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Test Program for the FAA Accelerated Wheel Load Test Facility to Develop Specifications for Reclaimed Asphalt Materials in New Asphalt Concrete Used on Airfield Pavements

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16. Abstract

There is considerable interest in the use of reclaimed asphalt in new asphalt concrete mixes used on airfield pavements, primarily due to cost savings and environmental benefits associated with substituting some of the virgin binder with the binder from the reclaimed asphalt. This report describes a study to determine the properties of these materials and the practicality of using them in new asphalt concrete on airfields. In laboratory tests conducted during this study, it was clear that although adding reclaimed asphalt to new mixes was likely to increase the stiffness of the mix (which in most instances was likely to improve the mix's rutting resistance properties), its cracking resistance properties were likely to be reduced. Preliminary findings from this study indicated that the asphalt binder in recycled asphalt shingles may not effectively mobilize and blend with virgin asphalt and could reduce the actual effective binder content in the mix, which could in turn lead to early cracking and raveling. Test results on the properties of blended virgin and reclaimed asphalt binders can be influenced by the chemistry used to extract and recover the binders. Fine aggregate matrix mix testing is considered to be a potentially appropriate alternative procedure to evaluate the properties of blended asphalt binder in mixes containing reclaimed asphalt. Reclaimed asphalt should not be considered as a generic material with consistent properties, and some form of mix performance testing will need to be undertaken to assess the influence of the binder replacement on longer-term performance. The known benefits of adding polymer to asphalt binders may also be compromised if some of the virgin binder is replaced with reclaimed binder. This is particularly important in airfield pavements where polymer-modified binders are commonly used. The use of a softer virgin binder to compensate for the stiffening effect of high reclaimed asphalt pavement binder replacement rates (i.e., above 25%) appears to be justified.

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LIST OF SYMBOLS AND ACRONYMS

sin(δ)	Phase angle
E_a	Activation Energy
µm	Micrometer
µstrain	Microstrain
G*	Complex shear modulus
J	Joules
KPa	Kilopascal
mol	moles (SI measurement pertaining to amount of material)
MPa	Megapascal
N_f	Fatigue life
S	Creep stiffness
6A2	Griffin-Spalding County Airport
AASHTO	American Association of State Highway and Transportation Officials
AC	Asphalt concrete
AL	Alabama
AMPT	Asphalt mix performance tester
ANOVA	Analysis of variance
APA	Asphalt Pavement Analyzer
ASTM	American Society for Testing and Materials
BBR	Bending beam rheometer
BOS	Boston Logan International Airport
CA	California
Caltrans	California Department of Transportation
DMA	Dynamic mechanical analyzer
DP	Dust proportion
DSR	Dynamic shear rheometer
FAA	Federal Aviation Administration
FAM	Fine aggregate matrix
FHWA	Federal Highway Administration
HMA	Hot mix asphalt
HVS	Heavy Vehicle Simulator
LVE	Linear viscoelastic
NAPMRC	National Airport Pavement and Materials Research Center
NCHRP	National Cooperative Highway Research Program
NY	New York
PAV	Pressure aging vessel
PG	Performance Grading
PM	Polymer modified
RA	Rejuvenating agent
RAP	Reclaimed asphalt pavement
RAS	Recycled asphalt shingles
RTFO	Rolling thin-film oven
SARA	Saturates, aromatics, resins, and asphaltenes
SHRP	Strategic Highway Research Program

SI	International System of Units
Superpave	Superior Performing Asphalt Pavement
TCE	Trichloroethylene
TSR	Tensile strength retained/ratio
UCPRC	University of California Pavement Research Center
U.S.	United States
VFA	Voids filled with asphalt
VMA	Voids in mineral aggregate

EXECUTIVE SUMMARY

Because of potential cost and environmental benefits, road agencies and some airport authorities are increasingly allowing the use of reclaimed asphalt pavement (RAP) and recycled asphalt shingles (RAS) in new mixes placed on highways. However, current Federal Aviation Administration (FAA) specifications do not permit their use in asphalt pavement placed on aprons, taxiways, or runways at federally funded airports. This report describes a study performed by the University of California Pavement Research Center in conjunction with the FAA to investigate the potential implications of using reclaimed asphalt in new asphalt concrete used in airfield pavements. The study included a literature review; preliminary testing to develop alternative methods for assessing the properties of virgin binders blended with reclaimed asphalt; the development of mix designs for mixes containing varying reclaimed asphalt contents; and testing to determine the properties of blended binders, fine aggregate matrix (FAM) mixes, and full-graded mixes.

Preliminary laboratory testing showed that the asphalt binder extracted and recovered from RAS could not be tested due to its very high stiffness. The RAS binder was not sufficiently workable to mold samples for testing in a dynamic shear rheometer or bending beam rheometer. The effect of RAP in increasing the stiffness of blended binders was dependent primarily on the asphalt binder grade and, to a lesser extent, on the source of the asphalt binder. The FAM mixes containing RAS showed similar stiffnesses to the corresponding control mixes (i.e., containing no reclaimed materials), suggesting that the RAS binder did not effectively blend with the virgin binder at the temperatures and mixing durations used in this study. The influence of rejuvenating agent on reducing the blended binder and FAM mix stiffnesses was evident. Reasonable correlations were observed between the stiffness of asphalt binder and the stiffness of FAM mixes. The specific chemical solvent used in the extraction process also may have influenced the RAP binder properties. These factors warrant further investigation.

Key observations from the mix design phase of the study include (1) that the FAA P-401 grading and volumetric property specification requirements were difficult to meet when RAP binder replacement rates exceeded 25%, and (2) that the RAP source had a notable influence on the volumetric properties.

Adding RAP increased the stiffness of the mixes, which in most instances improved the rutting resistance properties of the mix but diminished the cracking resistance properties. The degree of change in rutting and cracking resistance was dependent on the RAP source, with test results for each source ranking consistently across the different tests (i.e., the RAP from the New York source consistently had the least effect on mix performance, while the RAP from the California and Alabama sources consistently had the largest effect). Given that the mixes had the same gradation and binder content and similar volumetric properties, the results confirm that RAP cannot be considered as a generic material with consistent properties.

Adding RAP to mixes with polymer-modified binders appears to have limited effect in terms of improving rutting performance but a potentially significant effect in terms of reducing fatigue life. This implies that the known benefits of adding polymer to asphalt binders may be compromised by replacing some of the virgin binder with binder from RAP.

The use of a softer binder to compensate for the stiffening effect of high RAP binder replacement rates (i.e., above 25 percent) appears to be justified.

Laboratory testing in this study has clearly shown that although adding reclaimed asphalt (from RAP) to new mixes is likely to increase the stiffness of the mix, which in most instances will potentially improve the rutting resistance properties of the mix, the cracking resistance properties are likely to be worse. Given the interest in using reclaimed asphalt from recycled asphalt pavement for partial binder replacement in new mixes placed on airfield pavements, the benefits and risks of the process should be further quantified in controlled full-scale field studies and associated laboratory testing. Accelerated loading tests with the FAA's Heavy Vehicle Simulator are proposed as part of this research.

Future research phases should also include assessments of

1. the effects of reclaimed asphalt on the low-temperature properties of the mix.
2. the influence of different rejuvenating agents on mix properties and on short-, medium-, and long-term performance.
3. the influence of warm mix additives and the implications of producing mixes containing RAP at warm mix temperatures.
4. comparisons of test results on chemically extracted RAP binders with those from tests on FAM mixes.

1. INTRODUCTION.

1.1 BACKGROUND.

In the United States (U.S.), approximately 85% of the airfield pavements tracked by the Federal Aviation Administration (FAA) and 84% of the highway pavements tracked by the Federal Highway Administration (FHWA) are paved with asphalt concrete [1]. To perform effectively under heavy repetitive wheel loads and severe environmental conditions, these pavements require regular maintenance and periodic rehabilitation—processes that require continuous supplies of aggregate and asphalt binder, both of which are becoming increasingly scarce and more expensive. Consequentially, there is growing interest in the use of reclaimed asphalt pavement (RAP) and reclaimed asphalt shingle (RAS) materials in the production of new asphalt mixes to reduce costs and preserve nonrenewable resources. This report describes a study performed by the University of California Pavement Research Center (UCPRC) in conjunction with the FAA to investigate the potential implications of using reclaimed asphalt in new asphalt concrete used in airfield pavements.

Considerable research has been conducted on the use of RAP in highway pavements, and a number of state departments of transportation now allow between 15% and 25% (either by weight of total mix or by binder replacement) RAP in new mixes. However, the current FAA Advisory Circular (AC) P-401 [2] does not permit the use of RAP in mixes used in surface layers on runways and taxiways (RAP may be used in base layers and in surface layers on service roads) and does not permit RAS in any applications. Consequently, there is limited published information on the use of RAP and RAS in airfield pavements, despite the growing interest in its use. This project was therefore initiated by the FAA to investigate the potential use of RAP and/or RAS in airfield pavements.

The use of RAP and/or RAS in new asphalt mixes offers several potential environmental benefits as well as production and construction cost savings. Using RAP and/or RAS reduces the amount of emissions during production, preserves nonrenewable natural resources, and reduces the amount of material dumped in landfills. Incorporating RAP and/or RAS into new asphalt mixes replaces a portion of the virgin aggregate and binder, thereby reducing the costs associated with acquiring raw materials. Studies and short-term field observations on highway pavements where RAP has been added to the mix indicate that, to date, these pavements perform equally to or better than conventional mixes with no reclaimed materials. However, considerable uncertainty still exists with respect to these pavements' longer-term performance, especially in regard to the effects of the aged RAP binder on cracking.

1.2 PROBLEM STATEMENTS.

The following concerns need to be addressed before the FAA can revise its current specifications to allow the use of RAP and/or RAS in new asphalt mixes that are used on airfield pavements (i.e., runways, taxiways, and aprons).

- The degree of blending between reclaimed and virgin binders and the factors that influence it are not fully understood. Consequently, accurate determination of the effective asphalt binder replacement from the reclaimed material is difficult.

- The short- and long-term effects of RAP and RAS binders on the performance grade of the composite binder (i.e., virgin binder blended with binder from RAP or RAS) are unknown and need to be addressed.

- The performance of asphalt mixtures containing RAP and/or RAS is dependent on the properties of their constitutive components, which change during service after short- and long-term aging and as the new and aged binders diffuse over time. A simplified procedure using current Superior Performing Asphalt Pavement (Superpave) equipment is needed to simulate field conditions in the laboratory and to characterize the rheological properties of the blended binder with respect to rutting and cracking performance at high, intermediate, and low temperatures, without the need to chemically extract the binder from the mix.

- Potential problems that arise due to the incompatibilities of different virgin binders and different RAP or RAS binders have not been investigated, either in terms of the properties of the blended binder, or in terms of short- and long-term performance of the mix.

- The relationship between the long-term field performance of high RAP or RAS content mixes under heavy airfield pavement traffic and laboratory mix design and performance tests is not understood.

- The effects of the use of different warm mix asphalt technologies and the effects of producing RAP and/or RAS mixes at a range of temperatures below conventional temperatures, specifically with respect to blending of the aged and virgin binder, is unknown.

- The effects of the use of rejuvenating agents (RAs) on the properties and degree of blending of aged and virgin binder have not been quantified.

1.3 OBJECTIVES.

The objective of this project is for the UCPRC to guide and assist the FAA in designing and performing accelerated loading tests with the FAA Heavy Vehicle Simulator (HVS); interpreting the test results, specifically with regard to the behavior/performance of asphalt concrete mixes containing RAP and/or RAS; and determining their suitability for use in airport pavements. In this project, the UCPRC also provided guidance and assistance with the design, performance, and interpretation of the results from associated laboratory tests that can be used to define a set of laboratory tests that can analyze future mix designs. The research will ultimately assist in the development of specifications for the use of RAP and RAS in asphalt mixes used on airport pavements. The ultimate research goal is to minimize the risk of designing and producing mixes containing RAP and/or RAS that have poor constructability and durability in airfield pavements. The following tasks were conducted to mitigate these risks and meet the objectives listed above.

- A literature review on research related to the topic, with special emphasis on the work of the FAA, FHWA, and recent National Cooperative Highway Research Program (NCHRP) projects.

- Development of a testing matrix followed by a preliminary evaluation of the rheological and engineering properties of a range of asphalt binders, asphalt mastics, and asphalt mixes carried out in conjunction with ongoing projects undertaken by the UCPRC for the California Department of Transportation (Caltrans).

- Development of an experimental plan for accelerated wheel load testing with the FAA HVS and associated laboratory testing matrix.

- Preparation of a summary report detailing the study.

The expected results from this study will:

- Provide recommendations for work plans that will accommodate an appropriate range of accelerated wheel load tests and associated laboratory tests, the results from which will provide a satisfactory level of information and confidence to make informed decisions about the use of RAP and/or RAS in asphalt mixes used on airfield pavements.

- Develop and validate a simple procedure to assess the contribution of RAP and/or RAS on the final composite binder properties, using standard Superpave laboratory testing equipment and without the need for binder extraction.

- Evaluate the sensitivity of individual RAP and RAS sources to a specific binder grade and multiple RAP and RAS sources to a specific binder grade.

- Evaluate the high-, intermediate- and low-temperature properties of binders containing RAP and/or RAS blends.

- Evaluation of performance-related properties of mixes containing RAP and/or RAS in terms of resistance to permanent deformation (or rutting), fatigue cracking, and moisture damage.

It should be noted that this project was carried out as part of a larger comprehensive research study on using higher quantities of RAP and RAS in new asphalt mixes in road pavements (funded by Caltrans and the National Center for Sustainable Transportation (NCST)).

1.4 MEASUREMENT UNITS.

Although the FAA generally uses U.S. standard measurement units, metric units, recognized as the International System of Units (SI), have always been used by the UCPRC in the design and layout of accelerated loading test tracks, and for laboratory, accelerated loading, field measurements, and data storage. The Superpave Performance Grading (PG) System is also a metric standard and uses metric units. In this report, both English and metric units (provided in parentheses after the English units) are provided in general discussion. In keeping with UCPRC convention, metric units are used in laboratory data analyses and reporting. A conversion table is provided below in table 1.

Table 1. Conversion Table

APPROXIMATE CONVERSIONS TO SI UNITS				
Symbol	When You Know	Multiply By	To Find	Symbol
LENGTH				
in.	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	Km
AREA				
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
VOLUME				
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
NOTE: volumes greater than 1000 L shall be shown in m^3				
MASS				
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or “metric ton”)	Mg (or “t”)
TEMPERATURE (exact degrees)				
°F	Fahrenheit	5 (F-32)/9	Celsius	°C
		or (F-32)/1.8		
ILLUMINATION				
fc	foot-candles	10.76	lux	lx
fl	foot-lamberts	3.426	candela/m^2	cd/m^2
FORCE and PRESSURE or STRESS				
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa
APPROXIMATE CONVERSIONS FROM SI UNITS				
LENGTH				
mm	millimeters	0.039	inches	in.
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
AREA				
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2

Table 1. Conversion Table (Continued)

APPROXIMATE CONVERSIONS TO SI UNITS				
Symbol	When You Know	Multiply By	To Find	Symbol
VOLUME				
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
MASS				
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or metric ton)	1.103	short tons (2000 lb)	T
TEMPERATURE (exact degrees)				
°C	Celsius	1.8C+32	Fahrenheit	°F
ILLUMINATION				
lx	lux	0.0929	foot-candles	fc
cd/m^2	$candela/m^2$	0.2919	foot-lamberts	fl
FORCE and PRESSURE or STRESS				
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

Appropriate rounding should be made to comply with Section 4 of ASTM E 380 [3] (Revised March 2003).

2. LITERATURE REVIEW.

The literature relevant to the use of RAP and/or RAS in airfield pavements is discussed in sections 2.1 through 2.8.

