?

- The IDEAL-RT index value tests in the reheated condition indicated that HyRAP mix Sample 1, with a high production temperature and commensurate aging and a low binder content, had the best expected rutting risk and the RHMA-G mix had the worst rutting risk. The samples of HyRAP had increased rutting risk as the production temperature was reduced for Sample 2 to Sample 5 and as the binder content progressively increased, with Sample 4 having the highest binder content and a high rutting risk (low RT index value) similar to that of the RHMA-G samples.
- The HMA-M results were somewhat better than those of the RHMA-G samples and in the middle of the range of the HyRAP values. The effects of additional binder aging due to extended silo time were apparent in reducing the RT index value of the HMA-M Sample 2 mix compared with the Sample 1 mix.
- The effects of MTOA were greater on the HMA-M mix with no silo time, which had less RAP in it than the HyRAP mix, which was 100% RAP. The HMA-M mix Sample 2, which was aged in the silo, was affected by MTOA in a similar manner to the HyRAP samples (it fell in the middle of the range). The overall rankings did not change much. The RHMA-G mix was not subjected to MTOA for IDEAL-RT testing.

h. IDEAL-CT strength results after moisture-induced stress tester (MiST) moisture conditioning?

- Overall, there was little change in IDEAL-CT strengths after MiST conditioning for any of the mixes, with all samples having less than a 15% reduction in strength. The most sensitive was the first sample of HMA-M, which did not have time spent in the silo.
- The strength rankings did not change after MiST conditioning.
- The strength rankings did not change after MTOA conditioning followed by MiST conditioning for the HyRAP and HMA-M mixes. The RHMA-G mix was not tested with both conditioning processes.

i. Hamburg Wheel-Tracking testing related to permanent deformation and moisture damage resistance?

   - The HWT test results were considerably different for rutting than those from the repeated load triaxial test and the IDEAL-RT test. The HWT test results showed early rutting failure for HyRAP mix Sample 4, which does not have a high production temperature and had a binder content approximately 0.8% higher than the design binder content. This is followed in ranking by HyRAP mix Sample 5 (also high binder content) and Sample 2 (low binder content). HyRAP mix Sample 1, with a high production temperature and low binder content. All of the HyRAP HWT samples show an inflection point, indicating the potential that moisture damage is contributing to the rutting.
   - The two samples of the HMA-M and RHMA-G mixes have better Hamburg performance than the HyRAP mixes. The HMA-M samples showed variability related to the additional silo aging of Sample 2, which had better rutting performance than Sample 1. Sample 1 HMA-M mix showed an inflection point indicating potential moisture damage, while the more aged Sample 2 HMA-M mix and both the RHMA-G mix samples did not. There was no rain at Barstow, near the test sections, between April and June 2024, and little rain overall in early 2024.[7]
   - It should be noted that all of the HyRAP samples were tested at 3% air-void contents, which should improve their performance for both rutting and moisture sensitivity compared with the standard 7% air-void contents that the HMA-M and RHMA-G mixes were compacted to for HWT testing.

3. **What is the stiffness of the overall pavement and subgrade and the stiffness of the subgrade in the locations with HyRAP mix as measured by deflection testing compared with the stiffnesses (corresponding to structural capacity) where the control RHMA-G mix was placed the I-40 project?**
   - Deflections from the outermost sensor of the FWD showed generally similar subgrade stiffness under the HyRAP and RHMA-G overlay sections. The subgrade stiffnesses in Lane 2 were somewhat softer than under Lane 1 for both the HyRAP and RHMA-G sections.
   - Deflections from the sensor under the load of the FWD showed similar combined pavement structure and subgrade stiffness under the HyRAP and RHMA-G overlay sections.
   - The thin HyRAP and RHMA-G overlays were not expected to produce different pavement structural stiffnesses despite differences in the overlay stiffnesses because of the greater thickness of the underlying existing pavement layers.

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[7] Weather history in Barstow: https://weatherspark.com/h/y/1924/2024/Historical-Weather-during-2024-in-Barstow-California-United-States.

4. **How do the laboratory rutting test results for the different samples relate to the rutting performance of the sections where those materials were placed from construction in September 2023 to removal of Lane 2 mixes in July 2024.**
   - Comparison of the confined RLT at 50°C, IDEAL-RT, and HWT laboratory testing results for the HyRAP samples (all five were tested) shows a clear correspondence between increasing asphalt content and worse test results.
   - The performance-related laboratory rutting test results generally identified the potential for rutting problems with the Day 4 (Sample 4) mix; however, the RLT (Figure 5.16) and IDEAL-RT (Figure 5.21) results for Sample 1 of both the RHMA-G and the HMA-M digout patching mixes showed results that were only slightly better than the Day 4 HyRAP mix. The RHMA-G mix in Lane 2 has not rutted to an extent that it has had to be removed and replaced. Only the HWT test results (Figure 5.25) showed a clear distinction between the Day 4 HyRAP mix that rutted and the RHMA-G mix that did not rut.
5. **What is the global warming impact calculated from modeling using known job mix formulas of the different mixes used on the I-40 project and how do they compare with each other and with other mixes used in California, assuming same performance?**
   a. HyRAP mix considered with and without use of the natural gas-burning oxidizer used to reduce air pollution from the mixing plant and considering two sources of natural gas data?
      - Volatile organic compound (VOC) emissions that escape into the air at the plant and cause air pollution were not included in modeling because no data were available. HyRAP production without the oxidizer to burn the VOC at the plant results in approximately a 38% reduction in global warming impact (GWI). If a heat exchanger is used with the oxidizer to reduce its natural gas usage by 70%, then there is a reduction in GWI of about 30% for HyRAP production compared with using the oxidizer without the heat exchanger.
      - HyRAP production with the use of the oxidizer to reduce VOC emissions results in approximately a 32% increase in GWI compared with production of an HMA mix with no RAP and no haul distance for the virgin aggregate (i.e., the plant is at the quarry). There is about a 25% increase in GWI for the HyRAP compared with an HMA mix with 15% RAP and a 50-mile aggregate haul distance. The HyRAP is assumed to have no hauling emissions for the RAP because it is already on-site at the plant, and its hauling was part of previous projects.
      - However, there is little virgin aggregate left in parts of Southern California and aggregate must be hauled to mixing plants. There is about a 13% reduction in GWI for the HyRAP production using the oxidizer compared with the HMA with no RAP and a 100-mile haul distance. That reduction is about 37% when the HMA with no RAP has a 200-mile aggregate haul distance.

- If the oxidizer is not used at the HyRAP plant, there is a reduction of about 20% in GWI compared with the 15% RAP HMA with the 50-mile hauling distance. If the oxidizer is used but a heat exchanger is installed at the HyRAP plant to reduce the natural gas use of the oxidizer by 70%, then there is about a 10% reduction of GWI compared with the 15% RAP HMA mix with the 50-mile hauling distance.

b. Compared with that of the I-40 PG 64-28M HMA with 24% RAP and RHMA-G mix designs?

   - Of the three mixes used on the I-40 project, the RHMA-G mix had the highest GWI largely because of the lime used, followed by the HyRAP mix produced with the oxidizer, then the HMA-M with 25% RAP. If the oxidizer was not used in making the HyRAP mix then it would have the lowest GWI, about 50% less than the RHMA-G mix and almost 25% less than the HMA-M with 25% RAP.

c. Compared with that of hypothetical default HMA mixes in the Caltrans life cycle assessment software *eLCAP* (*environmental Life Cycle Assessment for Pavement*) with HMA with no RAP, with 15% RAP, and with no RAP/polymer-modified binder, and with an RHMA-G mix with no RAP; compared with HMA and RHMA-G mixes with California EPDs; and compared with a 30% RAP mix from the National Asphalt Pavement Association (NAPA) life cycle assessment tool *(1)*?

   - Compared with other mix types and mix designs, the HyRAP with the oxidizer and no heat exchanger is among the higher GWI producing mixes, similar to HMA-M with no RAP and a 50-mile haul distance and RHMA-G with a 50-mile haul distance and no lime treatment.
   - If the HyRAP is produced without the oxidizer or with the oxidizer and the heat exchanger, it has lower GWI than any of the other mixes evaluated, including HMA with 30% RAP.
   - Overall, the relative GWI impact of the HyRAP and whether it is beneficial or not dependent on whether the oxidizer or the oxidizer with the heat exchanger is used and on the truck haul distances of the alternative HMA and RHMA mixes. If the oxidizer is not used, then there will be increased VOC emissions contributing to air pollution that were not part of the modeling.
   - It must be emphasized that all of these comparisons assume same performance for all mixes. If a mix has a shorter life, then its GWI will increase commensurate with the reduced life of the alternative.

9.2.2 Summary of Conclusions

The HyRAP mix had a high variability of performance-related properties during its production for the I-40 project. Its potential performance is completely dependent on that variability, swinging from a high potential for cracking and low potential for rutting, to the opposite and in between, compared with the alternative HMA-M and RHMA-G mixes. The results indicate that construction variability of the binder properties in the HyRAP mix is subject to larger ranges of variability within the sources of variability than conventional mixes and that efforts should be made to reduce those ranges. Some of the same issues (variability of RAP binder contents and aging, control of RAP and recycling agent during mixing) will arise as RAP contents are increased in all HMA mixes, proportional with the amount of RAP and recycling agent included in the mixes. In general, the RHMA-G mix produced and used on the project had the best overall and consistent performance-related properties. However, the RHMA-G mix had a high GWI because of its higher binder content and the lime treatment applied to the aggregate.