2.1 RECLAIMED ASPHALT MATERIALS.

RAP is defined as "removed and/or reprocessed pavement materials containing asphalt binder and aggregates" [4]. As noted, it is mostly obtained by milling off aged or distressed pavement surface layers and is usually crushed and processed at an asphalt plant to produce well-graded aggregates, many still coated with asphalt binder. This processed material can then be incorporated into new mixes at varying percentages as a replacement for virgin aggregates and binders. RAP is by far the most recyclable material according to a survey conducted in the early 1990s by the FHWA and the U.S. Environmental Protection Agency (EPA), which stated that of the more than 90 million tons of RAP produced every year in the U.S., at least 80% of it could be recycled into new pavement construction projects [4].

RAS is another potentially valuable source of asphalt binder for use in pavement construction since shingles contain between 20% and 35% asphalt binder by weight of the shingle (other constituents include fine aggregates (20% to 38%), fillers (8% to 40%), and fiberglass and cellulosic fibers (2% to 15%)) [5]. The majority of RAS produced in the U.S. (approximately 10 million tons per year) is obtained from used roof shingles (i.e., tear-offs), with about 1 million tons obtained from production rejects. During asphalt shingle production, the binder is heavily oxidized during an air-blowing process. Additional aging occurs over time as the shingles are exposed to the sun and precipitation and subjected to daily and seasonal temperature extremes.

Consequently, the binder is highly aged by the time it is used in new pavement mixes, and although the binder contents in the shingles are high, the properties of the binder are very different from those recovered from RAP, particularly for the more heavily aged tear-off shingles.

RAP materials have been used in small quantities in new highway mixes for many years. However, in the past this material has been considered only as a replacement for virgin aggregate (i.e., black rock) and not as a part replacement for virgin asphalt binder. Consequently, the potential binder replacement and properties of the aged RAP binder were not taken into account in new mix designs. This generally did not result in any problems as long as the percentage of RAP was kept below approximately 15%. Recent studies and field observations [4 and 6-9] have demonstrated that the aged binder in reclaimed materials can blend appreciably with virgin binder, allowing for binder replacement to be considered if RAP and RAS are added to the mix. However, the properties of the virgin binder will be altered by the aged RAP and RAS binders, which could in turn influence the performance of a mix in terms of rutting, cracking, raveling, and/or moisture sensitivity.

2.2 ASPHALT BINDER CHEMISTRY.

Asphalt binder is obtained from the distillation of crude oil and is a blend of complex hydrocarbons containing thousands of different molecules [9]. More than 90% of asphalt binder consists of carbon and hydrogen with the remainder consisting of heteroatoms (sulfur, hydrogen, and nitrogen) and a few metallic elements (e.g., vanadium, nickel, and iron). The polar molecules of asphalt binder can be categorized into four main fractions, namely saturates, aromatics, resins, and asphaltenes (i.e., SARA fractions). The chemical composition and proportions of the SARA fractions are dependent on the source of the crude oil and on the refining process used to produce the binder [9 and 10].

Asphaltenes have the highest polarity and molecular weight, followed by resins, aromatics, and saturates [9]. These four main compounds can be assembled in a colloidal structure to model the properties and performance of asphalt binder. Asphaltene forms the core, which is covered by resins that are bridged to aromatics and dispersed in saturates, as shown in figure 1 [10].

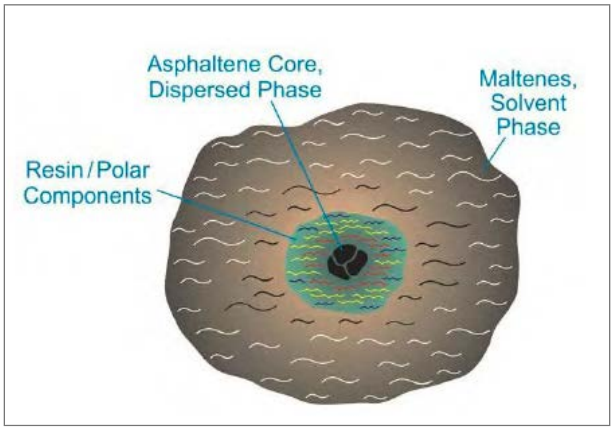


Figure 1. Asphalt Binder Colloidal Structure [9]

The stiffness and strength properties of asphalt binders are generally related to the asphaltenes and resins, while their viscous and plasticizing properties are generally related to the aromatics and saturates [11]. The rheological and desired performance properties of asphalt binders are therefore dependent on the properties of the individual fractions and their proportions, which change over the life of a pavement due to oxidation, volatilization, and other weathering mechanisms.

2.3 ASPHALT BINDER EXTRACTION FROM MIXES CONTAINING RECLAIMED ASPHALT.

A number of studies have been conducted to evaluate different solvents and methods for the extraction and recovery of asphalt binder from mixes [8 and 12-15]. Petersen et al. [16] evaluated different solvent types (trichloroethylene (TCE), toluene/ethanol, and a proprietary product known as *EnSolve*®) and three combinations of extraction and recovery methods (centrifuge-Abson, centrifuge-Rotavapor®, and Strategic Highway Research Program (SHRP) method-Rotavapor), and found there was no significant difference between solvent type or method when determining the asphalt binder content and rheological properties of the recovered binder. Another study using the reflux–Rotovapor recovery method also demonstrated that binder extracted using either TCE or *EnSolve* had relatively similar properties [14]. A study by Stroup-Gardiner et al. [17] found that using normal propyl bromide rather than TCE as a chemical solvent could reduce the amount of aging of the asphalt binder during extraction and recovery. The study also found that the binder content determined was not influenced by solvent type. However, incompatibilities between various types of propyl bromide and polymer-modified (PM) binders were recognized.

2.4 CHARACTERIZATION OF BLENDED VIRGIN AND RECLAIMED ASPHALT BINDERS.

The following methods for characterizing the properties of blended binders in mixes containing RAP and/or RAS were investigated in the literature and are discussed in sections 2.4.1 through 2.4.5.

2.4.1 Backcalculation of Blended Binder Properties.

Asphalt binder shear modulus can be predicted from the measured asphalt mix dynamic modulus using the Hirsch model [18 and 19]. The Hirsch model represents the stiffness of an asphalt mix as a function of the asphalt binder shear modulus and the mix volumetric properties, including voids in mineral aggregates (VMA) and voids filled with asphalt (VFA). This approach has been used to evaluate the level of blending between aged and reclaimed binders and to predict the performance grade of blended binders. Hajj et al. [12] predicted asphalt binder modulus from mix modulus using the modified Huet-Sayegh model. Zofka et al. [20] used creep stiffness (S) measurements at low temperatures, obtained from the inverse of creep compliance, with the Hirsch model to predict asphalt binder properties at low temperatures.

The Hirsch model can be used to predict the shear modulus, but it cannot be used to predict the phase angle. Both parameters are needed to understand the full viscoelastic behavior of asphalt binder. Phase angle is also a key parameter for determining the performance grade of asphalt binders. Typically, it is difficult, if not impossible; to do routine tests on asphalt mixes at the high and low performance grade temperature limits of the asphalt binder. Therefore, the measured modulus of the asphalt mix has to be shifted, using time-temperature superposition, to predict the asphalt binder moduli at the desired performance grade temperatures. Recent work by Bennert and Dongre [19] used analytical approaches developed by Bonaquist [18] and Rowe [21] to estimate the shear modulus and phase angle of asphalt binders from the properties of asphalt mixes. Mixes with 0%, 10%, and 25% RAP were assessed, and the results indicated that the measured shear modulus and phase angle of the recovered binders were comparable to the predicted values.

2.4.2 Testing Extracted and Recovered Binders.

To date, the majority of studies on the characterization and design of asphalt mixes containing RAP and/or RAS involve extraction and recovery of asphalt binder from the mix using chemical solvents [4, 6, 8, and 22-31]. The extraction and recovery method has long been criticized for being labor intensive, for its potential to alter binder chemistry and rheology, and for creating hazardous chemical disposal issues. Studies have also demonstrated that some of the aged binder may still remain on the aggregate after extraction, and thus the measured properties from the extracted and recovered binder may not completely represent the actual properties of the binder in the mix [6 and 16]. After extraction, asphalt binder can also stiffen due to potential reactions between the binder compounds and the solvent [32]. Typically, the extraction process also blends aged and virgin binders into a homogenous composite binder that may not be truly representative of the actual composite binder in the mix after production.

Three alternative methods to solvent extraction and recovery have been investigated for characterizing the properties of blended binders, namely producing and testing simulated RAP binders, testing the asphalt mortar of mixes containing both RAP and virgin binders, and testing only the fine aggregate matrix (FAM) of those mixes.

2.4.3 Testing Simulated RAP Binders.

RAP and RAS stockpiles are typically highly variable because they contain materials reclaimed from numerous different projects in different locations. The asphalt binders in these materials may have different binder grades, may have been originally refined from various crude oil sources, and may contain different modifiers including recycled tire rubber or polymers. Chemical extraction of these binders for use in research-based laboratory testing, with limited or no knowledge of their original grade, source, added modifiers, and properties, could lead to unexplained variability in the results.

Simulated RAP binders can be produced under controlled mixing and aging conditions and then blended with virgin binders as a means of providing some level of consistency to better understand key aspects of the testing and performance of composite binders [33 and 34]. Aging is carried out in single or multiple cycles in a pressure aging vessel (PAV). Changes in the properties of the binder during the course of the aging process are assessed by standard rheology tests with a dynamic shear rheometer (DSR) and bending beam rheometer (BBR).

2.4.4 Testing Asphalt Mortar.

Asphalt mortar tests are conducted using two mortar samples: one containing virgin binder plus fine RAP, passing the #50 (300 micrometer (µm)) and retained on the #100 (150 µm) sieves; and one containing virgin binder plus the fine aggregates obtained from processing RAP in an ignition oven (i.e., the RAP binder is burned off in the ignition oven). Conceptually, if the total binder contents and aggregate gradations are exactly the same for both samples, the differences between the rheological and performance properties of the two samples can be attributed to the RAP binder [35-37]. A number of studies have been conducted using this approach with DSR and BBR testing to assess the stiffness of the samples at high and low temperatures, respectively [35-37]. Ma et al. [35] developed a BBR testing procedure for asphalt mortar specimens made with single-size RAP material (100% passing the #50 sieve (300 µm) and retained on the #100 sieve (150 µm)). Based on the relationship between the asphalt binder and asphalt mortar properties, the low PG rating of the RAP binder could be estimated without the need for extraction and recovery of the binder. The asphalt mortar samples evaluated in that study had a maximum of 25% binder replacement from the RAP. Swierz et al. [36] continued this work and found that the BBR test on asphalt mortar was sufficiently sensitive to distinguish between different RAP sources and contents in blended binders up to 25% binder replacement. Asphalt mortar samples containing only RAS (up to 40% binder replacement) and a combination of RAP and RAS were also evaluated in the study. The work culminated in the development of a blending chart that estimates the PG of the blended binder in a mix based on the respective RAP and RAS percentages.

Hajj et al. [12] compared the performance grade properties of blended binder by using DSR and BBR testing of both recovered binder and asphalt mortar. The results were found to be dependent on the amount of RAP in the mix, and although the results of mixes with up to 50% RAP showed similar trends, the measured high, intermediate, and low PG temperatures of the mortar were lower than those measured on the extracted binder. The differences in results increased with increasing RAP content. The reasons for the differences were not forensically investigated, but were attributed in part to the influence of the extraction chemistry on full blending of the binders and possibly to the effect of the chemistry on additional hardening of the binders.

2.4.5 Testing FAM Mixes.

Testing FAM mixes as an alternative to testing asphalt mortar has also been investigated [13-15]. FAM mixes are homogenous blends of asphalt binder and fine aggregates (i.e., those passing the #4, #8, or #16 (4.75 mm, 2.36 mm, or 1.18 mm) sieves). The asphalt binder content and the gradation of the FAM must be representative of the binder content and gradation of the fine portion of a full-graded asphalt mix. Small FAM mix cylindrical or prismatic bars can be tested with a solid torsion bar fixture in a DSR, known as a dynamic mechanical analyzer (DMA). This testing approach is similar to that used for asphalt mortars in that two samples are tested, one containing virgin binder plus RAP and/or RAS, and the second containing virgin binder plus the aggregates obtained from processing RAP or RAS in an ignition oven. Any differences in the results can then be attributed to the RAP/RAS component of the FAM mix. Kanaan [37] evaluated the viscoelastic, strength, and fatigue-cracking properties of FAM mix specimens with different quantities of RAS. The results showed that FAM mix testing detected differences in the properties evaluated among the various mixes, and specifically that the stiffness and strength of the asphalt mixes increased with increasing RAS content. Under strain-control mode, the fatigue life of the FAM mix specimens decreased with increasing RAS content, while under stress-control mode, an opposite trend was observed.

2.5 QUANTIFYING DIFFUSION AND BLENDING BETWEEN VIRGIN AND RECLAIMED BINDERS.

A number of studies were conducted recently to better understand the diffusion and blending of aged and virgin binders.

McDaniel et al. [8] investigated whether RAP acts like a black rock, or if there is some level of blending occurring between the age-hardened binder in RAP and virgin binder. Asphalt mixes were prepared with 10% and 30% RAP content using RAP materials collected from three different locations (Arizona, Connecticut, and Florida) and two grades of virgin binder. The mixes were fabricated to simulate actual asphalt plant conditions, zero binder blending, and full-blending conditions. Statistical differences between the properties of the asphalt mixes fabricated at three blending conditions were only measured on the mix with 30% RAP. Based on these results, the investigators concluded that RAP should therefore not be considered as black rock and that significant blending does occur.

Bonaquist [18] evaluated the level of blending between reclaimed and virgin binder in mixes containing RAP and RAS. The shear modulus of the blended binder was predicted with the Hirsch model and then compared with the measured shear modulus of the recovered binder from the mixes. The results indicated that full blending occurred in an asphalt mix containing 35% RAP, but that only limited blending occurred between the virgin and RAS binder in a mix containing 5% RAS. The approach proposed by Bonaquist was used in other studies [21, 26, 27, and 38] to evaluate the level of blending between RAP and virgin binder in asphalt mixes containing RAP. Results from these studies indicated that complete blending occurred in most cases. Mogawer et al. [39] also evaluated the degree of blending between the aged and virgin binders by comparing the ratio of the measured mix dynamic modulus to the recovered binder modulus for the control and corresponding RAP mix. The study concluded that sufficient blending of the RAP and the virgin binders in the RAP mix were achieved.

Hung et al. [40] used extraction and recovery to investigate how aged RAP binder blended with virgin binder under normal mixing conditions. One source of RAP was mixed with virgin binder at different percentages. The results indicated that only a small percentage of the RAP blended with the virgin binder, with the remaining RAP binder forming a stiff coating around the RAP aggregate, thereby creating a composite black rock [40]. The investigators recommended further analysis to investigate a larger range of RAP sources and virgin binders under various mix conditions.

Yar et al. [34] evaluated and quantified the effects of time and temperature on diffusion rate and the ultimate blending of the aged and virgin binders through an experimental-based approach validated with analytical modeling of diffusion. The changes in the stiffness of a composite two-layer asphalt binder specimen (also known as a wafer specimen) were monitored in DSR tests. The wafer specimen was composed of two 1-mm-thick asphalt disks made with simulated RAP binder and virgin binder, respectively. This study revealed that the diffusion coefficient between two binders in contact can be estimated from DSR test results and that the diffusion mechanism can be modeled (i.e., Fick's second law of diffusion). The diffusion rate was found to increase with temperature, but the rate was influenced by binder chemistry. Only limited diffusion and blending occurred at temperatures below 100°C. Consequently, production temperatures and times would need to be appropriately selected at asphalt plants to ensure sufficient blending between the virgin binder and aged RAP binder. Kriz et al. [41] completed a similar study by testing two-layer binder specimens in a DSR and using the results to model diffusion. The results indicated that complete binder blending occurred within minutes after mixing in both hot mix and warm mix asphalt samples. Further simulations with the results indicated that binder film thickness in mixes could have a significant impact on the degree of blending and that further research was necessary to understand this.