The HyRAP mix offers potential substantial reductions in GWI if it can be produced using RAP sources that have been stockpiled at the mix production plant and produced without use of the oxidizer to reduce VOC emissions causing air pollution or if a heat exchanger can substantially reduce natural gas usage in the oxidizer. It was assumed in the LCA comparing the HyRAP mix with other mixes that the RAP was already at the mixing plant site and was not transported. The LCA also showed that transporting RAP long distances can nullify the benefits of using the 100% RAP mix with respect to GWI. The same analysis indicates that use of HyRAP is especially beneficial when there are limited virgin aggregate sources nearby and aggregate must be transported long distances. Urban areas tend to have higher quantities of RAP compared with rural areas because of the need to mill old asphalt off city streets and urban freeways to match the existing curb and gutter and other grade elevation restrictions. If the HyRAP mix must be produced using the oxidizer and without the heat exchanger, then it will cause more GWI compared with HMA alternatives unless the virgin aggregate for the other mixes is being hauled more than 100 miles.

9.3 Recommendations

The use of HyRAP can potentially offer major environmental benefits, or increase environmental impacts, depending on how it is produced and what it is being compared to, and assuming it performs as well as those alternatives. However, production consistency needs to be improved. Part of the reason for the highly inconsistent properties of the HyRAP mixes over the five days of paving was that many of the decisions made for the HyRAP production were driven by the long haul distance and its use on a high truck traffic project in the hot desert.

It is recommended that any further work in the development of HyRAP be done for use on projects closer to the HyRAP plant and with less risk from heavy truck traffic. The ability to achieve mix consistency during production through management RAP stockpiles, and process controls for the RAP, the recycling agent, and the mixing process should be demonstrated on a lower-risk project. This can include streets, passenger car lanes of routes with higher traffic, ramps, parking lots, and other locations that meet these criteria. The focus should be on reducing production variability and using mix designs that are able to balance the risk of age-related cracking with rutting.

It is also recommended that the age-related cracking and moisture susceptibility of these HyRAP mixes should be evaluated for several years to verify aging and moisture-related performance. In addition, it is recommended that it be determined if HyRAP can be produced without the oxidizer for VOCs and not have unallowable VOC emissions or with a heat exchanger. If it cannot, then there is little current possibility of achieving the desired GWI benefits, and the primary benefit is the preservation of aggregate resources where they are scarce and RAP is plentiful.

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APPENDIX A June 2023 HyRAP Test Memo for G3

HyRAP® Tested Under Fatigue and Dynamic Modulus

From: Irwin Guada, Jeff Buscheck, Angel Mateos, and John Harvey
University of California Pavement Research Center

To: Lance Fernandez, Matt Ramos
G3 Quality, Inc.

Re: UCB Agreement 055379-002

Date: October 19, 2023

Introduction

In September 2022, G3 contacted the UCPRC-Berkeley because it was interested in testing HyRAP® asphalt mix used on Caltrans project agreement No. 11A3437 in San Diego County (Expenditure Authorization 11-431524). The HyRAP® mix was used on an emergency repair basis on June 25, 2022, on the SD-163 southbound to SD-5 northbound connector in District 11. This mix uses 100% reclaimed asphalt pavement (RAP) and a recycling agent instead of virgin aggregate and binder.

In November 2022, the UCPRC-Berkeley agreed to test the HyRAP® mix using two test devices. Using a four-point bending test machine, the UCPRC determined mix flexural stiffness (also called flexural dynamic modulus) at different temperatures and frequencies (referred to as a frequency sweep) to produce a stiffness master curve and mix fatigue resistance according to AASHTO T 321. Using an asphalt mixture performance tester (AMPT), the UCPRC determined mix axial stiffness (also called axial dynamic modulus) to produce a stiffness master curve and flow number, a measure of rutting resistance at high temperatures, according to AASHTO T 378. In addition to these tests, the UCPRC ran the IDEAL-CT cracking test according to ASTM D8225, which produces a fracture cracking parameter and an indirect tensile strength, and the Hamburg Wheel-Track (HWT) test, which measures rutting under the effects of temperature and moisture damage at the same time, according to Caltrans specifications.

Specimen Preparation

The HyRAP® mix was produced using three bins from fractionating RAP aggregates. The mix paved on the Caltrans project contained RAP materials from a passing 3/8 in. bin, a coarse fines bin, and a fine fines bin. This mix was used in Caltrans project No. 11A3437, but it was not sampled for the testing performed by the UCPRC presented in the technical memorandum that is this appendix.

The HyRAP® mix tested by the UCPRC was sampled February 2, 2023, from the Manhole Adjusting Inc. asphalt plant in Colton, CA. The mix sampled for this study contained RAP materials fractionated into a 5/16 in. bin, a coarse fines bin, and a slurry sand bin to create the same gradation as was used on the Caltrans project. These bins were combined along with Viplex 50 recycling agent dosed at 1.7% by total mass of mix to produce a mix with a total binder content of approximately 5.8% by total weight of mix, where the binder consists of the RAP binder (determined from extraction) and the recycling agent, with no virgin asphalt binder added.

A sample of approximately one and a half tons of loose mix was collected from a hot drop at the Manhole Adjusting Inc. plant into 3.5-gallon metal buckets that were sealed and delivered to the UCPRC-Berkeley laboratory. The material was prepared for testing by UCPRC staff at the UCPRC-Berkeley laboratory using a rolling wheel compactor for flexural beams for flexural frequency sweep and fatigue testing, following California Lab Procedure LLP-AC3 (Sample Preparation and Testing for Long-Life Hot Mix Asphalt Pavements) and a gyratory compactor for AMPT, IDEAL-CT, and HWT specimens, according to the specified requirements.

Upon receipt, the buckets of HyRAP® mix were kept out of direct sunlight and at approximately 20°C. The material was reheated one time only to produce compacted specimens for testing, following standard UCPRC reheating protocol. In the buckets, the mix was heated to 135°C, run through a quartermaster before weighing to the required compaction mass, maintained for one to two hours at the compaction temperature, 143°C (the temperature recommended by Manhole Adjusting Inc.), and then compacted. The mix was compacted to a target air-void of 7.0%±1.0% for the different types of specimens tested at the UCPRC.

Test Results

The test results are presented here graphically for the four-point bending flexural tests of stiffness and fatigue life, followed by the axial tests of dynamic modulus and permanent deformation, including flow number. These are followed by the IDEAL-CT and HWT test results.

Four-Point Bending Tests

The results of the flexural dynamic modulus testing were fitted with a sigmoidal master curve, considering the time-temperature superposition principle, as shown in equations [1] and [2]. The master curve of the HyRAP® mix is shown in Figure 1 along with the master curves from other HMAs tested at the UCPRC in past studies, including mixes with PG 64-16 plain binder and PG 64-28 polymer-modified binder, and different RAP percentages from different RAP sources. The reference temperature for the master curves is 20°C and Table 1 shows—for each of the mixes—the parameters of the sigmoidal equation (δ, α, β, and γ) and the parameter of the time-temperature correspondence equation (β_T).

$$\log(E) = \delta + \frac{\alpha}{1 + e^{\beta+\gamma\cdot\log(f_{red})}} \quad [1]$$

where E is the flexural dynamic modulus; δ, α, β, and γ are fitting parameters; and f_{red} is the reduced frequency.

$$f_{red} = f \cdot a_T \quad [2]$$

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

Figure 2 shows the results of the flexural fatigue life, repetitions to failure versus strain level (Wöhler curve), for testing conducted at 20°C. The fatigue failure criteria for this test is the maximum of the curve of the stiffness times the repetitions versus repetitions alone, as specified in AASHTO T 321 (2022). Table 2 shows the equations for the Wöhler curve best fit lines.

Also shown in both Figure 1 and Figure 2 is the statewide median mix from the CalME Standard Materials Library, labeled Statewide Median. This represents a standard HMA mix with PG 64 grade binder with average performance from mixes sampled and tested across the state over approximately the last six years. Here, “average performance” is based on the median simulated pavement fatigue cracking performance predicted with the *CalME* software, which considers the interaction of stiffness and fatigue properties.

In addition to the statewide median mix properties, the figures and tables show results from mixes with PG 64-16 binders and RAP contents up to 25% of the mix sampled—primarily on recent high RAP pilots, two mixes with PG 64-28PM binders that were recently tested, and some other mixes. The results from the recently tested mixes generally have softer stiffness master curves than the statewide median mix and similar flexural fatigue performance.

The flexural stiffness test results show that the HyRAP® mix has higher stiffnesses than the recent PG 64 HMA mixes at frequencies lower than 0.1 Hz (equivalent to higher temperatures and slower speeds). At 1 Hz (equivalent to traffic loading at intermediate temperatures and speeds), the HyRAP® stiffness is within the range of other HMA mixes. At the higher frequencies, representative of colder temperatures and faster speed traffic, the stiffness values of the HyRAP® mix are lower than most other HMA mixes, except the polymer-modified mixes. The flexural fatigue results, performed at 10 Hz loading frequency, show that the HyRAP® mix has fatigue lives at a given tensile strain that are greater than the recent mixes with PG 64-16 binder or PG 58-22 binder with higher amounts of RAP and in between those of the two polymer-modified binder mixes.

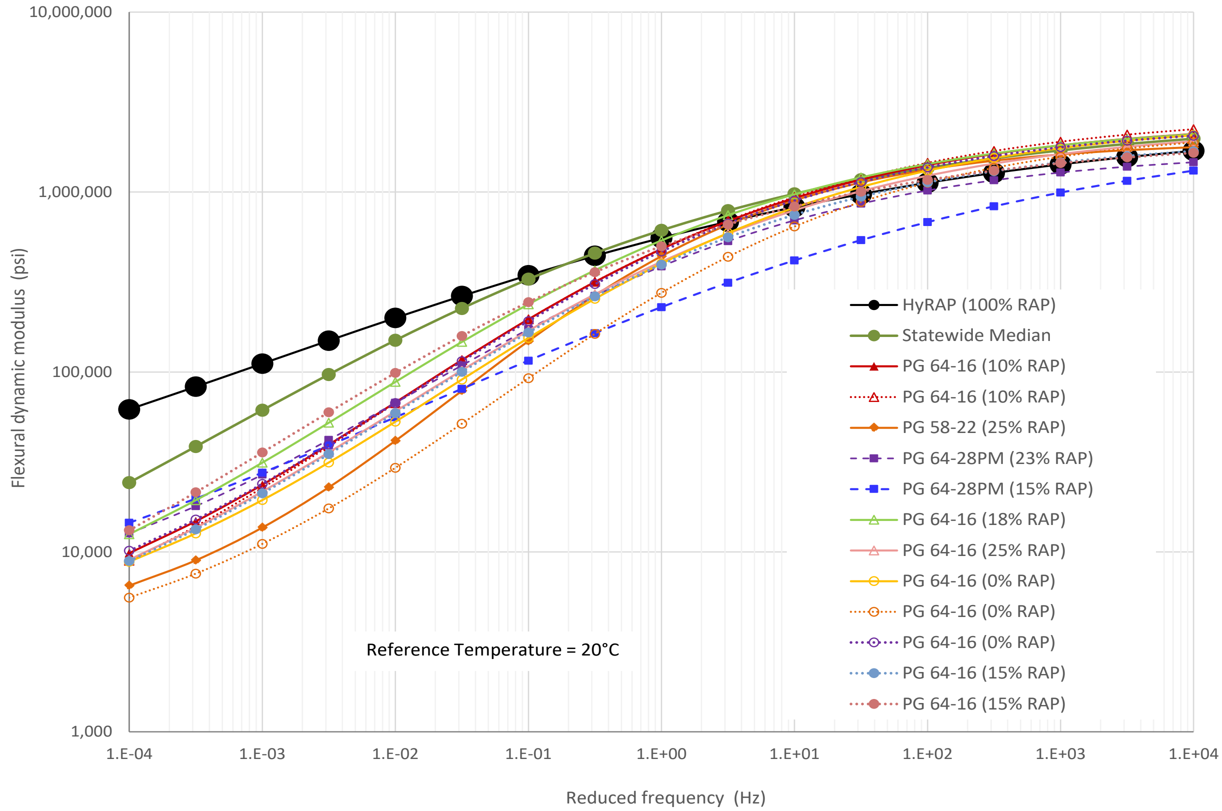


Figure 1: Flexural stiffness master curves of several HMA mixes and HyRAP® from AASHTO T 321.

Table 1: Master Curve and Shift Factors Equations Parameters for the Flexural Stiffness

Mix Type	δ	α	β	ϒ	βT
HyRAP® (100% RAP)	1.52	2.73	-1.13	-0.38	0.16
Statewide Median	—	—	—	—	—
PG 64-16 (10% RAP)	1.15	3.09	-1.20	-0.61	0.14
PG 64-16 (10% RAP)	0.98	3.30	-1.21	-0.58	0.14
PG 58-22 (25% RAP)	1.30	2.82	-1.23	-0.80	0.14
PG 64-28PM (23% RAP)	1.37	2.70	-1.15	-0.62	0.14
PG 64-28PM (15% RAP)	1.11	3.12	-0.70	-0.41	0.14
PG 64-16 (18% RAP)	1.10	3.14	-1.30	-0.58	0.14
PG 64-16 (25% RAP)	1.05	3.17	-1.14	-0.58	0.13
PG 64-16 (0% RAP)	1.22	3.03	-1.02	-0.62	0.14
PG 64-16 (0% RAP)	1.18	3.03	-0.82	-0.67	0.14
PG 64-16 (0% RAP)					
PG 64-16 (15% RAP)	1.08	3.06	-1.20	-0.60	0.13
PG 64-16 (15% RAP)	0.78	3.36	-1.52	-0.53	0.14

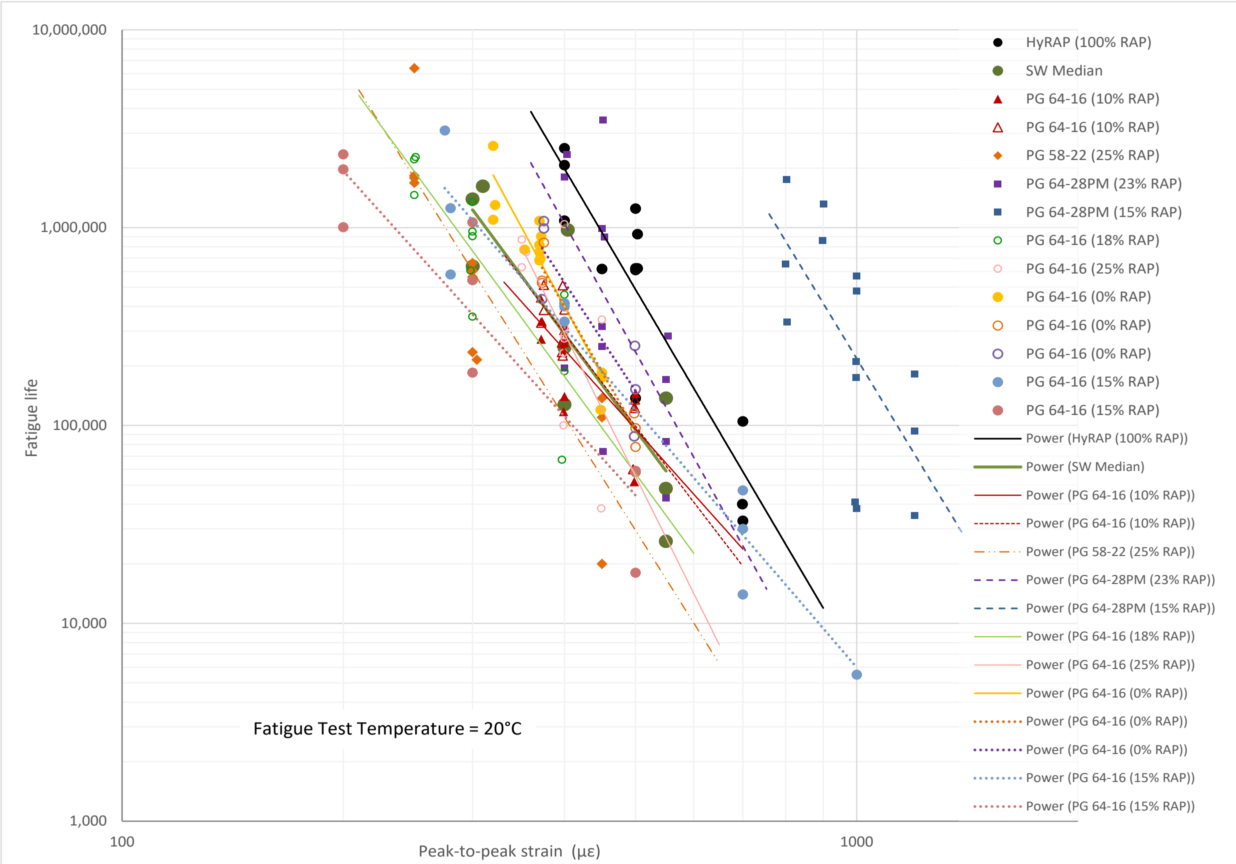


Figure 2: AASHTO T 321 fatigue life versus strain level for several HMA Mixes and HyRAP®.

Table 2: Best Fit Line Parameters for Fatigue Life Wöhler Curves

Mix Type	Equation	R-Squared
HyRAP® (100% RAP)	$5.00E{+}22x^{-6.303}$	0.811
Statewide Median	$3.25E{+}18x^{-5.015}$	0.754
PG 64-16 (10% RAP)	$1.51E{+}16x^{-4.149}$	0.559
PG 64-16 (10% RAP)	$1.17E{+}18x^{-4.843}$	0.757
PG 58-22 (25% RAP)	$2.64E{+}20x^{-5.910}$	0.785
PG 64-28PM (23% RAP)	$3.01E{+}23x^{-6.709}$	0.358
PG 64-28PM (15% RAP)	$5.50E{+}23x^{-6.134}$	0.442
PG 64-16 (18% RAP)	$2.83E{+}18x^{-5.074}$	0.734
PG 64-16 (25% RAP)	$7.91E{+}24x^{-7.468}$	0.479
PG 64-16 (0% RAP)	$2.52E{+}23x^{-6.840}$	0.886
PG 64-16 (0% RAP)	$2.34E{+}22x^{-6.444}$	0.958
PG 64-16 (0% RAP)	$3.04E{+}20x^{-5.672}$	0.783
PG 64-16 (15% RAP)	$5.45E{+}16x^{-4.32}$	0.942
PG 64-16 (15% RAP)	$5.83E{+}15x^{-4.119}$	0.870

Axial Dynamic and Permanent Deformation Tests

Figure 3 shows the results of the axial dynamic modulus tests, which produce the axial dynamic modulus master curve. The data were fitted with a sigmoidal master curve, considering the time-temperature superposition principle, as shown in equations [1] and [2]. Table 3 presents the parameters of the sigmoidal and time-temperature shift factor equations. The axial dynamic modulus master curve tends to produce higher stiffnesses than the flexural master curve, particularly at lower frequencies and higher temperatures, due to differences in the stress states of the two test methods. The flexural test is primarily controlled by tension where the binder plays a greater role at higher temperatures and slower frequencies, while the axial test is primarily under a combination of compression and shear stresses where the aggregate structure plays a greater role than in the flexural configuration. The test results are shown along with other HMA tested at the UCPRC in past studies, including mixes with PG 64-16 plain binder and PG 64-28 polymer-modified binder and different RAP percentages.

The dynamic modulus testing shows the HyRAP® data falling within the range of other HMA mixes. The HyRAP® mix tracks two different mixes, a PG 64-28PM mix with 15% RAP and PG 64-16 mix with no RAP. A statewide median axial stiffness master curve has not been developed.