A recent UCPRC study investigated diffusion and aging mechanisms during blending between new and age-hardened asphalt binders in hot and warm mix asphalt during production and paving [42]. The study investigated assumptions that blending between age-hardened and new binders could potentially be improved with the aid of warm mix additives. Two-layer asphalt binder samples composed of one layer of virgin and one layer of simulated RAP binder were tested in a DSR after conditioning at hot mix and warm mix production, storage, placement, and compaction temperatures. Complete blending between aged and new binders was achieved at hot mix temperatures, but only partial blending was achieved at warm mix temperatures.

Zhou et al. [5 and 43] characterized tear-off asphalt shingles and manufacturer waste asphalt shingles from various sources and the blending of extracted binders with virgin binder and RAP binder using DSR and BBR tests. The results showed that the binder extracted from tear-off shingles had distinguishably different properties than the binder from manufacturer waste shingles, and the study concluded that RAS source needed to be considered in any mix design if use of RAS was planned. Changes in the high and low performance-related temperatures were generally linear up to 30% RAS content and nonlinear thereafter. Zhao et al. [44] and Zhou et al. [45] also quantified the rate at which reclaimed binder was mobilized to blend with virgin binder in mixes containing up to 80% RAP and up to 10% RAS. This was achieved by measuring the large molecular size percentage using gel permeation chromatography. The results showed that the asphalt binder mobilization rate decreased with increasing RAP content. The rate of binder mobilization was 100% for 10 to 20% RAP content, 73% for 30% RAP content, and 24% for 80% RAP content. In the mixes containing RAS, the maximum mobilization rate peaked at up to 5% RAS content and then decreased with increasing RAS content thereafter.

Falchetto et al. [46] compared backcalculated asphalt binder creep stiffnesses S values, determined from the properties of asphalt mixes containing RAP or RAS, to the measured creep stiffness values of the binder chemically extracted from those mixes. The measured creep stiffness values were higher than the backcalculated stiffness values. The difference was attributed to forced blending between the virgin and age-hardened RAP or RAS binders during the solvent extraction process.

Arnold et al. [47] noted that small amounts of RAS can increase asphalt mix embrittlement temperatures resulting in poorer mix performance at low temperatures. The study found that incorporation of 2.5% RAS by total weight of mix resulted in an increase in the embrittlement temperature of about 10°C, which was attributed to partial blending between the RAS binder and the virgin binder. Mix performance improved when production temperatures were increased. The higher production temperatures would have increased the rate of blending between the RAS binder and the virgin binder, resulting in some reduction in the embrittlement temperature.

2.6 SELECTION OF VIRGIN BINDER FOR RAP/RAS MIXES.

Current practice (AASHTO M 323 [48]) specifies using one-grade softer virgin binder than specified for the pavement location when 15% to 25% RAP is used in the mix. This is intended to compensate for the stiffening effect of the aged reclaimed binder. For higher amounts of RAP, the PG of the virgin binder must be determined from a blending chart, which requires testing of extracted and recovered reclaimed binder [4 and 8].

Mogawer et al. [22] studied the performance data from a plant-produced asphalt mix with no RAP and two asphalt mixes with 10% and 30% RAP. A PG 64-28 virgin binder was used in the control mix and in the mix with 10% RAP. A softer PG 58-28 was used for the mix with 30% RAP to compensate for the stiffer, aged RAP binder. The mix with 30% RAP did not pass the Hamburg Wheel-Track Test requirement for moisture susceptibility. This observation raised a concern that the selection of virgin binder grade should be based on the desired performance of the mix rather than only on a change in binder grade according to the proposed RAP content.

Abbas et al. [25] evaluated the effect of different quantities of RAS (5%, 7%, and 10%) on the physical and chemical properties of a PG 58-28 unmodified binder. Incorporation of RAS binder improved the rutting resistance properties of the asphalt binder, but increased the thermal cracking susceptibility. RAS binder did not appear to influence binder fatigue performance. This finding differed from other studies in which fatigue life of mixes was reduced by adding RAS. Chemical analyses of original, rolling thin-film oven (RTFO)-aged, and PAV-aged blended binders conducted by Abbas et al. found that the addition of RAS binder can increase the asphalt binder aging potential in the long-term.

Swiertz et al. [36] evaluated the influence of RAP and RAS binder on the low-temperature grade of blended binder using a BBR test on asphalt mortar specimens (no solvent extraction and recovery of aged binder). The study found that the influence of the RAP and the influence of the RAS on the virgin binder properties can be combined into a single factor. Accordingly, a chart was developed to estimate the virgin binder low PG required in mixes containing both RAP and RAS.

Kriz et al. [41] found that the current AASHTO M 323 [48] specification recommendation for using a one-grade softer asphalt binder in mixes with 15% to 25% RAP may not be justified, as test results demonstrated that a binder grade change was not necessary for up to 25% RAP binder replacement for most of the blends investigated.

Sabouri et al. [49] investigated how incorporation of RAP changes the binder grade. Testing was performed on both PG 64-28 and PG 58-28 binders and at 0%, 20%, and 40% RAP binder replacement. Results showed that mixes with the softer binder (PG 58-28) had better fatigue resistance properties. The study suggested the use of a soft binder while maintaining the optimum binder content or increasing the asphalt layer thickness when incorporating high quantities of RAP in mixes.

2.7 PROPERTIES OF ASPHALT MIXES CONTAINING RECLAIMED ASPHALT.

The effects of RAP and RAS on the volumetric properties of new asphalt mix, blending between new and aged binders in asphalt mixes containing RAP and/or RAS, and the influence of RAP and RAS on mix performance are reviewed below in sections 2.7.1 and 2.7.2.

2.7.1 Effect of Reclaimed Asphalt on Mix Volumetric Properties.

Most of the literature reviewed recommended that the same volumetric criteria specified for conventional asphalt mixes, including VMA, VFA, and dust proportion (DP), should be followed for asphalt mixes containing RAP and/or RAS. However, studies have shown that mix volumetric properties can be altered by the addition of RAP and RAS.

Swamy et al. [50] found negligible changes in volumetric properties when up to 10% RAP was used in a mix, and that the effects of higher percentages of RAP (20% and 30%) on volumetric properties were inconsistent. Daniel and Lachance [51] observed increases in VMA and VFA values with increasing RAP up to 40%. The preheating of RAP materials was also found to influence volumetric properties. Studies in Minnesota [52] found that the volumetric properties of conventional mixes and mixes with 15%, 25%, and 30% RAP, mixes with 3% and 5% RAS, and mixes with combinations of RAP and RAS (10/5%, 15/5%, 25/5%, 15/3%, 25/3%) were similar and that all mixes satisfied the Minnesota Department of Transportation volumetric requirements.

Aurangzeb et al. [53] investigated the use of high percentages of RAP (30%, 40%, and 50%) in asphalt mixes to obtain desired volumetric and performance properties. The results showed that all of the mixes with RAP performed equally or better than the mixes prepared using virgin aggregate. Given that consistent and similar volumetric properties were achieved for all mixes, the researchers concluded that the performance properties of the tested mixes were a function of only their mechanical properties. Appropriate processing and fractioning of the RAP was recommended for high RAP mixes to ensure consistent quality.

Rubino [54] found that addition of 5% RAS by total weight of mix reduced the VMA slightly but marginally increased the VFA. The optimum virgin binder content reduced with the addition of RAS, but not by the amount of theoretically available RAS binder. Rubino concluded that it was possible to design high-quality asphalt mixes with high quantities of RAP and small quantities of RAS that met the designed volumetric properties.

Kvasnak et al. [55] investigated the best method of determining the bulk specific gravity of RAP aggregates, which is used for determining the VMA. Asphalt mixes with known aggregate properties were produced and aged, after which the aggregates were recovered for further analysis. The maximum theoretical specific gravity was determined for each mix and then used to estimate the bulk specific gravity of the aggregates. The study concluded that the bulk specific gravity of aggregates can be successfully estimated from the measured maximum theoretical specific gravity of the mix and then used to determine the VMA of the mix when a regional absorption value is known.

A joint study conducted by the National Center for Asphalt Technology and the University of Nevada-Reno [55 and 56] investigated three methods for characterizing RAP for binder content and aggregate properties, namely the ignition method, centrifuge extraction, and reflux extraction. Laboratory-produced RAP materials were prepared with aggregates from four different sources. TCE was used as the solvent in both extraction methods. The properties of the virgin aggregates were compared to those of the recovered aggregates, with the results indicating that the asphalt binder content was best determined using the ignition oven method and that centrifuge extraction had the least effect on the gradation of the material recovered [55]. The combined bulk specific gravity of the aggregate recovered using the ignition method was the closest to the true values, except for the limestone aggregates [56]. The study found that solvent extraction was the most appropriate method for determining the gradation and specific gravity of the coarse and fine aggregates in mixes with RAP contents higher than 25%. However, the study concluded that any method used to recover RAP will cause some error in the determination of bulk specific gravity, especially if the degree of asphalt absorption is not known. Mixes containing up to 50% RAP had variances in VMA of up to ±0.5%.

Mangiafico et al. [57] conducted a statistical analysis on how different variables influence the volumetric properties of mixes containing RAP. The selected variables included aggregate properties, gradation, filler properties, binder content, and binder properties. All mix design parameters were found to be statistically significant with respect to the complex modulus of a mix. When assessing fatigue resistance, the aggregate properties, aggregate gradation, and interaction of the binder content and binder properties were found to be the most significant.

Stroup-Gardiner and Wagner [58] investigated the used of RAP in Superpave designed mixes. Splitting the RAP stockpile into fine and course fractions increased the potential for maximizing RAP binder replacement to meet Superpave aggregate gradation requirements.

2.7.2 Effect of Reclaimed Asphalt on Mix Performance Properties.

The Virginia Department of Transportation evaluated the effect of higher RAP percentages (20% to 30%) on performance properties and the relative cost for specific paving projects in 2007 [59]. The predicted performance of the control and high RAP mixes were found to be equal based on the results of rutting, fatigue, and moisture susceptibility testing. The addition of RAP did increase the high-temperature performance grade of the virgin binder by one or two grades, and in some cases, it increased the low-temperature grade by one (from -22°C to -16°C). No construction problems were observed with the high RAP mixes and adding RAP to the mix did not increase production or construction costs.

The constructability and accelerated field performance of RAP mixes were evaluated at the NCAT test track [60 and 61]. Mixes with 20% RAP content were more easily compacted than mixes with 45% RAP content. Mixes with 45% RAP and a softer binder (PG 58-28) required less compaction effort than the same mix with stiffer binder (PG 76-22 PM). A warm mix additive did not improve compaction. All the mixes evaluated showed acceptable rutting performance, but some low-severity longitudinal cracking, attributed to reflection cracks and/or construction defects was observed. Laboratory rut testing using an Asphalt Pavement Analyzer (APA) on specimens sampled from the track showed that the use of RAP reduced the rutting potential. Specimens from the section with 45% RAP content and softer binder (PG 58-22) had a lower dynamic modulus than the mix with a stiffer binder, which could adversely affect mix durability at high-strain conditions. The mixes with 45% RAP had shorter fatigue life than the mixes with 20% RAP and the control mixes with no RAP. However, in these tests fatigue life did not appear to be influenced by the stiffness of the virgin binder.

Shah et al. [62] performed complex dynamic modulus and complex shear modulus tests on virgin binder and binder recovered from mixes with 15%, 25%, and 40% RAP. The results showed no statistical difference between the control binder and binder from the mixes with 15% and 25% RAP. Some differences were observed in the dynamic modulus of the control binder and the binder extracted from the mix with 40% RAP. Stiffening of the mix with increasing RAP content did not occur as expected.

Li et al. [52] evaluated the stiffness and low-temperature fracture properties of asphalt mixes containing 0%, 20%, and 40% RAP from two sources and with two grades of base binder (PG 58-28 and PG 58-34). The results indicated that the mix stiffness (dynamic modulus) increased with increasing RAP content. Using a softer virgin binder reduced the stiffness of the control and RAP mixes. The fracture energy of the mixes at low temperatures decreased with increasing RAP content. The source of the RAP did not influence performance at low temperatures, but was found to be significant in influencing stiffness at higher temperatures.

Mogawer et al. [39] evaluated how the stiffness and performance of plant-produced RAP are affected by plant type and production parameters. Tests included dynamic modulus, moisture susceptibility, Hamburg Wheel-Track, cracking, and workability. The results indicated that mixes with up to 30% RAP showed moisture damage susceptibility and rutting and low-temperature cracking performance that were similar to the control mixes. Workability was found to be a potential construction issue because mix workability decreased with an increase in RAP content. The results also showed that selection of the virgin binder grade for mixes with high RAP content should be based on the desired performance, given that notable differences were observed in performance between similar mixes with different virgin binder PG grades. In another study, Mogawer et al. [22] investigated the performance characteristics of plant-produced mixes with up to 40% RAP. The results showed improved rutting and moisture damage resistance with increasing RAP content, but reduced cracking resistance, compared to the control with no RAP.

Anderson et al. [63] compared the long-term field performance of mixes with no RAP and mixes containing up to 25% RAP. Based on the available performance data, the study found that pavement sections with RAP had better rutting resistance than the control sections, but exhibited a lower ride quality and more cracking.

Kim et al. [64] investigated the effects of using PM binder in mixes with 0%, 15%, 25%, and 35% RAP on laboratory rutting (APA) and cracking (indirect tensile strength) tests. No significant differences were noticed in the results between the different mixes.

Tarbox and Daniel [65 and 66] investigated the effect of long-term aging on asphalt mixes containing RAP. Mixes with 0%, 20%, 30%, and 40% RAP were compacted and then aged in an oven for 2, 4, or 8 days at 185°F (85°C) before testing. A comparison of dynamic modulus test results showed that the susceptibility of mixes to aging-related stiffness increases reduced with increasing RAP content. Similar results were obtained in a similar study completed by Singh et al. [67].

Watson et al. [68] monitored the performance of pavement test sections in Georgia constructed with mixes containing 5% asphalt shingles (manufacturer waste). Similar performance to the control sections with no RAS was observed after 2.5 years of trafficking.

Ozer et al. [69] evaluated laboratory performance-related properties of mixes containing up to 7.5% RAS by total weight of the mix. Permanent deformation resistance improved with incorporation of RAS, but fatigue resistance was reduced. No significant difference in the fracture properties of the mixes containing different RAS contents was observed when tested under monotonic loading at low temperatures. Improvements in fatigue resistance and fracture properties of high RAS content mixes were observed when a softer grade virgin binder (PG 46-34 instead of PG 58-28) was used. Similar results were obtained in a similar study by Cooper et al. [70].

Research by Williams et al. [71] studied the influence of adding 5% RAS to mixes containing between 25% and 50% fractionated RAP. Laboratory- and plant-produced samples from a field demonstration project on the Illinois Tollway were compacted in a laboratory and then evaluated in terms of dynamic modulus, flow number, tensile strength ratio (TSR), beam fatigue, and disc-shaped compact tension tests. Stiffening of the mix caused by incorporation of RAS was more noticeable at lower RAP contents. Mixes with RAS also had higher rutting resistance than the mixes with no RAS. No moisture damage problems were observed in any of the mixes. However, cracking resistance decreased in mixes with increasing RAS content and in mixes with both RAP and RAS when the reclaimed material content exceeded 40%. Mixes with 35% RAP and 5% RAS and a softer PG 58-22 virgin binder had acceptable cracking performance. In another related study, Williams et al. [72] compared the performance of mixes with and without RAS by testing cores sampled from highway test sections. Test results, together with pavement condition survey data indicated that mixes containing up to 5% RAS had similar performance to control sections with no RAS in terms of rutting, fatigue cracking, and low-temperature cracking resistance.