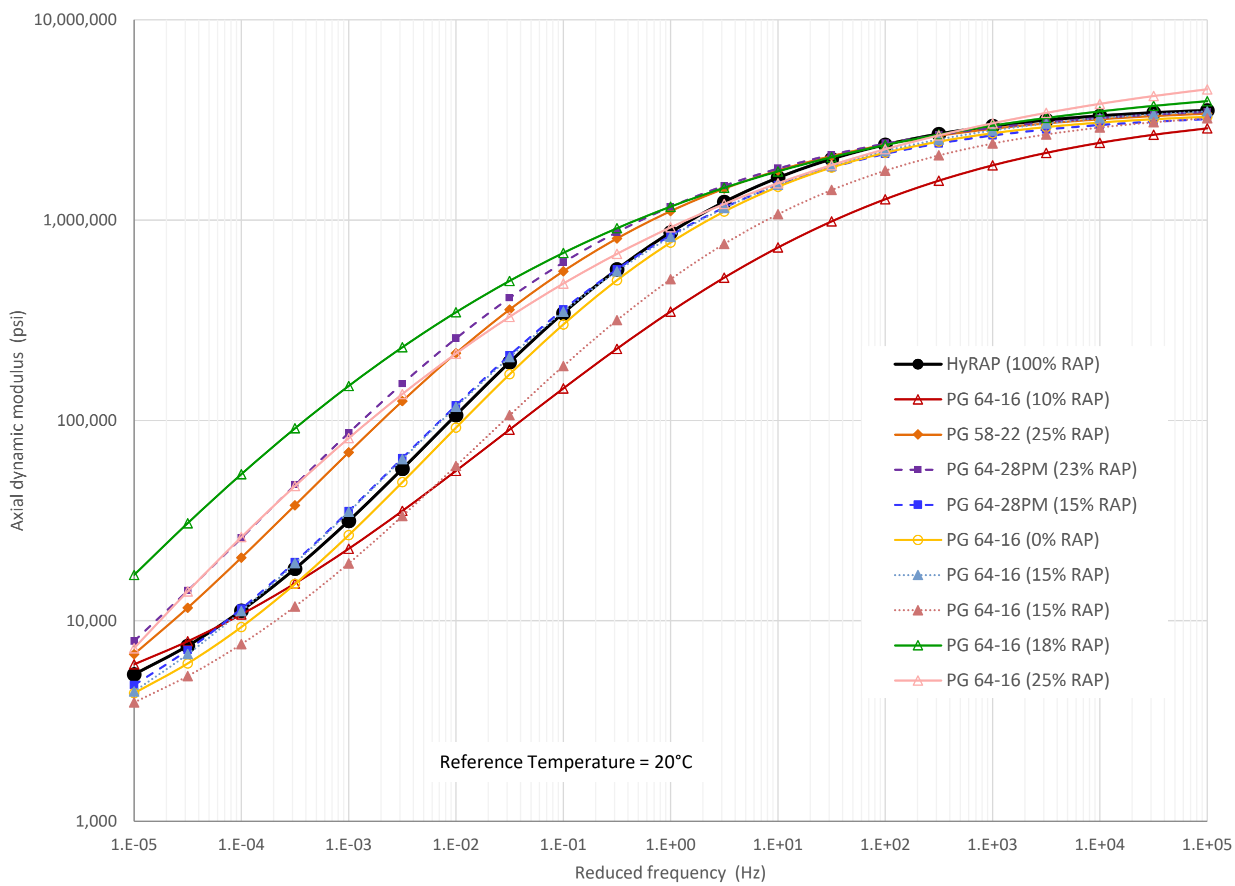


Figure 3: AASHTO T 378 axial dynamic modulus for several HMA mixes and HyRAP®.

Table 3: Master Curve and Shift Factors Equations Parameters for the Axial Dynamic Modulus Stiffness

Mix Type	δ	α	β	ϒ	βT	Error
HyRAP® (100% RAP)	1.12	3.29	-1.43	-0.65	0.10	3.80
PG 64-16 (10% RAP)	1.13	3.29	-0.78	-0.50	0.10	8.77
PG 58-22 (25% RAP)	0.53	3.88	-1.85	-0.55	0.10	3.55
PG 64-28PM (23% RAP)	0.24	4.19	-1.95	-0.51	0.11	4.52
PG 64-28PM (15% RAP)	0.87	3.51	-1.55	-0.61	0.10	6.56
PG 64-16 (0% RAP)	1.00	3.39	-1.42	-0.64	0.10	0.93
PG 64-16 (15% RAP)	0.73	3.70	-1.50	-0.57	0.10	4.40
PG 64-16 (15% RAP)	0.97	3.44	-1.09	-0.59	0.10	7.11
PG 64-16 (18% RAP)	-2.01	6.57	-2.20	-0.34	0.11	1.92
PG 64-16 (25% RAP)	-3.05	7.74	-2.04	-0.32	0.10	0.53

Figure 4 and Figure 5 show the results of the unconfined and confined repeated load triaxial permanent deformation testing at 45°C and 55°C, respectively. The results show the permanent deformation axial strain up to 5% axial permanent deformation, defined as failure, or 20,000 cycles, when the test was stopped if failure had not been reached. The test results are shown along with test results from other HMA mix types, including mixes with different maximum aggregate sizes, different binder grades, mixes with different RAP percentages, and polymer-modified mixes.

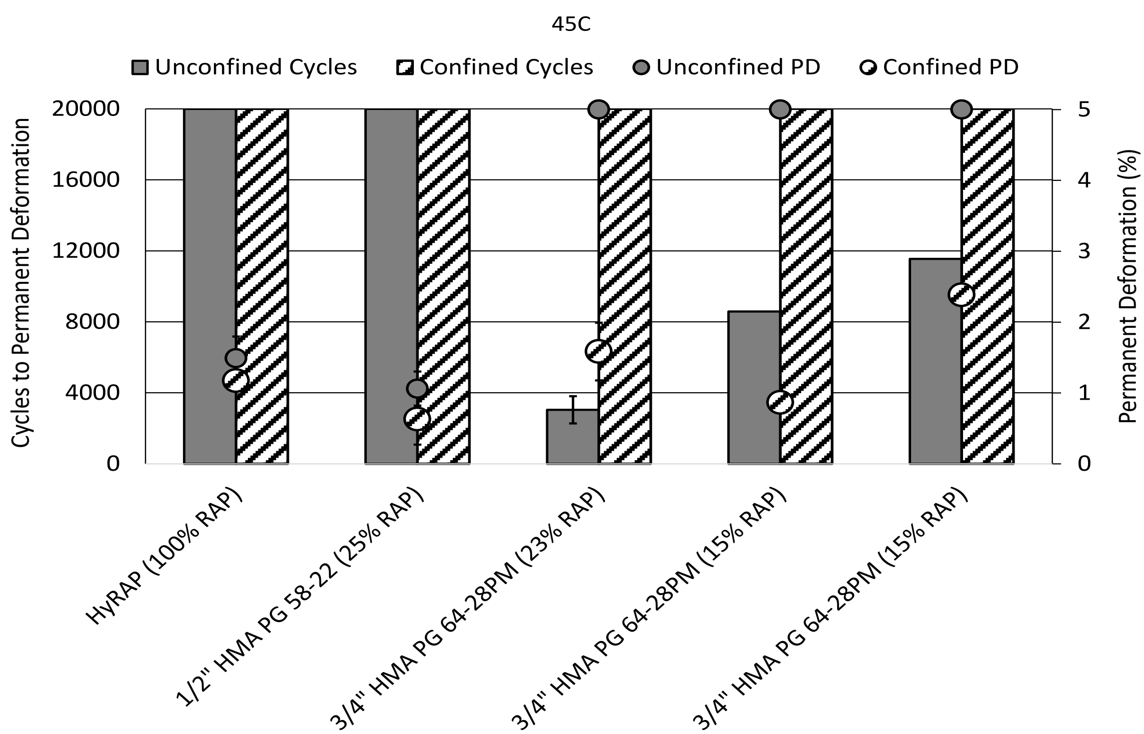


Figure 4: AMPT repeated load test at 45°C for several mixes and HyRAP®.

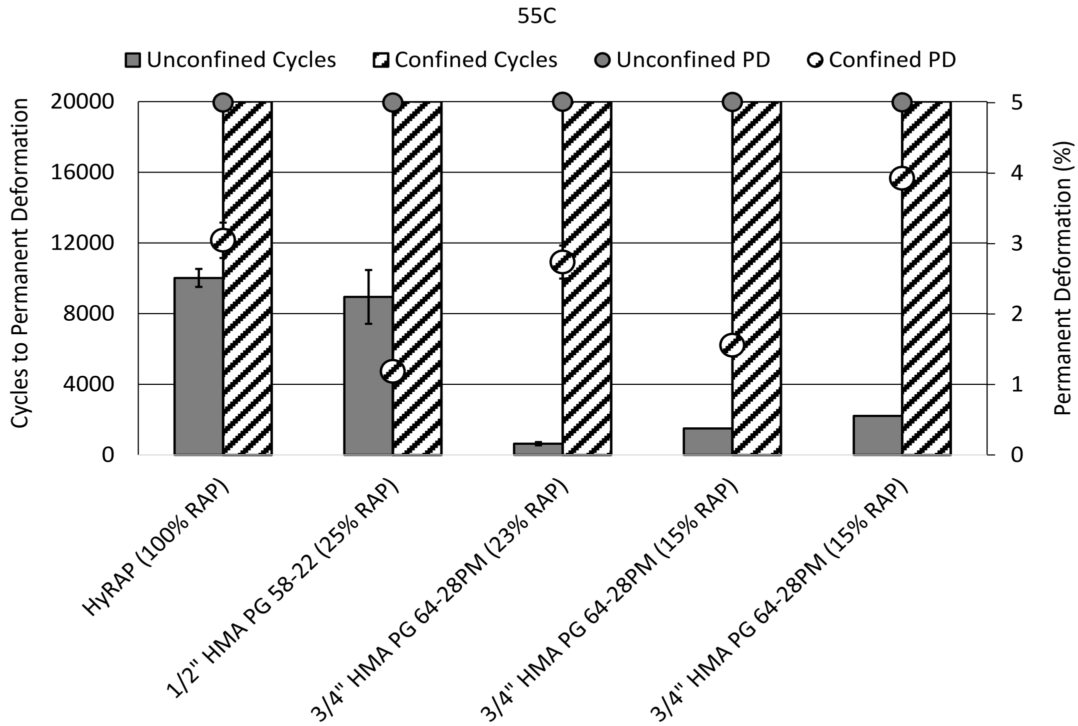


Figure 5: AMPT repeated load test at 55°C for several mixes and HyRAP®.

These permanent deformation tests show a highly rut resistant mix at 45°C. Most unconfined tests will achieve 5% permanent deformation by 20,000 repetitions. The HyRAP® along with a 1/2 in. HMA with PG 58-22 binder and 25% RAP permanently deformed less than 2% after 20,000 cycles in the 45°C unconfined tests. In the confined tests at 45°C, the HyRAP® was comparable with the other mixes.

In the confined tests at 55°C, the HyRAP® mix was comparable to other mixes, reaching about 3% permanent deformation. In the unconfined tests at 55°C, the HyRAP® mix showed better rut resistance than most other mixes, allowing 10,000 cycles before reaching 5% permanent deformation.

The permanent deformation tests also determine the flow number. The flow number represents the number of cycles at which the rate of increase in permanent deformation transitions from a constant rate to an increasing rate of damage, illustrated in Figure 6. Figure 7 through Figure 10 present the flow numbers for the same permanent deformation tests shown in Figure 4 and Figure 5. Figure 7 through Figure 10 show the flow numbers along the top and the permanent axial strain at the flow number of cycles below, and the errors bars for both the flow number and the axial permanent deformation represent one standard deviation.

Figure 7 and Figure 8 show results of the confined tests at 45°C and 55°C, respectively. These confined flow numbers show that the HyRAP® mix is rut resistant, similar to the polymer-modified mixes. The flow number for these mixes at 45°C and 55°C suggests little temperature effect in this range of temperatures. The HyRAP® flow numbers at 45°C and 55°C are equivalent.

Figure 9 and Figure 10 show results of the unconfined tests at 45°C and 55°C, respectively. Under unconfined tests between 45°C and 55°C, the HyRAP® mix exhibits higher rutting resistance than the polymer-modified mixes and similar to the 1/2 in. HMA with PG 58-22 binder. Between the two temperatures, the reduction in flow number is similar among the mixes shown, about 20%.

Generally, the unconfined test condition would be considered more damaging than the confined test condition, because the confinement would engage the bulk properties of the mix. However, the HyRAP® mix at 45°C unconfined produced a larger flow number than the confined tests at 45°C or 55°C.

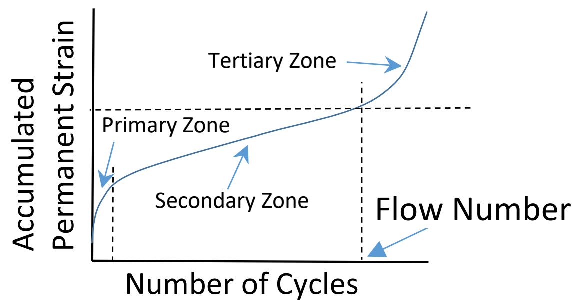


Figure 6: Illustration of flow number test.

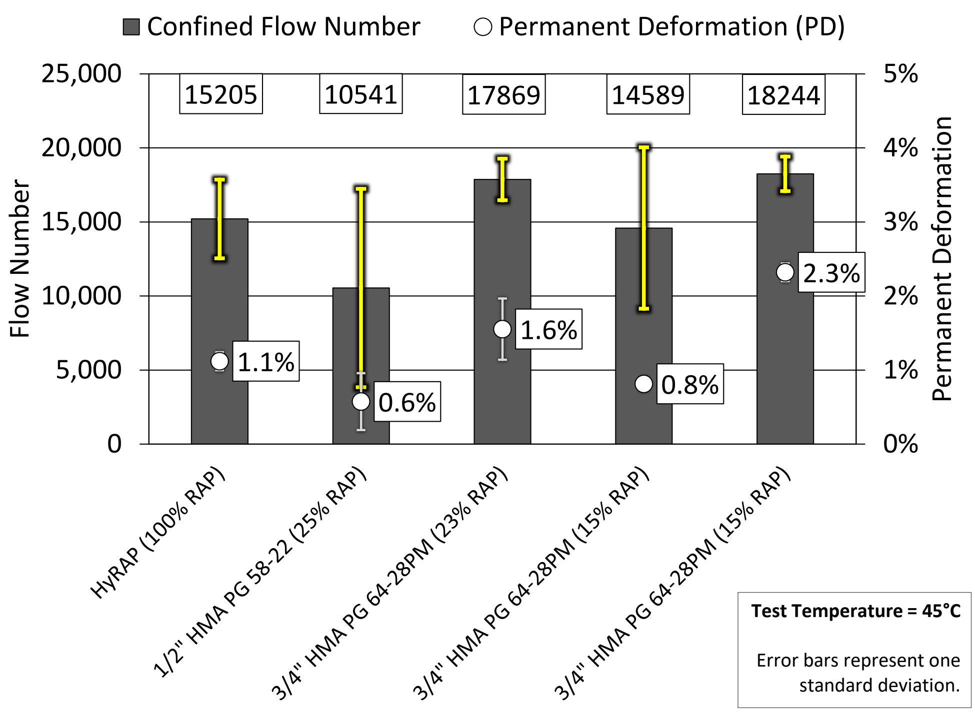


Figure 7: Confined flow number results at 45°C.

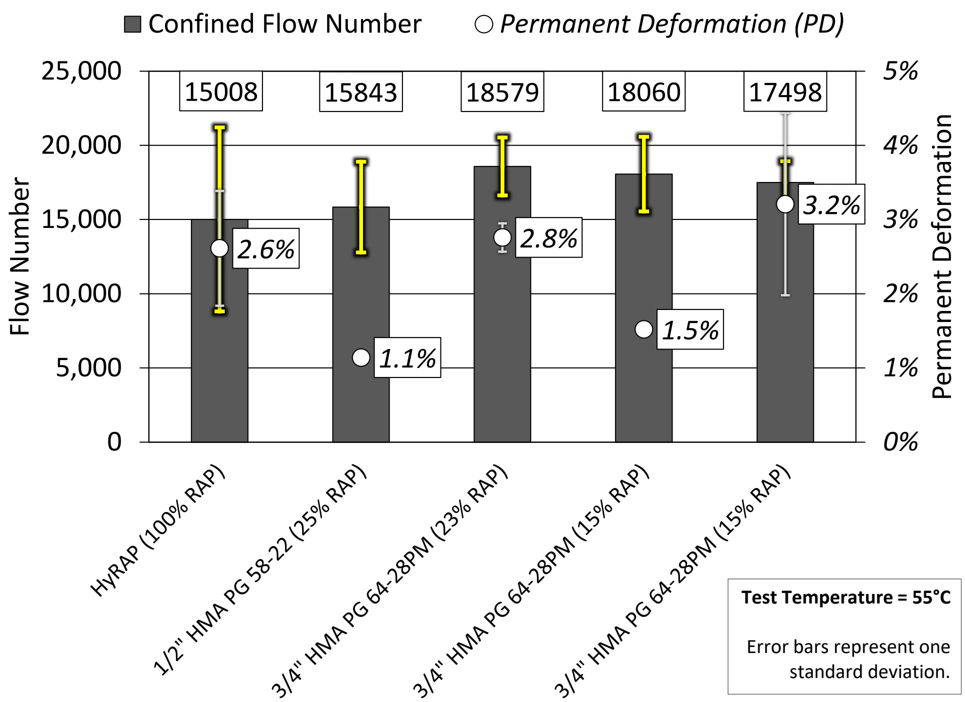


Figure 8: Confined flow number results at 55°C.

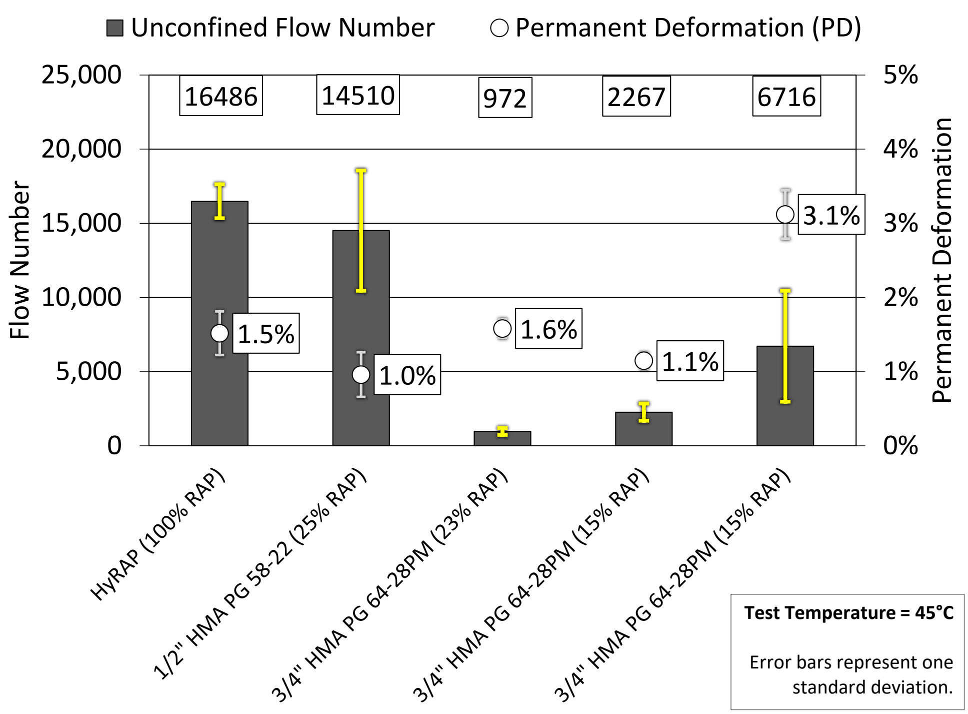


Figure 9: Unconfined flow number results at 45°C.