2.8 AIRFIELD PAVEMENT SUPERPAVE MIX DESIGNS INCORPORATING RAP.

Both Marshall and Superpave methods are described in the FAA P-401 [2] for designing asphalt mixes for airport pavements. The Marshall method has been the primary mix design method in the past; however, as most state and local departments of transportation have moved to the Superpave design method, there has been increasing interest in moving to Superpave design for airfield pavements as well.

Cooley et al. [73] compared typical Marshall and Superpave asphalt mix design methods for airfield asphalt mixes. The study concluded that the three mix design specifications have many similarities, but the Superpave method requires appropriate volumetric criteria for selecting appropriate aggregate gradations, aggregate shape, and optimum asphalt binder contents for specific airfield pavement applications. Cooley et al. [74] also developed specification requirements for using the Superpave gyratory compactor for airfield mixes with properties comparable to the Marshall method.

Hajj et al. [75] reviewed the literature on the use of RAP in asphalt for airfield pavements. The review concluded that the use of RAP would improve the rutting resistance of mixes. Environmental distresses, such as block cracking and raveling, were the primary type of distress reported and although they can affect functional performance, they do not directly influence load bearing capacity under heavy aircraft loading. The review identified Griffin-Spalding County Airport (6A2) near Griffin, Georgia and Boston Logan International Airport (BOS) in Boston, Massachusetts as both using RAP in the surface courses of runways and taxiways. In the 6A2 project, a Superpave mix containing 17% RAP in the surface layer of the runway and taxiway pavements was placed in 1999. After 8 years in service, the surfaces were reportedly still in good condition with no visible rutting, but some moderate raveling, moderate severity transverse cracking, and some cracks at longitudinal construction joints. In the BOS project, a latex-modified PG 64-22 mix containing 17% RAP was placed in a section of taxiway in 2001. The pavement was assessed to be in excellent condition after 1 year, with no visible rutting. No concerns were raised about the constructability of the RAP mixes at either project. The review also reported on LEDFAA1.3 airfield pavement design software analyses of pavement designs with asphalt mixes containing zero and 20% RAP mixes. The results indicated that addition of 20% RAP to a mix increased the life of a pavement under a small- and large-hub airfields, and general aviation traffic mix.

A study by Guercio and McCarthy [76] showed that warm mix asphalt containing RAP passed the required volumetric properties specified in FAA P-401 [2]. However, performance test results showed that the control hot mix without RAP performed better that the warm mix with RAP in terms of rutting and fatigue cracking.

2.9 LITERATURE REVIEW SUMMARY.

The literature review provided a number of key points relevant to this UCPRC study.

- The asphalt binder in RAP and RAS can blend appreciably with virgin binder in new mixes. The level of blending between the aged and new binders depends on the chemical composition of the individual binders. To ensure the optimal performance of mixes containing high quantities of reclaimed asphalt, the compatibility of reclaimed and virgin asphalt binders from different sources and with different performance grades must be well understood.

- Appropriate methods for extracting aged binder from reclaimed asphalt materials are still being developed and are focusing on the effects of extraction solvents on the properties of recovered binders. The solvents currently being used are considered to be aggressive enough to fully blend the binders extracted from new mixes containing aged and virgin binders, and thereby provide potentially misleading binder replacement values and nonrepresentative PG ratings of the blended binders.

- Alternative methods to the use of extraction and recovery are being explored to better characterize the performance properties of virgin binders blended with the aged binders in RAP and RAS. Tests on mortar and FAM mixes warrant further investigation.

- Adding RAP to a new asphalt mix can alter the volumetrics and performance of the mix. However, volumetric requirements can still be met with relatively high RAP contents. Compared to equivalent mixes without RAP, rutting performance was generally improved by the addition of RAP, but cracking performance was generally lower. Conflicting results with regard to laboratory test performance were reported.

- Given that the use of RAP as binder replacement and not just as aggregate replacement is relatively new, there is limited knowledge on the long-term field performance of mixes containing high RAP contents (i.e., above 25% binder replacement), specifically with regard to the rate of binder aging and its effect on stiffness and susceptibility to cracking. Conventional laboratory aging procedures have not been verified for high RAP mixes.

- Only limited published research on the use of RAP and/or RAS in airfield pavement mixes was located.

3. EXPERIMENT DESIGN.

This study focused on evaluating the effect of virgin binder source and PG on the performance properties of blended binder in mixes containing a high proportion of reclaimed asphalt (i.e., ≥25%) obtained from RAP and/or RAS. The work was undertaken in two phases:

- Phase 1 assessed different test methods to characterize blended binder in mixes containing relatively high quantities of RAP and RAS without the need for extracting and recovering asphalt binders from asphalt mixes. Phase 1 was subdivided as follows:
  - Phase 1a: Preliminary asphalt binder testing to assess the variability of three California (CA) RAP sources and to compare the properties of field-sampled materials with those of a simulated RAP prepared in the laboratory. The rheological properties of the virgin binders, recovered RAP binder, recovered RAS binder, and the blended binders (virgin binder and RAP and/or RAS binder) at various replacement rates were determined.
  - Phase 1b: Preliminary testing on mortar samples to determine the rheological properties of asphalt mastics made with virgin binders, virgin fine aggregates, and various quantities of fine RAP. Mortar samples were prepared on a subset of the materials tested in Phase 1a.
  - Phase 1c: Preliminary testing to determine the rheological properties of FAM mix specimens containing different quantities RAP and RAS (by binder replacement rate) and various virgin binders.

- Phase 2 focused on evaluating the performance-related properties of asphalt binders, FAM mixes, and asphalt mixes containing high quantities of RAP (25% and 40% by binder replacement) for use in airfield pavements. Phase 2 was subdivided as follows:
  - Phase 2a: Mix design, carried out according to the FAA mix design specification [2].
  - Phase 2b: Blended binder rheology characterization using conventional testing (DSR on extracted binders) and the FAM mix testing procedures developed in Phase 1.
  - Phase 2c: Full-graded mix performance testing including frequency sweep tests, flexural beam frequency sweep tests, repeated load triaxial (flow number), APA, Hamburg Wheel-Track tests, and flexural beam fatigue tests.

Although the effect of RAP on the low-temperature cracking performance of mixes, the effect of producing mixes containing RAP with warm mix additives at warm mix temperatures (i.e., potentially less blending between virgin and RAP binders at lower production temperatures), and the potential role of different RAs on the blending of virgin and aged binders were all considered to be important components of the study, no testing was undertaken to assess these variables due to time and budget constraints.

4. PHASE 1a: PRELIMINARY ASPHALT BINDER TESTING.

This phase of the study focused on the characterization of extracted and recovered asphalt binder from RAP and RAS materials and a review of the accelerated aging processes used to prepare simulated RAP binder. The experimental plan for this part of the study included two main tasks:

- Determine the performance grades of the binders and the gradations of the aggregates recovered from three different RAP sources and one RAS source.
- Identify an appropriate method for aging virgin binders to produce a simulated RAP binder with properties similar to those of the recovered RAP binders. One PG 64-16 binder was used in this experiment.

4.1 EXPERIMENT DESIGN.

4.1.1 Material Sampling and Testing Factorial.

Table 2 summarizes the sampling and testing factorial for the materials assessed in Phase 1a.

Table 2. Experimental Design Factors and Factorial Levels for Phase 1a

Factor	Factorial Level	Details
Asphalt binder source and grade	1	PG 64-16 (sourced from Refine A)
RAP source	3	RAP-A (Sacramento) RAP-B (San Francisco Bay Area) RAP-C (Southern CA)
RAS source	1	Tear-off shingles (Oakland)

4.1.2 Asphalt Binder Testing.

4.1.2.1 The PG of Virgin Asphalt Binder.

PG of the virgin asphalt binder was determined in accordance with AASHTO M 320 [77].

4.1.2.2 The PG of Extracted Asphalt Binder.

In 2001, investigators in the NCHRP 9-12 project [8] proposed guidelines for the use of RAP in the Superpave mix design method. These proposed guidelines require determination of the PG of the RAP binder for mixes containing more than 25% RAP to ensure that an appropriate virgin binder performance grade can be accurately selected from a blending chart. The following procedure, proposed in the NCHRP study guidelines, was used for determining PG of the reclaimed asphalt (RAP and RAS) binders used in this study.

- Asphalt binder extraction and recovery

    1. Obtain a representative sample of reclaimed asphalt material (about 1000 g) that will provide approximately 50 to 60 g of recovered binder (assuming 5% RAP binder content).

    2. Extract and recover the asphalt binder from the reclaimed asphalt following the AASHTO T 164 [78] procedure. Toluene or n-propyl bromide may be used as the chemical solvent. Document the use of any other solvents on the test sheet. Nitrogen blanketing is recommended to prevent undesired binder oxidation during extraction.

- Asphalt binder PG

    1. Determine the PG of the extracted reclaimed asphalt binder according to AASHTO M 320 [77]. Rotational viscometer, binder flash point, mass loss, and PAV are not required for reclaimed asphalt binder grading. PAV aging is not necessary given that the reclaimed asphalt binder has already been aged in the pavement (for RAP) or on a roof (for RAS).

2. Perform a DSR test with 25 mm parallel plate geometry on the recovered reclaimed asphalt binder (AASHTO T 315 [79]) to determine the critical high temperature of the binder (temperature at which the complex shear modulus (G*) divided by the phase angle (sin(δ)) (G*/sin(δ)) is 1.0 kPa)).

3. Age the extracted reclaimed asphalt binder in a RTFO, AASHTO T 240 [80].

4. Perform a DSR test with 25-mm parallel plate geometry on the RTFO-aged recovered reclaimed asphalt binder to determine the critical high temperature of the binder after RTFO aging (temperature at which G*/sin(δ) is 2.2 kPa).

5. Calculate the high PG limit of the recovered reclaimed asphalt binder based on the lowest temperatures obtained in Steps 2 and 4.

6. Perform a DSR test with 8-mm parallel plate geometry on the RTFO-aged recovered reclaimed asphalt binder to determine the critical intermediate temperature (temperature at which G* x sin(δ) is 5000 kPa).

7. Perform a BBR test (AASHTO T 313 [81]) on the RTFO-aged recovered reclaimed asphalt binder to determine the critical low temperatures (temperature at which creep stiffness [S] is equal to 300 MPa and temperature at which m-value is 0.30).

8. Calculate the low PG limit of the recovered reclaimed asphalt binder based on the highest (least negative) temperatures determined in Step 7.

4.1.2.3 Frequency Sweep Tests.

The RTFO-aged binders (virgin, RAP, and blended) were tested with a DSR using 8-mm parallel plate geometry with a 2-mm plate-to-plate gap setting at 4°C, 20°C, and 40°C at frequencies ranging between 0.1 Hz and 100 Hz at each temperature. The amplitude strain was set at 1.0% to ensure the binders behaved in a linear viscoelastic (LVE) range. The measured complex shear modulus values (G*) were used to construct asphalt binder master curves at the reference temperature (i.e., 20°C) by fitting the data to the sigmoidal function shown in equation 1. The testing frequencies at any testing temperature were converted to the reduced frequency at the reference temperature using a time-temperature superposition principle (equation 2) with the aid of an Arrhenius shift factor (equation 3).

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

where: $\delta, \alpha, \beta,$ and γ are sigmoidal function parameters
f_r is the reduced frequency at reference temperature T_r.

$$log(f_r) = log(a_T(T)) + log(f) \quad (2)$$

where: $a_T(T)$ is the shift factor value for temperature T(°K)
f is the testing frequency at testing temperature T(°C)
f_r is the reduced frequency at reference temperature T_r(°C)

$$log(a_T(T)) = \frac{E_a}{Ln(10)\times R}(\frac{1}{T} - \frac{1}{T_r}) \quad (3)$$

where:
E_a is an activation energy term (Joules (J)/moles (mol))
R is the universal gas constant (J/(mol·K)
T_r is the reference temperature (°K)

The parameters of the sigmoidal function as well as the activation energy term in the Arrhenius shift factor equation were estimated using the Solver add-in feature in Microsoft® Excel® by minimizing the sum of square error between predicted and measured values. Examples of the measured shear modulus and the corresponding master curve at 20°C for an asphalt binder are shown in figures 2 and 3, respectively.

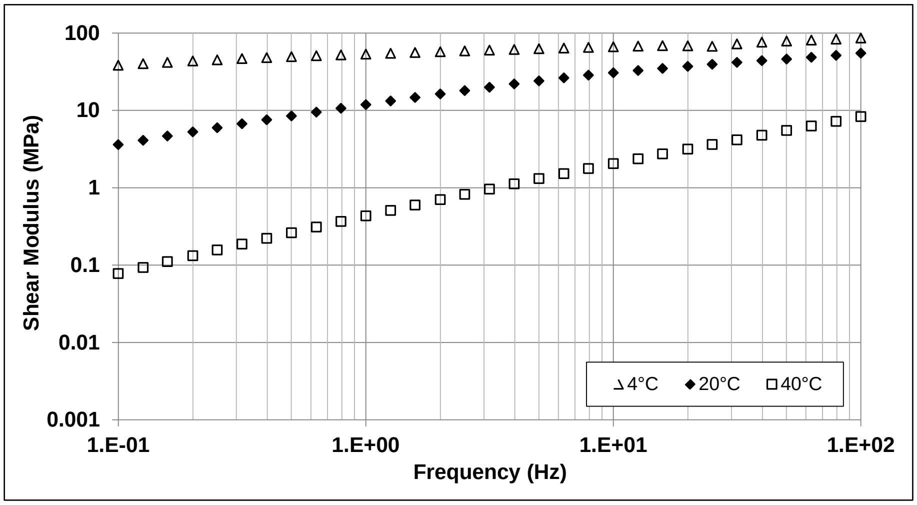


Figure 2. Example of Measured Shear Modulus of an Asphalt Binder at 20°C

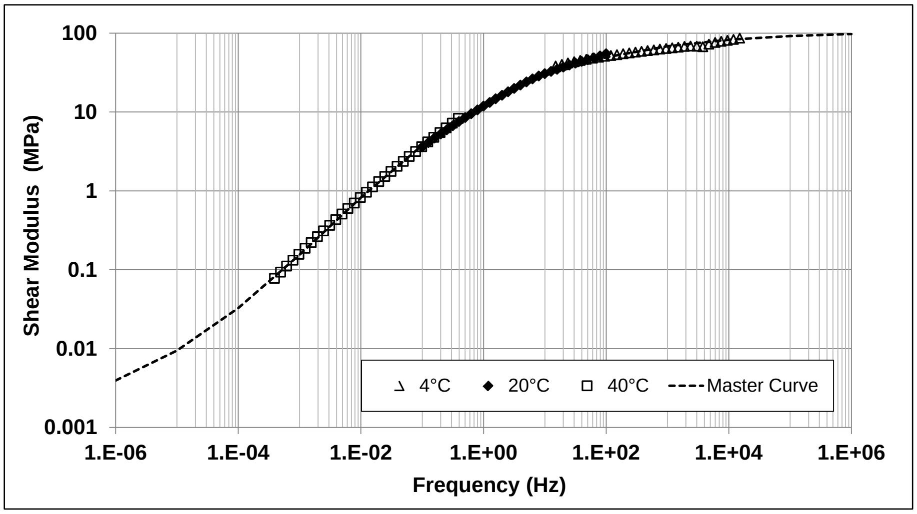


Figure 3. Example of a Developed Master Curve for an Asphalt Binder at 20°C

4.2 GRADATION AND BINDER CONTENT.

Following AASHTO T 248 [82], 5000 g samples of each RAP and RAS material were sampled and sent to a contracting laboratory for extraction and recovery of the asphalt binder and determination of the RAP and RAS aggregate gradations. The binder was extracted using TCE (AASHTO T 164 [79]) and recovered using the Abson method (ASTM D 1856 [83]). Gradations were determined in accordance with AASHTO T 30 [84]. The results are summarized in table 3.