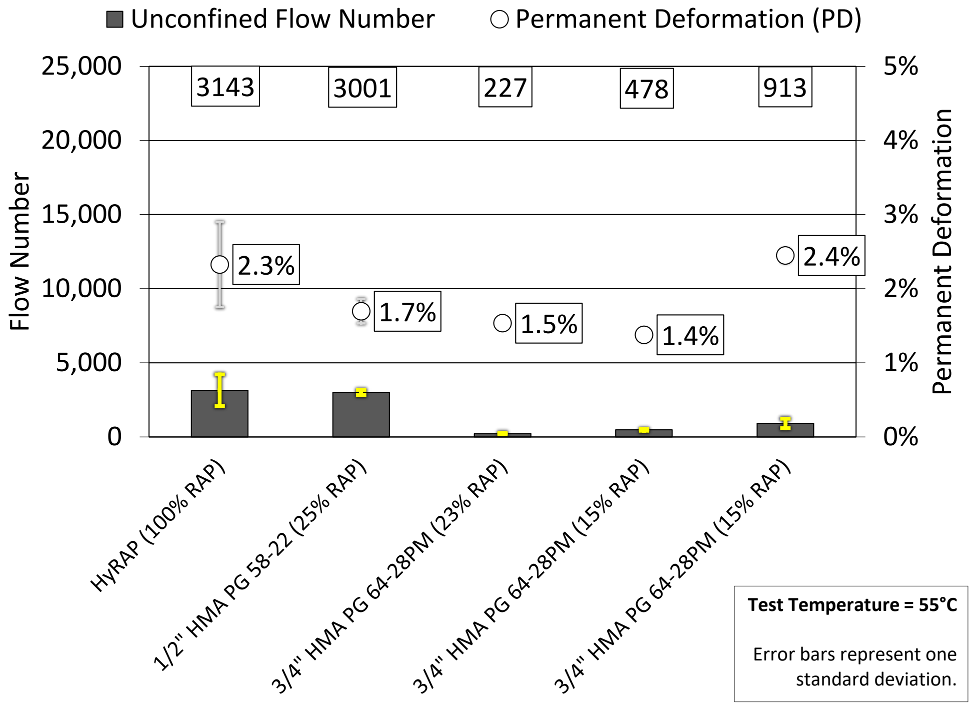
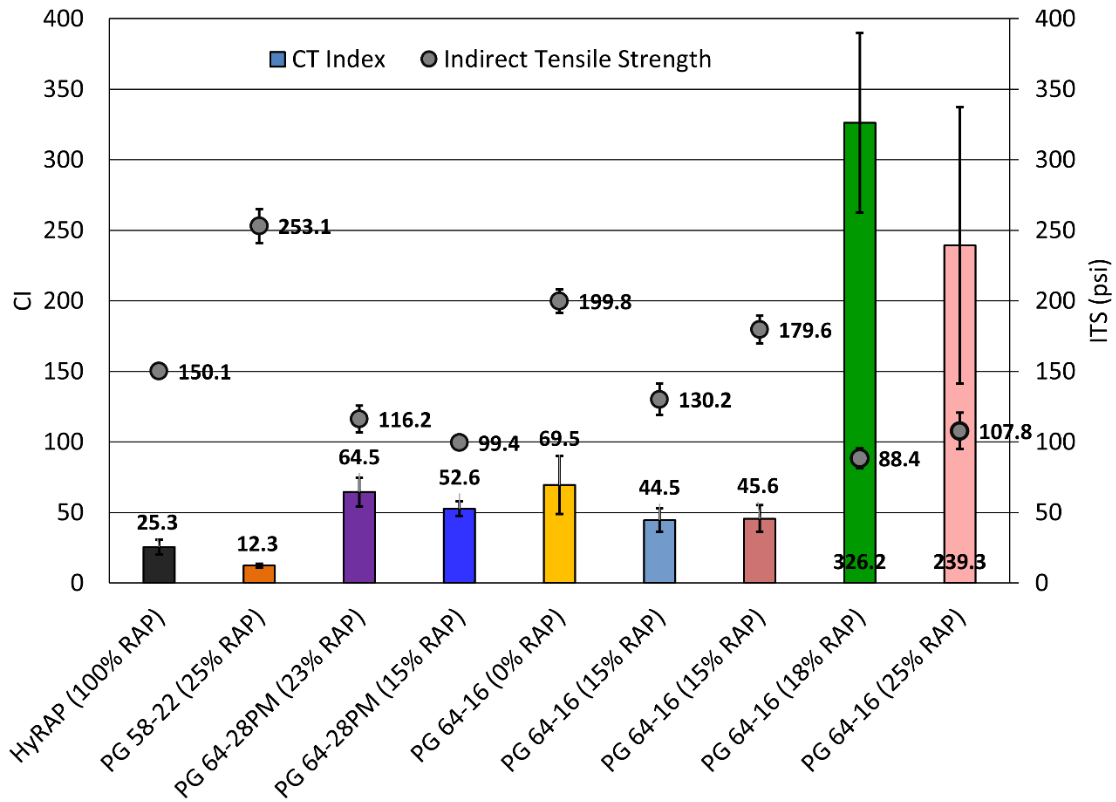


Figure 10: Unconfined flow number results at 55°C.

IDEAL-CT

Figure 11 shows the results of the IDEAL-CT test, which produces both an indirect tensile strength (ITS) and a tracking tolerance index (CT Index). The test results are shown along with test results from other HMA mix types, including mixes with different binder grades, mixes with different RAP percentages, and polymer-modified mixes.

The ITS for the HyRAP® mix is within the range of other HMA mixes. However, the CT Index is markedly lower than the other mixes except for the mix with PG 58-22 binder and 25% RAP, indicating that the deformation energy needed to cause fracture at 20°C is less and/or the post-peak load versus deformation curve is steeper (CT Index is calculated using both types of information).

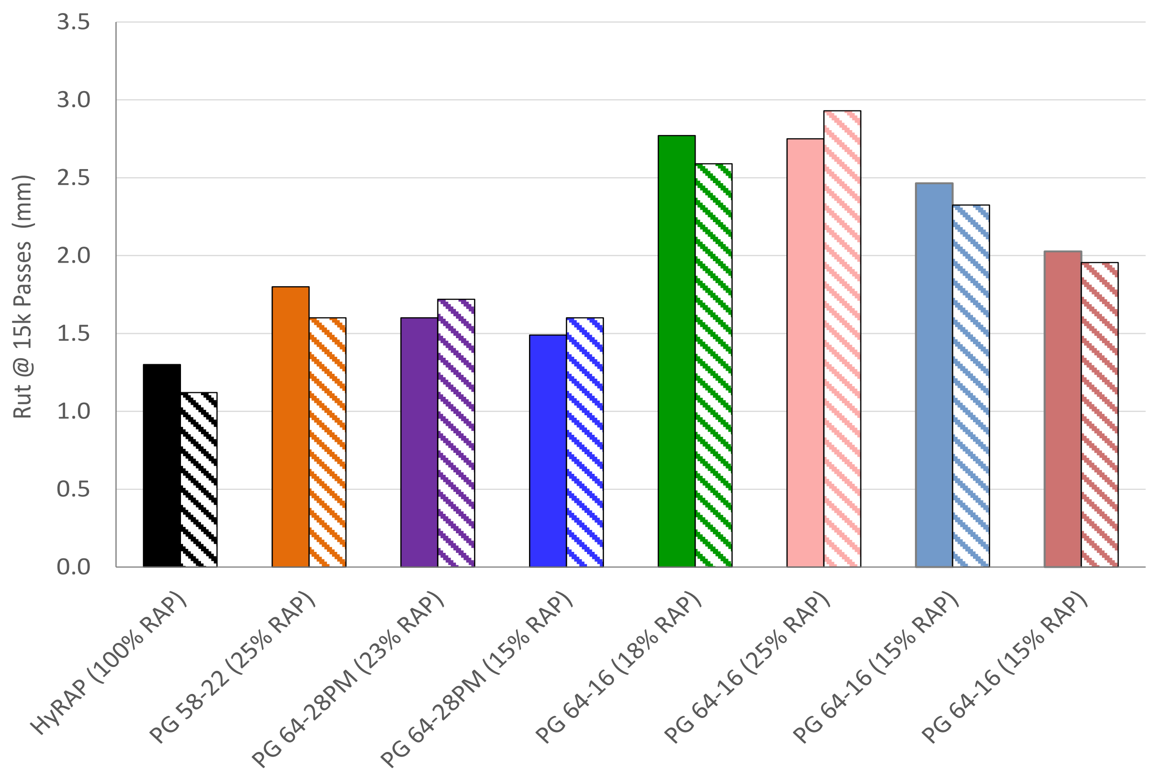


Note: The higher RAP mixes may contain recycling agent.

Figure 11: IDEAL-CT test for several mixes and HyRAP®.

Hamburg Wheel-Track Test

Figure 12 shows the results of the Hamburg Wheel-Track test, which produces data from two specimens at the same time. The test results are shown along with test results from other HMA mix types, including mixes with different binder grades, mixes with different RAP percentages, and polymer-modified mixes. These tests show the HyRAP® mix is highly resistant to rutting and water damage, exhibiting the lowest rut values of the mixes shown.



Note: The higher RAP mixes may contain recycling agent.

Figure 12: Hamburg Wheel-Track test for several mixes and HyRAP®.

Results: Comparison With Other HMA Mixes With 25% or Less RAP

Comparison of the following performance-related test results for the HyRAP material and those of HMAs with unmodified and polymer-modified binder and RAP contents at or below 25% indicates the following:

- Stiffness master curve:
  - Flexural: The HyRAP® material shows that at lower frequencies, below 0.1 Hz, the influence of stiffer binder is evident compared to unaged binders. At the higher frequencies, above 1.0 Hz, the drop in mix stiffness, compared to the recent PG 64-16 mixes, may come from the smaller aggregate size. The smaller aggregate size results in less aggregate interlock. The maximum size aggregate of the other mixes is 3/4 in. versus the ⅜ inch for the HyRAP®. The HyRAP® mix has stiffness that is closer to that of the statewide median PG 64-16 mix, representing mixes that have been sampled and tested over approximately the last six years.
  - Axial: The HyRAP® material lies in the middle of the data, at both the highest and lowest frequencies. In the range of 10 Hz to 1000 Hz, the HyRAP® is among those with the highest stiffness.
  - Differences between the stiffness reported by flexural beam loading and that of axial compression loading is common. Figure 1 represents flexural dynamic modulus in bending conducted on a 2 in. thick beam, whereas Figure 3 represents axial dynamic

modulus in compression conducted on a 6 in. thick cylindrical core. At low reduced frequency (equivalent to high temperature), the HyRAP® mix is much stiffer than the other HMAs in bending (flexural) but not in axial compression. This outcome can potentially be attributed to the smaller aggregate size (less aggregate interlock) of the HyRAP® mix compared to the other HMAs (at low reduced frequency the aggregate interlock considerably contributes to the mix stiffness in compression).

- Flexural four-point beam fatigue with controlled deformation loading:
  - The fatigue life versus strain tests show that the HyRAP mix performs better than other recent HMAs with unmodified binder and better than the statewide median mix. The HyRAP® fatigue life is comparable to the mixes with polymer-modified binder; in particular, it has higher fatigue life than the PG 64-28PM with 23% RAP and lower fatigue life that the PG 64-28PM with 15% RAP, both with no recycling agent.
- Repeated load triaxial permanent deformation:
  - Confined: According to the confined repeated load testing at 45°C and 55°C, the HyRAP® material performs comparably to the other mixes tested, which include polymer-modified mixes with 15% to 25% RAP. All the confined tests ran the entire duration with 20,000 repetitions. The final confined permanent deformation at 45°C of the HyRAP® was 1.2% on average and the range was 0.6% to 2.4%. The final confined permanent deformation at 55°C of the HyRAP® was 3.0% on average, and the range was 1.2% to 3.9%.
  - Unconfined: From the unconfined repeated load testing at 45°C and 55°C, the HyRAP® material performs better than the other mixes, which include 3/4 in. polymer-modified mixes with 15% to 25% RAP and one 1/2 in PG 58-22 mix. All the tests at 55°C reached 5% permanent deformation, but the HyRAP® material required the most repetitions, 10,000 repetitions. The 1/2 in. PG 58 mix required 9,000 repetitions, and the polymer-modified mixes required 2,200 or less repetitions. At 45°C, the polymer-modified mixes endured less than 12,000 repetitions before reaching 5% permanent deformation. The final permanent deformation of the HyRAP® at 45°C after 20,000 repetitions was 1.5% while the lowest value was 1.1% from the 1/2 in. PG 58 mix.
- Flow number:
  - Confined: According to the flow number from the confined repeated load testing at 45°C and 55°C, the HyRAP® material performs comparably to the 3/4 in. polymer-modified mixes with 15% to 25% RAP. The flow number changed only slightly for the HyRAP® and polymer-modified mixes between the tests conducted at 45°C and 55°C.
  - Unconfined: According to the flow number from the unconfined repeated load testing at 45°C and 55°C, the HyRAP® material performs comparably to the 1/2 in. PG 58-22 mix and better than the polymer-modified mixes with 15% to 25% RAP. For both the HyRAP® and 1/2 in. PG 58-22 mixes, the flow number from the unconfined repeated load testing at 45°C is greater than the flow number from the confined testing at 45°C.

- IDEAL-CT:
    - IDEAL-CT indirect tensile strength (ITS): The ITS for the HyRAP®, at 150 psi, falls in the middle of the range of values for PG 64 mixes, ranging between 88 psi and 200 psi. The PG 58 mix has the highest ITS at 253 psi. The ITS is driven by the intermediate-temperature PG grade stiffness. For the HyRAP® material, the stiffer binder may benefit the ITS value.
    - IDEAL-CT Index: The CT Index for the HyRAP® material, at 25, is lower than all the PG 64 mixes, including with and without RAP. Only the PG 58 mix, at 12, had a lower CT Index. The CT Index is dominated by the fracture energy and the post-peak slope, which are both related to the indirect tensile strength. The relatively low CT Index suggests that the mix may be more brittle in regard to fracture and crack propagation at intermediate temperatures.
- Hamburg Wheel-Track test:
    - The Hamburg Wheel-Track tests show that the HyRAP® mix is highly resistant to rutting and water damage, exhibiting the lowest rut values of the mixes shown, only 1.3 mm after 15,000 passes.
    - Polymer-modified mixes also had low rut values between 1.5 mm and 2.0 mm: 1.6 mm, 1.7 mm, and 1.8 mm. Unmodified PG 64 mixes had rut values that ranged between 2 mm and 3 mm.

Conclusions

The mechanical properties of the HyRAP® mix agree in some regards with the expectations for a mix with 100% RAP content. Compared to other recent HMAs, primarily from high RAP pilot projects, that have current standard RAP contents (at or below 25% RAP, by aggregate replacement), the HyRAP® mix stiffness is relatively high and its rutting resistance is very high. The stiffness is somewhat softer than the CalME Standard Materials Library statewide median PG 64 stiffness curve, which reflects mixes collected over approximately the last six years. Nonetheless, while the addition of RAP typically results in decreased fatigue cracking resistance at a given strain, as measured by the four-point bending fatigue test, the four-point bending fatigue resistance of the HyRAP® mix was above the resistance measured in other mixes with plain binder and standard RAP content and above that of the statewide median mix. In fact, its fatigue cracking performance was comparable to some mixes with polymer-modified binder. This is a very positive outcome, as meeting the fatigue cracking performance is the main challenge of the mixes with high RAP content.

The only parameter where the HyRAP® mix did not meet the values measured in other HMAs is the IDEAL-CT Index. The CT Index of the HyRAP® mix was below the values measured in other recent HMAs with plain binder and 25% or less RAP content. It should be mentioned that previous UCPRC studies do not show correlation between the CT Index and the fatigue resistance. CT Index after MTOA (not performed here) is thought to be more related to age-related cracking (block cracking) but the experiment to confirm that hypothesis is pending.

APPENDIX B Caltrans Office of Asphalt Pavement HyRAP Test Section Briefing Document, September 28, 2023

Barros, C. 2023. HyRAP Test Section Placement Briefing Document. California Department of Transportation, Office of Asphalt Pavement, Pavement Program. September 28, 2023.

HyRAP® Test Section Placement

HyRAP® is a proprietary hot mix asphalt produced at a plant in Colton, CA. The product consists of fractionated reclaimed asphalt pavement (RAP) with a recycling agent (RA) and dry polymer additive binder (website: HyRAP® Overview - HyRAP). The current Caltrans Section 39 specification does not allow the use of 100% reclaimed asphalt pavement nor recycling agents in hot mix asphalt. The current maximum allowed RAP content is 25% and RAP contents between 15% and 25% required a change in the virgin binder grade.

Starting on Wednesday, September 20, a HyRAP® test section of approximately 3,000 tons was placed on the mainline of eastbound I-40 near Newberry Springs (EA 08-1N1604) from PM 26.0-27.5.

Office of Asphalt Pavement staff visited the jobsite on September 21. Below are photos from the visit.

Figure 1 – HyRAP paving operation

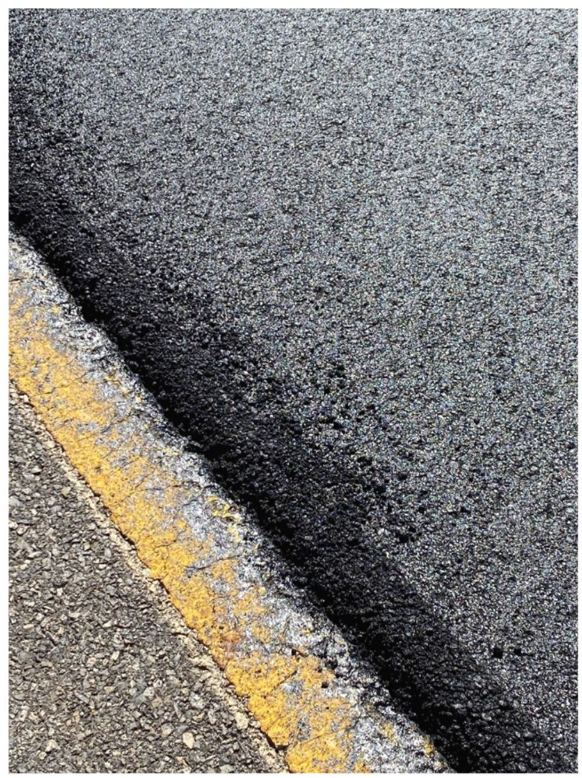


Figure 2 – Closeup of HyRAP mat

Construction Site Observations

During the visit, the resident engineer was also present at the paving operation. There was general concurrence that the paving operation was proceeding well and that the HyRAP® mat looked uniform. Both OAP staff and the resident engineer observed that the maximum aggregate size (5/16 in.) is less than our standard 3/4 in.) mix or the smallest maximum aggregate size that is typically used in thin overlays (1/2 in.). Since the Caltrans standard mix uses larger aggregates, the in-place field performance and testing data will be important in determining future use in a heavy truck traffic high-speed mainline application.