Table 3. Extraction and Recovery Results for RAP and RAS Samples

Gradation (% Passing)					
Sieve Size					
mm	in./mesh	RAP A	RAP-B	RAP-C	RAS
19.0	3/4	100	100	100	100
12.5	1/2	100	98.5	94.8	100
9.50	3/8	98.8	89.2	87.6	100
4.75	#4	81.2	54.7	66.0	98.9
2.36	#8	59.4	34.3	47.6	96.2
1.19	#16	43.1	24.4	35.8	74.3
0.60	#30	30.4	18.1	26.0	49.7
0.30	#50	19.1	12.5	17.2	42.2
0.15	#100	10.2	6.8	10.0	30.1
0.075	#200	5.8	3.9	6.0	18.8
Binder Content					
Total mix		4.95	4.41	4.94	23.67
Mass of dry aggregate		5.20	4.62	5.20	31.01

4.3 BINDER TESTING: RAP.

The critical PG temperatures of the recovered RAP binders, determined according to AASHTO M 320 [77], are provided in table 4 and the PG values are listed in table 5.

Table 4. High, Intermediate, and Low Critical Temperatures of RAP Binders—1

<table>
<tr><th>Critical Temperature Range and Aging Condition</th><th>Test Parameter</th><th colspan="2">RAP-A (°C)</th><th colspan="2">RAP-B (°C)</th><th colspan="2">RAP-C (°C)</th></tr>
<tr><td>High (Unaged)</td><td>G*/sinδ ≥1.00 kPa</td><td colspan="2">92.8</td><td colspan="2">88.0</td><td colspan="2">95.2</td></tr>
<tr><td>High (RTFO-aged)</td><td>G*/sinδ ≥2.20 kPa</td><td colspan="2">86.9</td><td colspan="2">88.1</td><td colspan="2">89.0</td></tr>
<tr><td>Intermediate (RTFO-aged)</td><td>G* x sinδ ≤5000 kPa</td><td colspan="2">43.9</td><td colspan="2">41.2</td><td colspan="2">41.3</td></tr>
<tr><td>Low (RTFO- and PAV-aged)</td><td>See below</td><td colspan="2">-6.3</td><td colspan="2">-7</td><td colspan="2">-6.4</td></tr>
<tr><td colspan="2">Low-Temperature Grade Determination</td><td>S (MPa)</td><td>m</td><td>S (MPa)</td><td>m</td><td>S (MPa)</td><td>m</td></tr>
<tr><td colspan="2">Tested at 0°C</td><td>310</td><td>0.262</td><td>348</td><td>0.272</td><td>239</td><td>0.258</td></tr>
<tr><td colspan="2">Tested at -6°C</td><td>NA</td><td>NA</td><td>163</td><td>0.328</td><td>NA</td><td>NA</td></tr>
<tr><td colspan="2">Tested at -10 C</td><td>127</td><td>0.365</td><td>NA</td><td>NA</td><td>89.9</td><td>0.374</td></tr>
</table>

NA = Not applicable

Table 5. Performance Grades of Extracted and Recovered RAP Binders

Performance Grade	RAP-A (°C)	RAP-B (°C)	RAP-C (°C)
Continuous	86.8 -6.3	88.1, -7.0	89.0, -6.4
Full	82, -4	88, -4	88, -4

The results were considered to be reasonably representative of an aged binder. It is not known whether the chemical solvents used in the extraction process influenced the results in any way. Further research (beyond the scope of this study) is required to evaluate the influence of different chemical solvents on the extraction and recovery of binders from RAP materials, including those containing PM binders and asphalt rubber binders.

4.4 BINDER TESTING: RAS.

The binder recovered from the RAS could not be tested according to AASHTO M 320 [77] since it was not sufficiently workable to allow molding of the test specimens after 3 hours of heating at 190ºC, as shown in figure 4. This observation was consistent with other studies, which reported high PG limits of RAS binder in excess of 120°C and estimated limits to be as high as 240°C [43 and 85].

Figure 4. Recovered RAS Binder After 3 Hours of Conditioning at 190ºC

4.5 EVALUATION OF PROPERTIES OF SIMULATED RAP BINDERS.

4.5.1 Background.

The proposed testing required a large quantity of binder. Obtaining this quantity of binder using the AASHTO T 164 [77] process was considered to be inappropriate and impractical given the amount of mix required and a method for producing a simulated RAP binder was instead explored.

Different techniques have been used to prepare simulated RAP and most focus on laboratory aging of loose mix in a forced draft oven [55 and 86]. A number of recent studies have proposed approaches for preparing simulated RAP binder by aging virgin binders in a PAV. Bowers et al. [33] recommended two PAV cycles based on the results of chemical analyses of the binders using Fourier transform infrared spectroscopy (FTIR). Another study by Yar et al. [34] recommended two or more PAV cycles, given that each PAV cycle supposedly simulates 7-10 years of field aging.

4.5.2 Test Results.

A PG 64-16 asphalt binder was used in this part of the study. Samples of the binder were aged in a PAV for 40 and 60 hours at 100ºC and under 2.1 MPa of air pressure. The PG grades of these aged binders were then determined following the NCHRP 9-12 guideline for RAP binder grading [8]. The results are listed in table 6. A comparison of the PGs of the PAV-aged binders with the PGs of the extracted RAP binders (see table 4) indicated that the critical high PG temperature of the 60-hour PAV-aged binder was comparable to the high PG of the recovered RAP binders. However, neither of the PAV-aged binders had low-temperature properties that were comparable to the recovered binders. The reason for this is not clear and will be investigated in a separate study. Possible reasons include but are not limited to the influence of the aggregates on the recovered binders, the influence of the extraction chemistry on the binder, or that the PAV does not uniformly age all components of the binder.

Table 6. Critical Temperatures for 40- and 60-Hour PAV-Aged Binders

Critical Temperature	Performance Grade	
	At 40 hours (°C)	At 60 hours (°C)
High (unaged)	88.9	93.6
High (RTFO-aged)	82.1	86.7
Intermediate	28.7	31.9
Low	-19.8	-17.2

4.6 PHASE 1a TEST SUMMARY.

Preliminary laboratory testing to investigate the properties of binders recovered from RAP and RAS samples and simulated RAP binders prepared in the laboratory revealed the following:

- Asphalt binder extracted and recovered from RAS could not be tested due to its very high stiffness. The RAS binder was not sufficiently workable to mold samples for testing in a DSR and BBR.
- The guidelines recommended in NCHRP 9-12 [8] for determining the performance grade of binders recovered from RAP samples were considered to be appropriate for this UCPRC study. Recovered binders from three different RAP sources were tested according to these guidelines.
- Initial attempts to produce a simulated RAP binder in the laboratory with performance properties comparable to recovered binders provided mixed results. Various PAV test scenarios were considered, but only the high critical temperature of the simulated binder was similar to the recovered binders. The low critical temperatures were significantly different. It is not clear whether this was attributable to the aging procedure or to the effect of the extraction chemicals.

5. PHASE 1b: PRELIMINARY MORTAR TESTING.

Phase 1b of this study focused on evaluating techniques that do not require chemical extraction for characterizing the performance properties of composite asphalt binders. Based on a preliminary literature review [12] and discussions with other practitioners, asphalt mortar testing in a DSR was investigated as a potentially appropriate approach for this testing. Asphalt mortar is defined as a homogeneous blend of asphalt binder and fine aggregates passing the 300 μm (#50) sieve and retained on the 150 μm (#100) sieve. The asphalt binder content and the aggregate gradation of the mortar must be representative of the binder content and gradation of the same fine portion of a full-graded asphalt mix. Two samples are tested in this process: one sample consisting of virgin binder plus RAP, and the other consisting of virgin binder plus the aggregates obtained from processing RAP in an ignition oven (i.e., the RAP binder is burned off in an ignition oven). Any differences in the critical temperatures can then be attributed to the RAP binder, provided that the aggregate gradations and total binder contents are exactly the same for both samples.

The experimental plan for this phase of the study included preparing asphalt mortar specimens at various binder replacement rates (15%, 25%, 30%, and 35%) and performing DSR tests on them. Only one source of RAP was considered for this testing since the Phase 1a test results on recovered binders from three different CA RAP sources indicated that the binder properties were similar (see table 4). A softer binder (PG 58-22) was selected for this initial mortar testing as it would likely be more workable and easier to test in the DSR than the stiffer PG 64 or PG 70 binders.

5.1 EXPERIMENT DESIGN.

5.1.1 Material Sampling and Testing Factorial.

Table 7 summarizes the sampling and testing factorial for the materials assessed in Phase 1b.

Table 7. Experimental Design Factors and Factorial Levels for Phase 1b

Factor	Factorial Level	Details
Asphalt binder source and grade	1	PG 58-22[1] (sourced from Refinery A)
Aggregate type	1	Granitic
RAP source	1	RAP-A (Sacramento)
RAP content (by binder replacement)	4	0%, 15%, 25% and 35%

[1] PG 58-22 binder was selected as it was considered to be more workable as a mortar than stiffer binders.

5.1.2 Sample Preparation.

The mortar sample preparation procedure developed by Hajj et al. and summarized in figure 5 [12] was investigated prior to sample preparation. Hajj et al. were able to measure high and intermediate temperatures of the mortar samples in a DSR and low temperatures in a BBR. However, most of the mortar samples tested had relatively low RAP binder replacement values (<15% by weight of the binder), and consequently the tests were not unduly influenced by the high stiffness typical of samples with higher RAP binder replacement values.

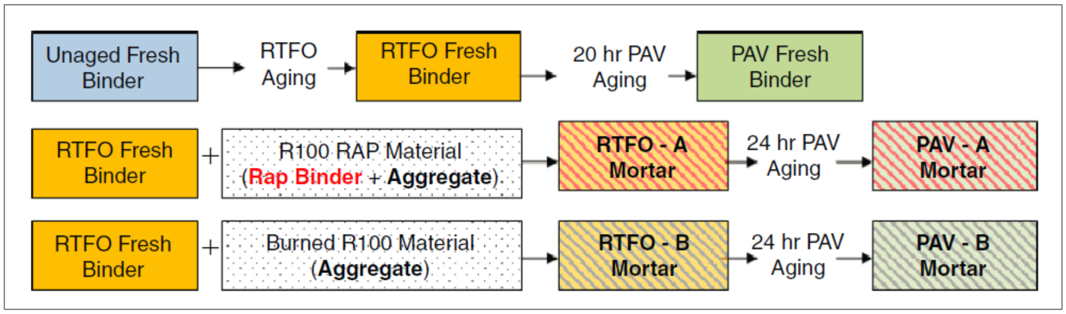


Figure 5. Sample Preparation for Asphalt Mortar Testing [12]

The same procedure was followed for preparation of the samples used in this study. PG 58-22 virgin binder was mixed with single-size fine RAP material passing the 300 µm (#50) sieve and retained on the 150 µm (#100) sieve at 15%, 25%, 30%, and 35% binder replacement rates. The mix temperature was set at 163°C (325°F), which is typical of plant production temperatures of high RAP-content mixes. The binder content of the fine RAP was set at 10% by weight of the mortar, based on ignition oven test results.

Attempts to fabricate DSR and BBR test specimens from the mortar samples provided varied results. Samples with binder replacement rates of 25% and less were sufficiently workable to fabricate the required specimens. Samples with higher binder replacement rates (i.e., more than 30%) were unworkable and specimens could not be fabricated. Given that this study was focused on investigating the influence of higher binder replacement rates on the performance properties of the blended binders, only limited DSR testing on the mortar samples was undertaken.

5.2 PRELIMINARY TEST RESULTS.

Asphalt mortar specimens were tested in a DSR with 25-mm parallel plate geometry and with 2-mm plate-to-plate spacing to measure the rheological properties of the mortar at high in-service temperatures.

Limited amplitude sweep strain tests were performed on selected asphalt mortar samples to determine the LVE range of behavior at which the stiffness of the mortar was independent of the level of applied stress or strain. The amplitude sweep strain tests were performed by measuring the shear modulus of the mortar specimens at 58°C and 1.59 Hz when the applied shear strain amplitude increased from 1% to 16%. The test results are shown in figure 6. The results show that the LVE region narrowed increasingly with increasing RAP content in the mortar. This trend was expected given that the stiffness of blended binders is influenced by the age-hardened RAP binder, which reduces the tolerable strain level in LVE behavior.

Other observations from the testing procedure and results include the following:

- The gradation and binder content of mortar specimens may not be representative of the mortar fraction in corresponding full-graded mixes.

- The conditioning times and temperatures required to prepare workable mortar specimens may not be representative of asphalt plant conditions, which may affect the degree of binder aging and consequently, the DSR test results.

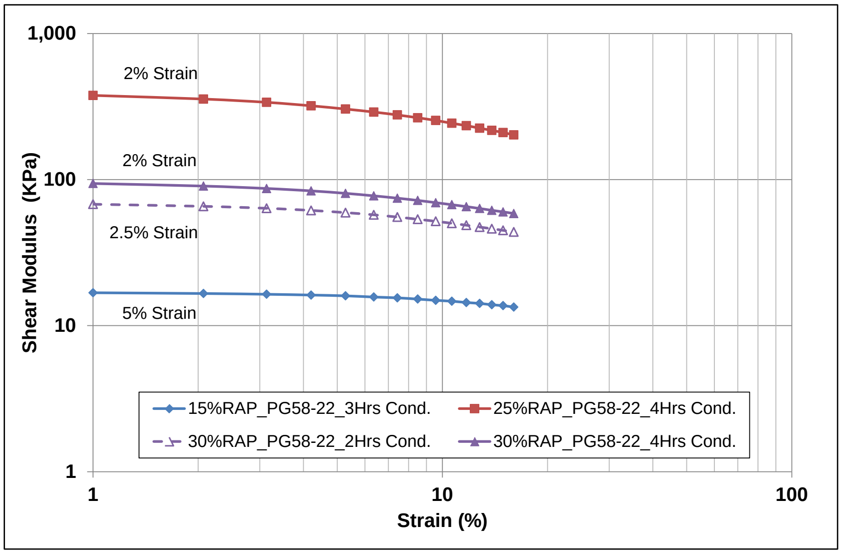


Figure 6. Results of Amplitude Sweep Strain Tests on Asphalt Mortar

5.3 PHASE 1b TEST SUMMARY.

Preliminary laboratory testing to investigate the properties of asphalt mortars prepared in the laboratory revealed the following:

- Mortar samples with binder replacement rates of up to 25% were sufficiently workable to fabricate specimens that could be tested in a DSR. Samples with binder replacement rates greater than 25% were generally unworkable and specimens could not be fabricated satisfactorily.

- Although the mortar test deserves further investigation, it may not be appropriate for testing samples with high binder replacement rates (i.e., >25%). Given that this study was focused on investigating the influence of binder replacement rates of up to 40% on the performance properties of the blended binders, the use of mortar testing was considered unsuitable for the remainder of the study.

6. PHASE 1c: PRELIMINARY FAM TESTING.

FAM mixes are defined as a homogeneous blend of asphalt binder and fine aggregates with size passing either the 4.75 mm (#4), 2.36 mm (#8), or 1.18 mm (#16) sieves. The asphalt binder content and the aggregate gradation of the FAM mix must be representative of the binder content and gradation of the fine portion of the full-graded asphalt mix. The performance properties are determined by testing small cylindrical or beam specimens of the FAM mix with a solid torsion bar fixture in a DSR, known as a DMA. Based on the literature review, the FAM mix approach was considered a potentially appropriate alternative to binder extraction and recovery and asphalt mortar testing.

6.1 EXPERIMENT DESIGN.

6.1.1 Material Sampling and Testing Factorial.

Table 8 summarizes the sampling and testing factorial for the materials assessed in Phase 1c.