The resident engineer noted that the first day of paving did not go smoothly as there were some initial problems at the asphalt plant. Additionally, some of the material arrived below the temperature compaction range and had to be removed and replaced with material at the appropriate temperature the following day, which resulted in one additional day being added to the paving operation.

Testing Support by UC Davis – Pavement Research Center (UCPRC)

Staff from UCPRC were present at the HyRAP® plant in Colton, CA to obtain samples during all five days of paving and to collect preliminary data for a cradle-to-gate environmental life cycle assessment (LCA). Additionally, samples of the control RHMA-G and Type A polymer-modified mixes will be taken from the conventional paving portions of the I-40 project so the HyRAP® material can be comparatively evaluated for field performance and in terms of performance-related laboratory test properties and in mechanistic-empirical performance simulation with *CalME*. According to the project schedule the mainline paving for this project will occur in the fall of 2023 or spring of 2024 paving windows. UCPRC will write a report once the testing is completed to assist in further assessment of the material.

Initial Observations

- The cost of HyRAP® on this project is significantly higher than hot mix asphalt and rubberized hot mix asphalt.
- HyRAP® is a proprietary product that does not conform to our current Section 39 Standard Specification, nor nSSP specifications for other technologies under review with 40% to 100% RAP.
- The HyRAP® product is manufactured with the following raw components: Coarse 5/16 in. RAP aggregates, fine slurry sand, a recycling agent (RA-1, Viplex-50), and a dry polymer additive (medium density, oxidized low molecular weight, Epolene EE-2).
- The environmental impacts of these two additives (the RA and the dry polymer additive) have not been provided and are not currently available in the NAPA EPD tool.
- In conversations with Manhole Adjusting Inc., the market for this product will only be in Southern California where there is a general surplus of available millings and RAP aggregates rather, than statewide.

- The gradation in the HyRAP® mix is much finer than the standard Caltrans hot mix asphalt gradation. A finer mix (5/16 in. max) is more suitable for parking lots, ramp applications, low volume, or local agency roads instead of the Caltrans mainline.
- HyRAP® consists of 100% RAP aggregates, which amounts to ~98% of the total mixture. An additional ~2% of virgin, petroleum-based additives are added as a binder for the mix.
- The HyRAP® plant demonstrated a production rate of 150-250 tons/hour. A conventional asphalt plant may be rated up to 600 tons/hour and average 350 tons/hour.
- The HyRAP® drying drum heating process is similar to conventional warm and hot mix asphalt production, where a natural gas burner is used to, directly and indirectly, heat the aggregates. In conventional hot mix asphalt with 25% or less RAP aggregates, typical aggregate heating temperatures are 350F to 450F. In the traditional system, the virgin aggregates are superheated by direct flame for drying and elevated temperatures. The RAP aggregates are separately incorporated after the direct flame combustion zone in the drying drum or a pugmill, and the drying and heating are achieved through flame-free, heat transfer between the superheated virgin aggregates and RAP. See Appendix.
- In the HyRAP® plant, 40% of the aggregates are heated by direct natural gas flame to the elevated production temperature (650F+). During this heating process, the aged asphalt binder that coated the reclaimed aggregates is partially to fully combusted by the burner flame, producing volatile emissions. To mitigate these emissions, Manhole Adjusting Inc. uses a natural gas thermal oxidization scrubber. The amount of heat energy per ton of mix is unknown and the energy used for the thermal oxidizing scrubbers, which are rare for hot mix asphalt production, is unknown.
- Natural gas can contribute up to 40% of a hot mix asphalt production (A1 to A3) greenhouse gas emissions and the additional energy consumed in the HyRAP® manufacturing process by the thermal oxidizer should be considered in the holistic sustainability of the product. An environmental product declaration (EPD) was not available for HyRAP®.

Next Steps

The Office of Asphalt Pavement will look at the testing data and the report from UCPRC. It is important that any technology considered by Caltrans has equal or better performance than conventional, modified, or rubberized warm or hot mix asphalt, depending on its application.

The testing plan for UCPRC is:

- Mix testing and *CalME* simulations of HyRAP®
    - The UCPRC will be testing the mixture's fundamental performance-related engineering properties (flexural stiffness master curve and flexural fatigue, stiffness, permanent deformation), which will be input to *CalME* simulations.
    - The UCPRC will perform volumetric and performance-related QA/QC tests such as the IDEAL-CT and HWT tests to measure the crack and rut resistance index.

- Estimated LCA of HyRAP®
  - The UCPRC will use the job mix formula sheet and ask for additional inputs such as the production temperatures, transportation distances, and additive information (recycling agent and dry polymer) to estimate the product's cradle-to-gate (A1-A3) environmental impacts.
    - Manhole Adjusting Inc. is requested to measure the following metrics per ton with the plant being used for this mix per ISO 14025:2006 and ISO 21930:2017.
      - Quantity of natural gas (Therms)
      - Quantity of diesel or other fuels
      - Quantity of water
      - Electricity usage (kWh)
  - The UCPRC will use the existing pavement LCA database developed for *eLCAP* (Caltrans tool) in addition to the primary collected data to evaluate the environmental impacts (such as GWI, particulate matter, smog formation, etc.) of the 100% RAP mixture—named “HyRAP®.” This mix will be compared with the high RAP and RAS (recycled roofing shingles) pilot project mixes that Caltrans is currently evaluating.

Photos at Plant by UCPRC from First Day of Construction

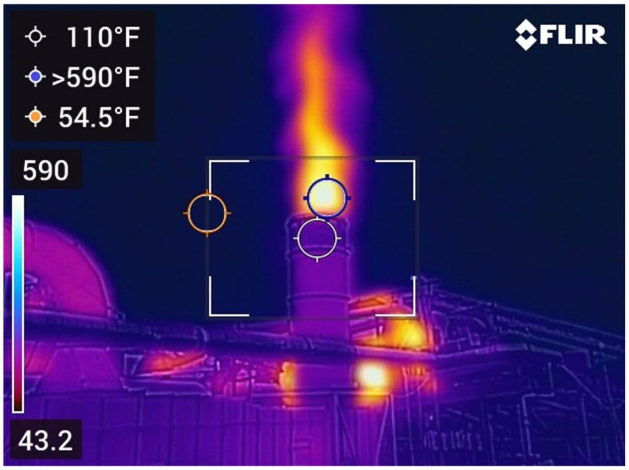


Figure 3 – Thermal oxidizing scrubber

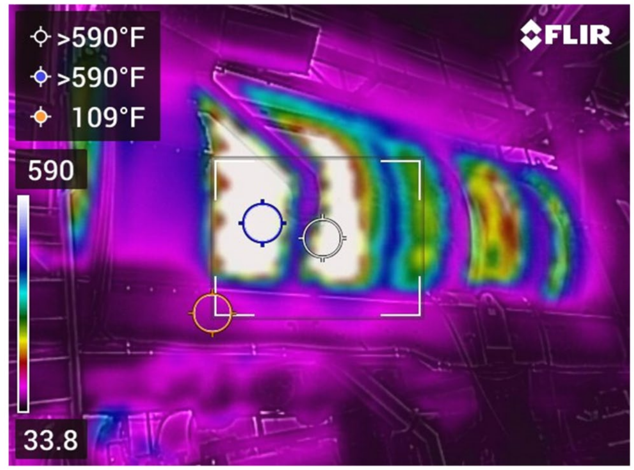


Figure 4 – Dryer drum

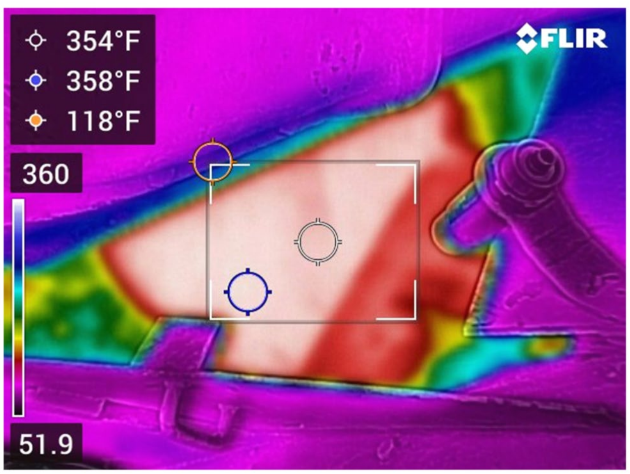


Figure 5 – HyRAP prior to loadout

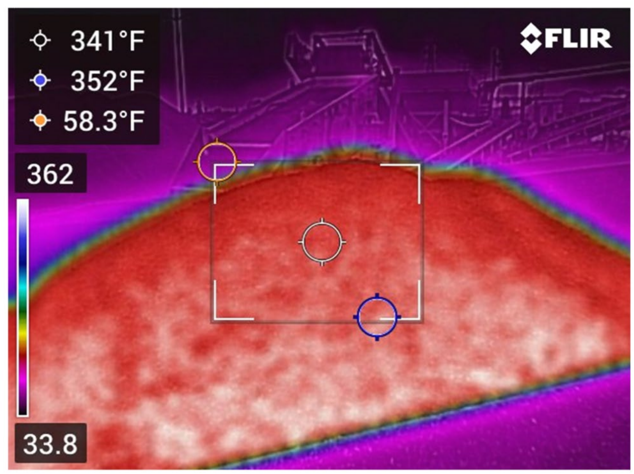


Figure 6 – HyRAP loaded into a truck

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