Table 8. Experimental Design Factors and Factorial Levels for Phase 1c

Factor	Factorial Level	Details
Asphalt binder source and grade	5	PG 64-16 and PG 58-22 (sourced from Refinery A) PG 64-16[1] and PG 58-22 (sourced from Refinery B) PG 64-16 (sourced from Refinery C)
Aggregate type	1	Granitic
RAP source	1	RAP-A (Sacramento)
RAS source	1	Tear-off shingles (Oakland)
RAP content (by binder replacement)	3	0% (all five binders tested) 25% (all five binders tested) 40% (two Refinery A binders tested)
RAS content	1	5% total weight of mix (~15% by binder replacement)
RA	1	Petroleum based (sourced from Refinery C) 12% by weight of total binder used in the mix

[1] Although PG 64-16 binder was requested from Refinery B, the binder supplied met the requirements for PG 64-22.

6.1.2 Asphalt Binder Testing.

Asphalt binder testing was carried out as described in section 4.1.2. In this phase, only the high PG limits of the blended binders were determined. Low-temperature testing (in a BBR) was not performed since the low-temperature properties of the blended binders were not the primary focus in this phase.

6.1.3 Blended Binder Preparation.

Blended asphalt binders were prepared by mixing virgin asphalt binders and recovered RAP binder at rates of 75:25 and 60:40 (representing binder replacement rates of 25% and 40%), and recovered RAS binder at a rate of 85:15 (representing a binder replacement rate of 15%). The binders were mixed with a glass stirrer until a homogeneous blend was obtained. After mixing, the blended binders were conditioned in an RTFO according to AASHTO T 240 [80] to simulate the short-term aging that occurs during asphalt mix production. Attempts to prepare a homogenized recovered RAS and virgin binder blend were again unsuccessful (see discussion in section 4.4), and therefore blended binder testing was only conducted on blended extracted RAP and virgin binders.

6.1.4 Trial FAM Mix Sample and Specimen Preparation.

Trial FAM sample and specimen preparation methods were based on those cited in the literature [13-15]. Mixes were prepared with material passing the 4.75 mm (# 4), 2.36 mm (# 8), and 1.18 mm (# 16) sieves. The 4.75 mm (# 4) and 2.36 mm (# 8) mixes provided satisfactory quantities of FAM; the 1.18 mm (# 16) mixes were difficult to sieve and very large samples needed to be prepared to obtain sufficient quantities of mix to prepare compacted specimens.

6.1.5 Fine Aggregate Matrix Mix Sample and Specimen Preparation Method.

After a series of trial tests, the following refined procedure was developed and adopted for the preparation of FAM mix samples and specimens for this study:

1. Prepare a full-graded asphalt mix at optimum binder content with virgin binder and virgin aggregates according to AASHTO R 35 [87].

2. Short-term age the loose asphalt mix for 2 hours at the mix compaction temperature following AASHTO R 30 [88].

3. Determine the theoretical maximum specific gravity according to AASHTO T 209 (RICE test) [89].

4. Sieve the loose asphalt mix to obtain approximately 1.5 kg of material passing the selected sieve, i.e., 4.75 mm (#4), 2.36 mm (#8), or 1.18 mm (#16). Where required, gently tamp down the mix to break up agglomerations. Mixes passing the 1.18 mm (# 16) sieve are not recommended given that large volumes of material need to be prepared to obtain sufficient mix to prepare compacted specimens.

5. Sieve the RAP material to obtain approximately 1.5 kg of the required gradation, i.e., 4.75 mm (#4), 2.36 mm (#8), or 1.18 mm (#16).

6. Determine the binder content of the fine mix by extraction and recovery (AASHTO T 164 [78]). (Extraction and recovery was used in this UCPRC study as an alternative to ignition oven testing (AASHTO T 308 [90]) due to concern about losing very fine aggregate particles during the ignition process).

7. Determine the binder content and gradation of the fine RAP particles by extraction and recovery.

8. Determine virgin binder, virgin aggregate, RAP, and RAP aggregate quantities for selected binder replacement values based on the binder content and aggregate gradations determined from the extraction and recovery tests (Steps 6 and 7).

9. Prepare asphalt mixes with different percentages of RAP based on the required binder replacement rate.

10. Determine the theoretical maximum gravity of the FAM mix.

11. Short-term age the loose FAM mix by conditioning for 2 hours at the mix compaction temperature following AASHTO R 30 [88].

12. Compact the FAM mix in a Superpave gyratory compactor (following AASHTO T 312 [91]) to fabricate a specimen with 150-mm diameter and 50-mm height with 10% to 13% target air-void content.

13. Subject the compacted specimen to long-term aging if required for the testing phase (e.g., 5 days at 85°C following AASHTO R 30 [88]).

14. Core 12.5-mm cylindrical FAM mix specimens from the 150-mm diameter specimen. Examples of a 150-mm compacted specimen and cored 12.5-mm specimens are shown in figure 7.

Figure 7. The FAM Mix Specimens Cored From a Superpave Gyratory-Compacted Specimen

15. Determine the air-void content of the FAM mix specimens by first determining the saturated surface-dry (SSD) specific gravity (AASHTO T 166 [92]) and then calculating the air-void contents with this and the previously measured theoretical specific gravity (Step 10) according to AASHTO T 269 [93].

16. Dry the FAM mix specimens and store them in a sealed container to prevent damage and excessive shelf-aging prior to testing.

After preparation of a number of trial mixes, it was observed that the 4.75-mm mixes had visible, large aggregates relative to the diameter of the 12.5-mm core. It was concluded that the presence of these larger aggregates could potentially influence the test results and introduce variability between test results within the same mix. Consequently, all further testing was restricted to mixes prepared with material passing a 2.36-mm (#8) sieve.

6.1.6 Test Setup for FAM Mix.

FAM mix specimens were tested using a solid torsion bar DMA fixture in an Anton Paar MCR302 DSR.

When performing tests on FAM mix specimens, special attention must be given to ensuring that the specimen is correctly aligned and securely clamped in the DSR. Each specimen must be carefully inspected and checked to ensure that its edges are clean and undamaged in the clamping zone, and that there are no localized weak areas (e.g., aggregates torn out during coring) that could influence the results. In other studies [13-15, and 37], reference is made to the use of steel caps, glued to both ends of the FAM mix specimen, to secure the specimen in the testing frame. Initial testing at the UCPRC compared tests with and without the caps, but this approach was ultimately not pursued based on discussions with the DSR manufacturer, who stated that the glue zone between the cap and the specimen would likely have a significant influence on the results. Instead, a custom clamp recommended by the DSR manufacturer was used. Figure 8 shows the fixed specimen in the DSR-DMA used in this project.

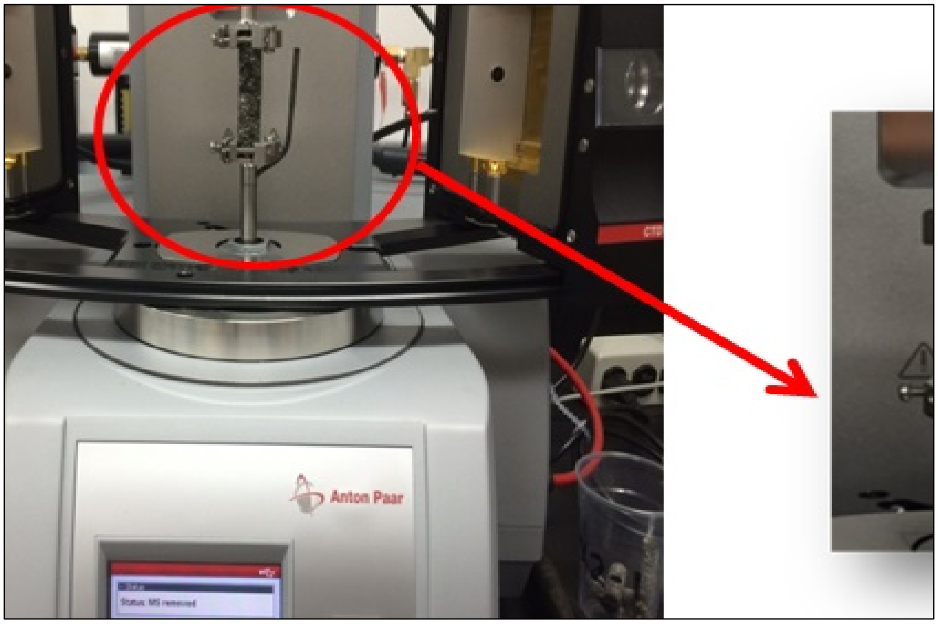


Figure 8. Torsion Bar Fixture Used for FAM Mix Testing

6.1.7 Amplitude Sweep Tests.

Amplitude sweep tests were performed on the FAM mix specimens to determine the LVE range of material behavior. The shear modulus of each FAM mix specimen was measured at 4°C and a frequency of 10 Hz when the shear strain increased incrementally from 0.001% to 0.1%. An example test result is shown in figure 9. The shear stiffness of the FAM mix specimen is independent of the rate of shear strain in the LVE region.

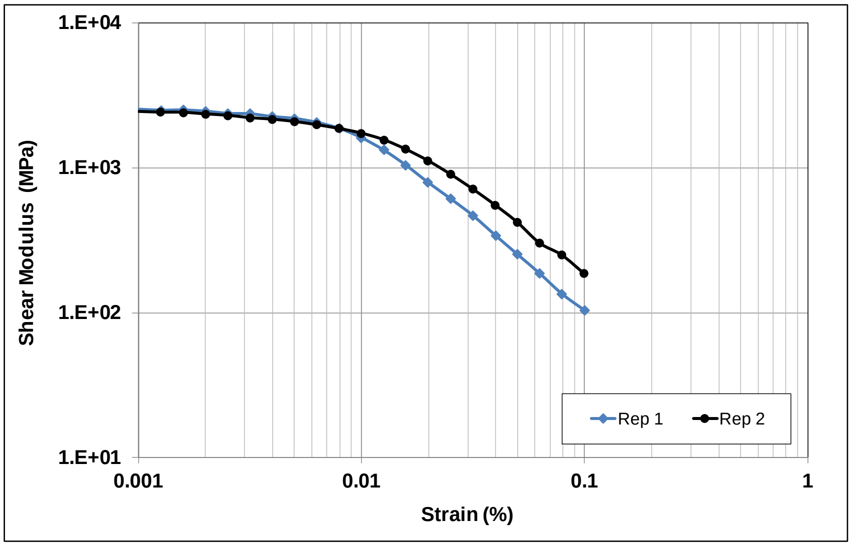


Figure 9. Example Test Results for FAM Mix Specimen Amplitude Sweep

6.1.8 Frequency Sweep Tests.

Frequency sweep tests measured the complex shear modulus in a wide range of frequencies (0.1 Hz to 25 Hz) at three different temperatures (4°C, 20°C, and 40°C). Based on the results of the amplitude sweep tests, frequency sweep tests at a strain rate of 0.002% were completed to ensure that the material was in the LVE region. FAM mix specimen shear modulus master curves were constructed based on time-temperature superposition principles using the measured moduli over the range of temperatures and frequencies. Equations 1, 2, and 3 were used to construct shear modulus master curves for the FAM mix specimens. Examples of shear modulus and developed master curves at the 20°C reference temperature for a FAM mix are shown in figures 10 and 11, respectively.

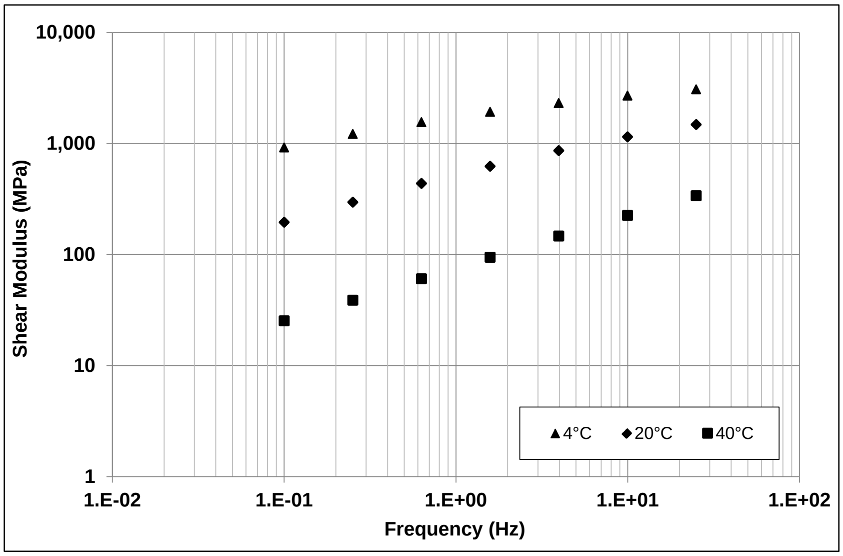


Figure 10. Example of Measured Shear Modulus of a FAM Mix Specimen at 20°C

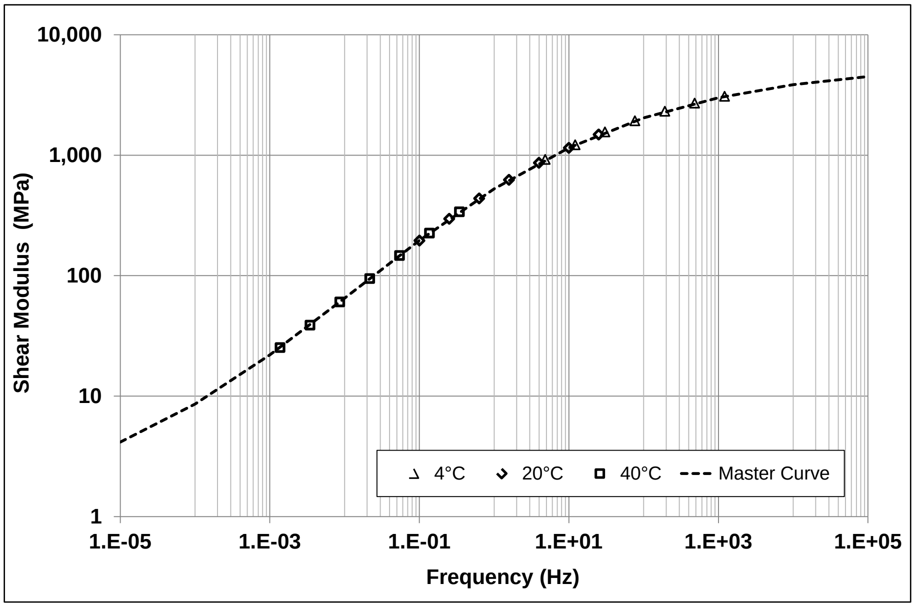


Figure 11. Example of Shear Modulus Master Curve of a FAM Mix Specimen at 20°C

6.2 CHARACTERIZATION OF RAP, RAS, AND BLENDED BINDERS.

6.2.1 Characterization of RAP and RAS Binders.

Representative samples of RAP and RAS materials were collected and sent to a contracting laboratory for extraction and recovery of the asphalt binder. The binder was extracted using TCE (AASHTO T 164 [78]) and recovered using the Abson method (ASTM D 1856 [83]). The extracted RAP binder was tested according to the NCHRP 9-12 guidelines [7] discussed in section 4.1.2.

The PG criteria and mean temperature values of the recovered RAP binders are listed in table 9 and suggest a mean grading equating to PG 87-6. The results were considered to be reasonably representative of an aged binder. It is not known whether the chemical solvents used in the extraction process influenced the results.

Table 9. High, Intermediate, and Low Critical Temperatures of RAP Binders—2

Critical Temperature	Test Parameter	Mean Temperature[1] (°C)	S (MPa)	m
High (Original)	G*/sinδ ≥ 1.00 kPa	92.8 (~ 93)	Not applicable	
High (RTFO-aged)	G*/sinδ ≥ 2.20 kPa	86.9 (~87)		
Intermediate (RTFO-aged)	G* x sinδ ≤ 5,000 kPa	43.9 (~44)		
Low @ 0°C (RTFO-aged)	Tested at 0°C	-6.3 (~6)	310	0.262
Low @ 10°C	Tested at 10°C		127	0.365

[1] Mean of two tests

The binder recovered from the RAS could not be tested according to AASHTO M 320 [77] since it was not sufficiently workable to allow molding of the test specimens after 3 hours of heating at 190ºC. This finding was consistent with the testing of extracted RAS binders discussed in section 4.

6.2.2 Characterization of Blended RAP and Virgin Binders.

A second sample of RAP material was sent to an external laboratory for binder extraction and recovery. A toluene-ethanol mix (85:15), which has been shown to have a less detrimental effect on the chemistry and rheology of extracted asphalt binders [41], was used as the solvent in this extraction. The recovered RAP binder was blended with the different virgin binders to simulate 25% and 40% binder replacement. A partial factorial testing experiment was completed to evaluate the properties of these blended binders (see table 8) as follows:

- All five binders were tested at 25% binder replacement.
- Two binders (sampled from Refinery A) were tested at 40% binder replacement.
- One binder (Refinery A PG 64-16) was tested with an RA at 40% binder replacement.

The virgin and blended binders were short-term aged in an RTFO and then tested in a DSR (8-mm parallel plate with 2-mm gap setting) to measure the shear moduli of the binders at three temperatures (4°C, 20°C, and 40°C) and a range of frequencies (0.1 to 100 Hz). The master curve parameters for the evaluated binders are provided in table 10.

Table 10. Master Curve Parameters for Virgin and Blended Binders

Binder Replacement (%)	Mix Identification[1]	Master Curve Parameters				
		δ	α	β	γ	E_a (J/mol)
0	PG 64A	-3	4.73	1.32	0.69	191,301
	PG 64B	-3	4.61	1.34	0.70	194,798
	PG 64C	-3	4.89	1.29	0.78	191,105
	PG 58A	-3	4.53	1.08	0.76	181,467
	PG 58B	-3	4.49	0.80	0.81	167,421
25 (RAP)	25%RAP_PG 64A	-3	5.04	-1.39	-0.62	203,802
	25%RAP_PG 64B	-3	5.02	-1.49	-0.58	211,663
	25%RAP_PG 64C	-3	4.98	-1.75	-0.69	211,792
	25%RAP_PG 58A	-3	5.08	-1.12	-0.60	195,467
	25%RAP_PG 58B	-3	5.07	-1.03	-0.61	192,711
40 (RAP)	40%RAP_PG 64A	-3	4.99	-1.83	-0.61	217,237
	40%RAP_PG 64A+RA	-3	5.05	-1.14	-0.67	198,743
	40%RAP_PG 58A	-3	5.01	-1.52	-0.58	208,848
15 (RAS)	Not tested					

[1] A, B, and C denote the source refinery.

δ, α, β, and γ = Sigmoidal function fitting parameters used to construct master curves

E_a = An activation energy term

Figure 12 shows the master curves of the five virgin binders evaluated. The following observations were made:

- The moduli of the PG 58 asphalt binders were lower than the PG 64 binders, as expected. The PG 58-22 binder from Refinery B was softer than the equivalent binder from Refinery A.
- The three PG 64 binders had similar shear moduli, with one binder (from Refinery C) being slightly softer at low frequencies and stiffer at high frequencies.

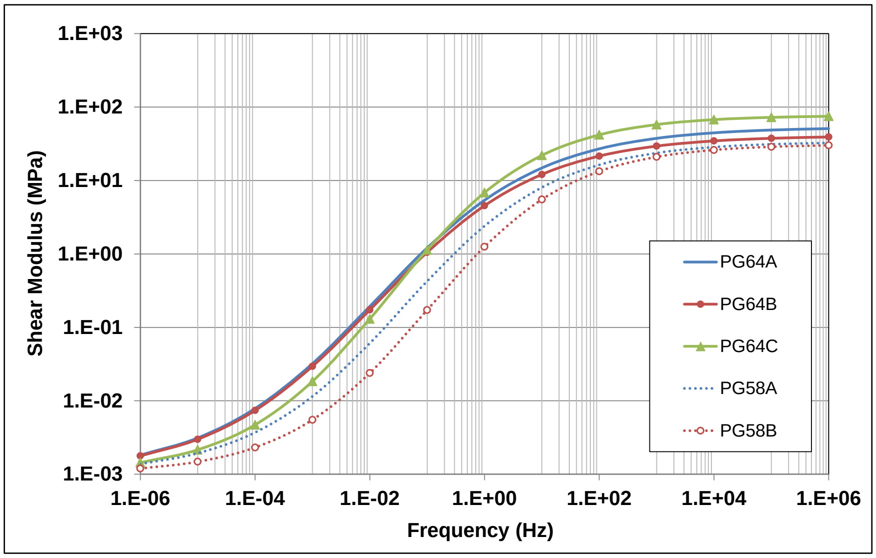


Figure 12. Shear Moduli of Virgin Asphalt Binders at 20°C

Figure 13 shows the shear modulus master curves for blended binders with 25% RAP binder replacement. Although the RAP binder reduced the differences between the moduli of the five asphalt binders, the ranking of the binders was still controlled by the properties of the base binders. The master curves of the blended binders merged at high frequencies (>1000 Hz), regardless of the base binder source and grade.

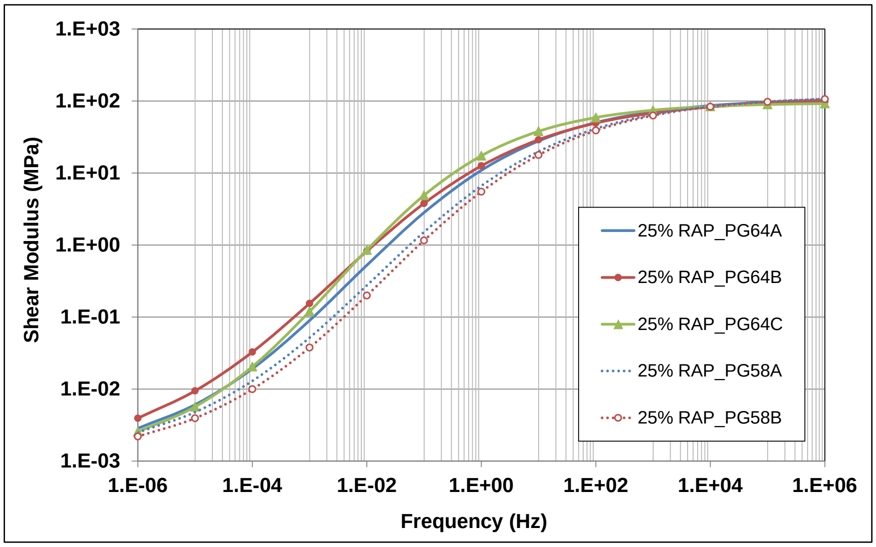


Figure 13. Shear Moduli of Binders With 25% RAP Binder Replacement at 20°C

Figure 14 shows the shear modulus master curves for blended binders containing 40% RAP binder replacement. The PG 64-16 base binder blends were stiffer than the PG 58-22 blends, as expected. The RA reduced the stiffness of the blended binder to a level approximately equal to that of the virgin binder.

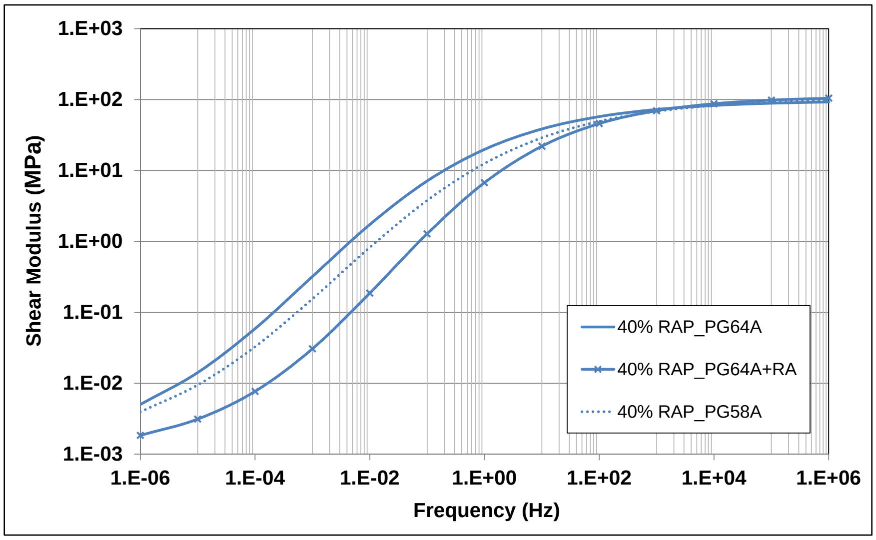
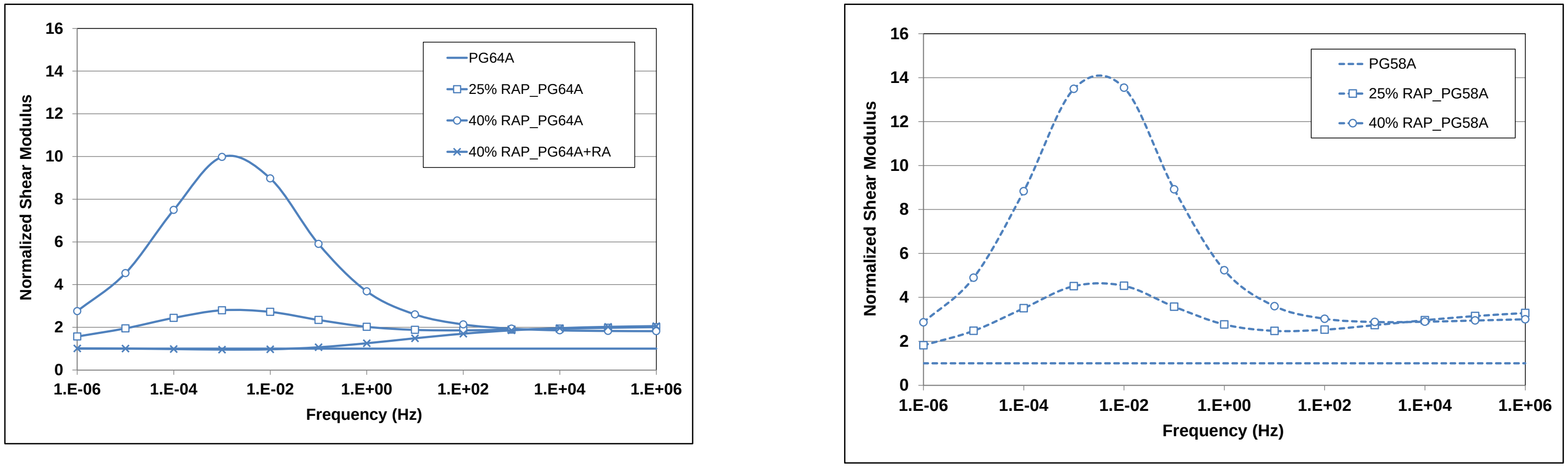


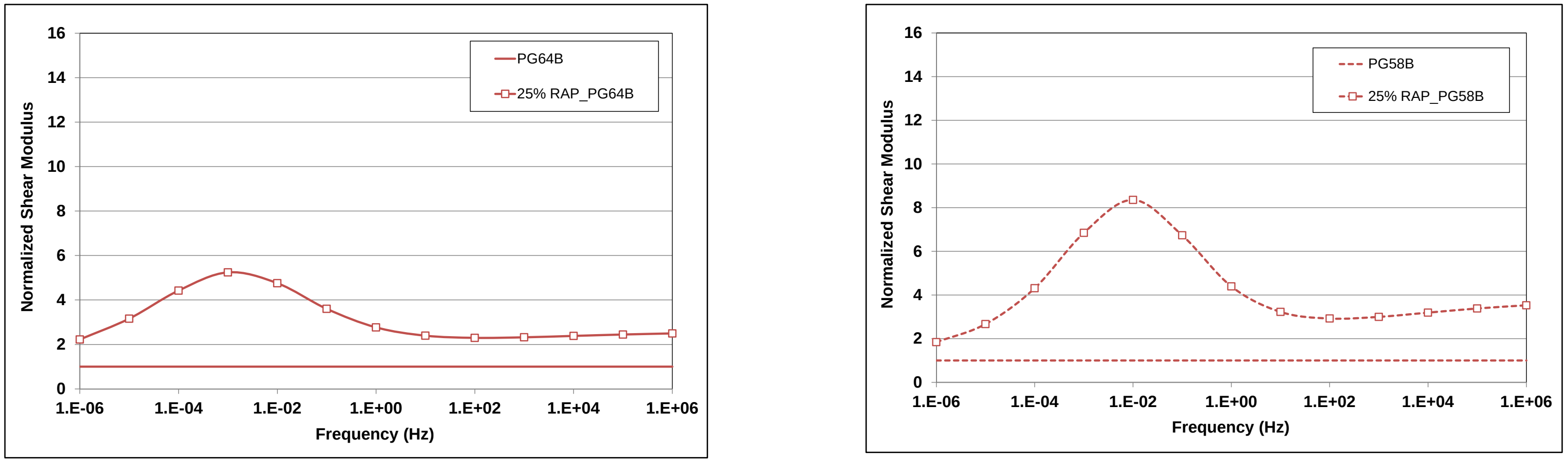
Figure 14. Shear Moduli of Binders With 40% RAP Binder Replacement at 20°C

The master curves of the blended binders were normalized to their corresponding virgin binder master curves to make comparing the effects of incorporating RAP into the different virgin asphalt binders (figure 15) easier to observe.



PG 64-16 (Refinery A)

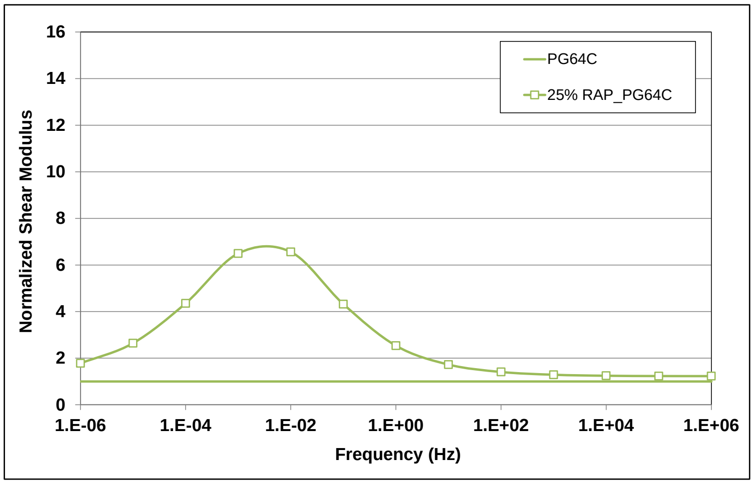
PG 58-22 (Refinery A)



PG 64-16 (Refinery B)

PG 58-22 (Refinery B)

Figure 15. Comparison of Normalized Shear Moduli Master Curves for Blended Binders



PG 64-16 (Refinery C)

Figure 15. Comparison of Normalized Shear Moduli Master Curves for Blended Binders (Continued)

This analysis showed the following:

- Using 25% RAP binder replacement increased the modulus of the virgin binder by up to eight times, depending on the binder source, binder grade, and testing frequency.
- The stiffness of the PG 58 binders increased more than that of the PG 64 binders for binders from the same refinery.
- The binders from Refinery A were least affected by the addition of RAP.
- Using 40% RAP binder replacement increased the stiffness of the blended binder by up to 13.5 times that of the virgin binder.
- After an RA was added, the normalized curve confirmed that the shear modulus of the blended binder with 40% RAP binder replacement was similar to that of the virgin binder over the range of testing frequencies.
- Increases in the shear modulus of blended binders mostly occurred in the frequency range of 0.00001 Hz and 0.1 Hz.

6.3 FINE AGGREGATE MATRIX MIX TEST RESULTS.

FAM mix specimens were prepared according to the procedure described in section 6.1.5. A total of 26 FAM mixes were evaluated. The binder contents of the RAP and RAS were determined to be 7.1% and 23.7% respectively, by total weight of the mix, using the AASHTO T 164 [78] asphalt binder extraction test. The target aggregate gradation used was the same for all the FAM mixes regardless of the binder grade and RAP or RAS content, and is shown in figure 16. The gradation and quantity of virgin aggregate were adjusted according to the quantity and gradation of the RAP and/or RAS in the mix to meet the target FAM gradation.

The FAM mixes containing RAS had a slightly coarser gradation than the FAM mixes with virgin binder only and with RAP binder due to the coarser gradation of the RAS materials. However, the difference was not significant given that only 5.4% RAS (by total weight of mix) was used.

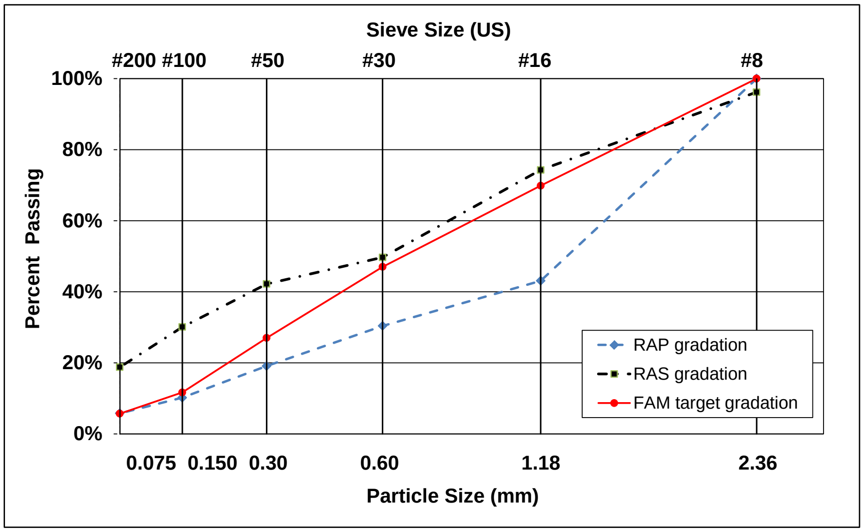


Figure 16. Gradation of FAM, RAP, and RAS Materials

6.3.1 The FAM Mix Specimen Air-Void Content.

A main consideration regarding the repeatability of test results using FAM mix specimens is the range of air-void contents per mix type. Figures 17 and 18 show the air-void contents measured on the specimens (four specimens per mix). The air-void contents of the RAP specimens ranged between 10.5% and 12.5%, which was within the target range and considered acceptable for this study. The air-void contents of the RAS binder specimens were generally higher than the RAP binder specimens. Air-void contents were considered in all test result analyses.

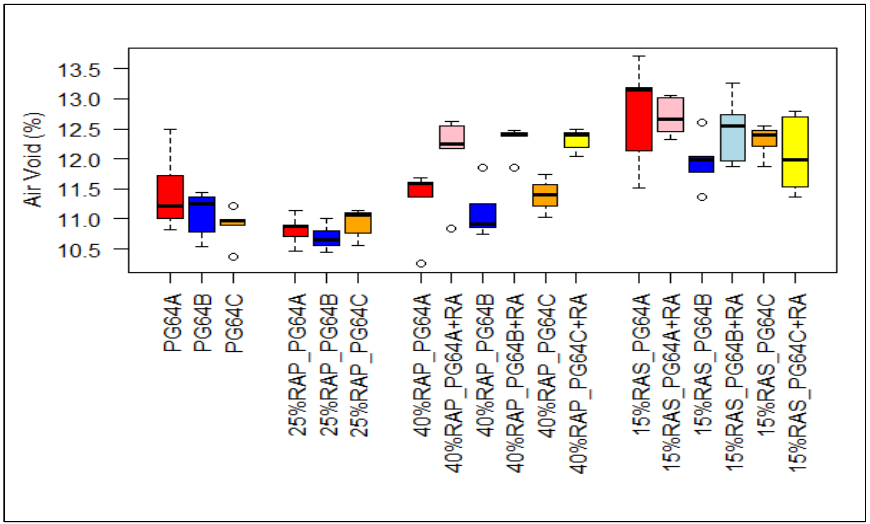


Figure 17. The FAM Mix Specimen Air-Void Contents for PG 64 Mixes

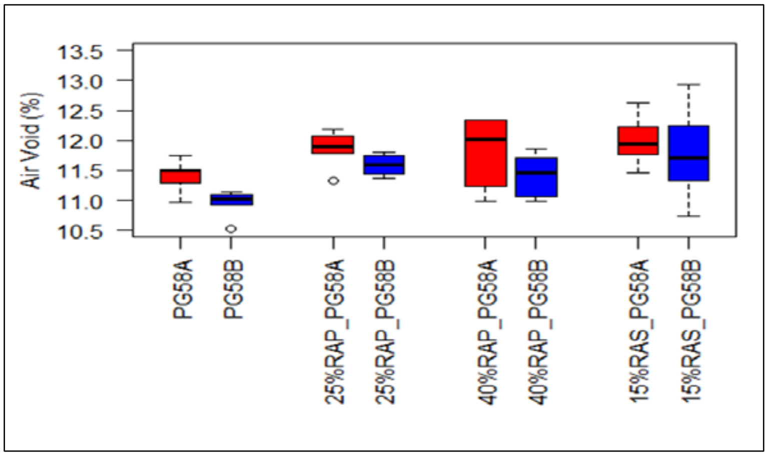


Figure 18. The FAM Mix Specimen Air-Void Contents for PG 58 Mixes

<u>6.3.2 Amplitude Sweep Strain Test Results</u>.

The strain limits for LVE behavior of the FAM mixes, determined from the results of the amplitude sweep test, are shown in figures 19 and 20. The following observations were made:

- The LVE strain limits were influenced by virgin binder grade, binder source, and RAP or RAS content. The effect of binder source appeared to have a lesser influence on the results of the PG 64 binders compared to the PG 58 binders.
- The RAP binder appeared to mobilize and blend with the virgin binder during mixing, thereby changing the viscoelastic properties of the mix as shown by the reduction in the LVE strain limit.

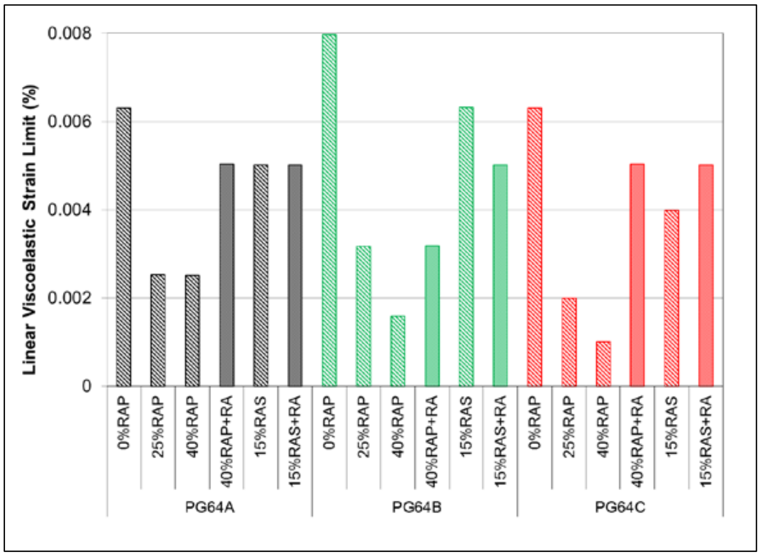


Figure 19. Fine Aggregate Matrix Mix Specimen LVE Range for Mixes With PG 64 Virgin Binders

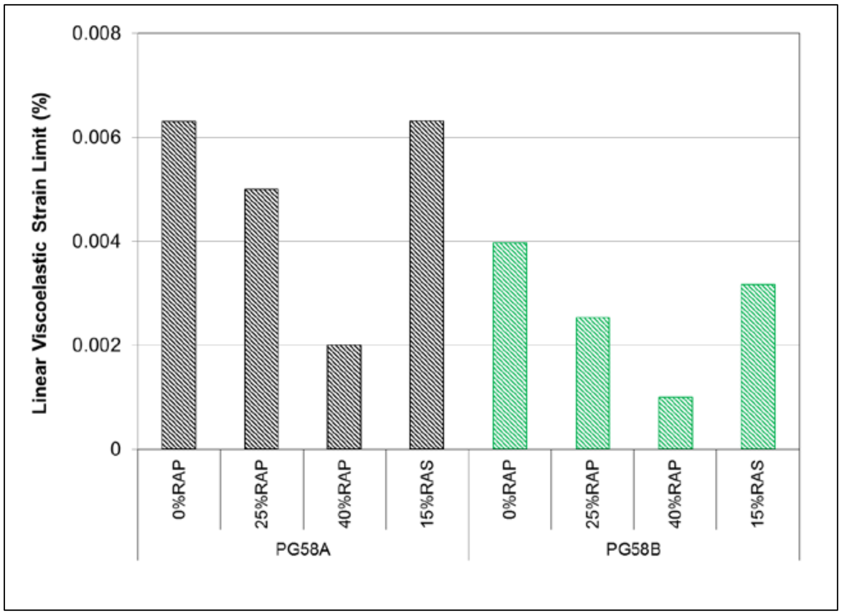


Figure 20. Fine Aggregate Matrix Mix Specimen LVE Range for Mixes With PG 58 Virgin Binders

- The LVE strain limit decreased with increasing RAP content, as expected. Replacing 25% of the virgin binder with aged binder from the RAP resulted in between 20% and 70% reduction in the LVE strain limit. Replacing 40% of the virgin binder resulted in between and 70% and 90% reduction.

- Reductions in LVE were also noted on the mixes containing RAS, with the change consistent with the percent binder replacement (15%).

- The RA had a notable influence on the mixes containing RAP, but only a marginal influence on the mixes containing RAS. This implies that the RAS binder might not have been effectively mobilized at the mix production temperatures used in this study and did not effectively blend with the virgin binder even when an RA was added. In this case, the observed reductions in LVE on the RAS mixes can probably be attributed to the effective lower virgin binder content, rather than the effect of the stiffer blended binder.

6.3.3 Frequency and Temperature Sweep Test Results.

Sigmoidal function master curves were constructed using the measured shear modulus at various combinations of temperature and frequency. The estimated parameters of the sigmoidal function (equation 1) and activation energy term in the Arrhenius shift factor (equation 3) for the FAM mixes are provided in table 11.

Table 11. Master Curve Parameters for FAM Mixes

Binder Replacement (%)	Mix Identification[1]	Master Curve Parameters				
		δ	α	β	γ	E_a (J/mol)
0	PG 64A	0	3.76	-0.96	-0.52	164,414
	PG 64B	0	3.87	-0.93	-0.43	174,701
	PG 64C	0	3.63	-1.41	-0.62	172,503
	PG 58A	0	3.71	-0.79	-0.52	162,828
	PG 58B	0	3.74	-0.53	-0.51	158,722
25 (RAP)	25%RAP_PG 64A	0	4.17	-1.06	-0.39	176,435
	25%RAP_PG 64B	0	3.99	-1.19	-0.38	179,082
	25%RAP_PG 64C	0	4.10	-1.22	-0.45	179,341
	25%RAP_PG 58A	0	3.96	-1.07	-0.42	170,216
	25%RAP_PG 58B	0	3.99	-1.19	-0.38	165,906
40 (RAP)	40%RAP_PG 64A	0	4.21	-1.06	-0.34	180,414
	40%RAP_PG 64A+RA	0	3.84	-1.03	-0.46	166,743
	40%RAP_PG 64B	0	4.08	-1.14	-0.36	177,121
	40%RAP_PG 64B+RA	0	4.14	-0.86	-0.40	170,255
	40%RAP_PG 64C	0	4.60	-0.94	-0.35	173,209
	40%RAP_PG 64C+RA	0	3.95	-1.17	-0.49	167,399
	40%RAP_PG 58A	0	4.10	-1.15	-0.38	171,885
	40%RAP_PG 58B	0	4.29	-0.85	-0.36	169,832
15 (RAS)	15%RAS_PG 64A	0	3.74	-0.93	-0.45	170,253
	15%RAS_PG 64A+RA	0	3.80	-0.70	-0.48	162,233
	15%RAS_PG 64B	0	3.65	-0.88	-0.42	171,575
	15%RAS_PG 64B+RA	0	3.47	-0.87	-0.49	169,124
	15%RAS_PG 64C	0	3.77	-1.18	-0.53	166,295
	15%RAS_PG 64C+RA	0	3.98	-0.74	-0.54	160,332
	15%RAS_PG 58A	0	3.79	-0.88	-0.42	170,828
	15%RAS_PG 58B	0	3.82	-0.65	-0.44	161,161

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[1] A, B, and C denote the source refinery.

The shear modulus master curves for the FAM mixes differentiated by binder replacement rate are shown in figures 21 through 24 and differentiated by binder source are shown in figures 25 through 29. Normalized shear modulus master curves are included with the latter group of plots to better illustrate the effect of the RAP and RAS. The normalized curves were obtained by dividing the shear moduli of the FAM mixes with binder replacement by the corresponding shear moduli of the control mixes at each respective frequency.

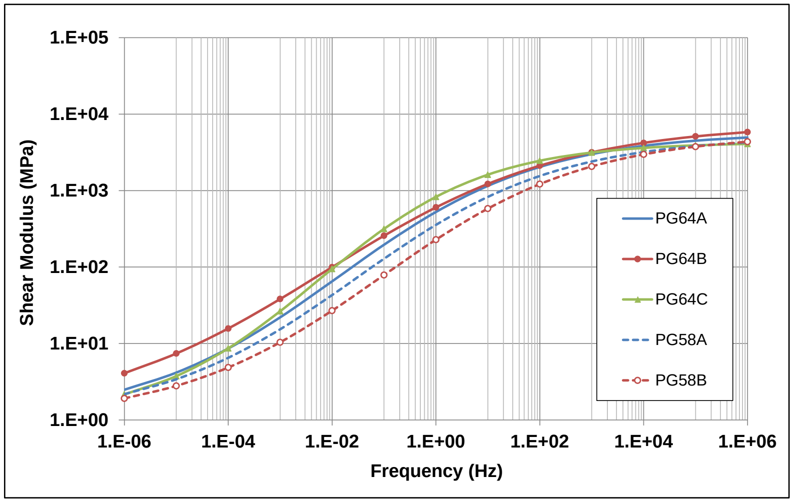


Figure 21. Shear Modulus Master Curves of Control FAM Mixes

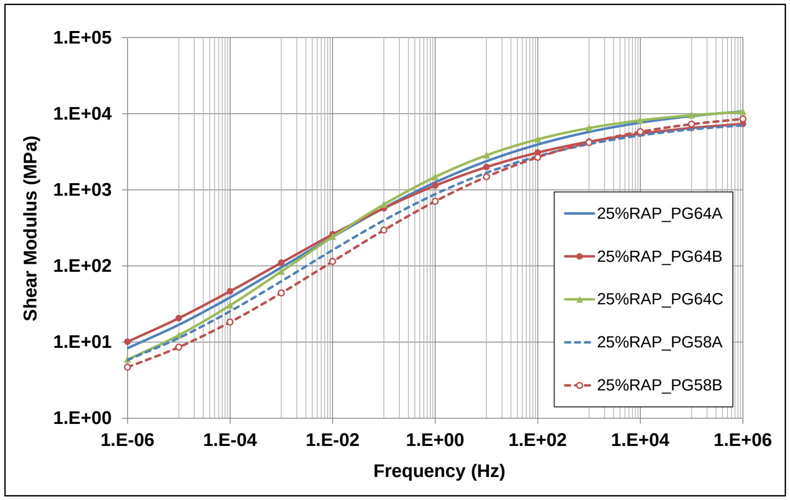


Figure 22. Shear Modulus Master Curves of FAM Mixes With 25% RAP Binder Replacement

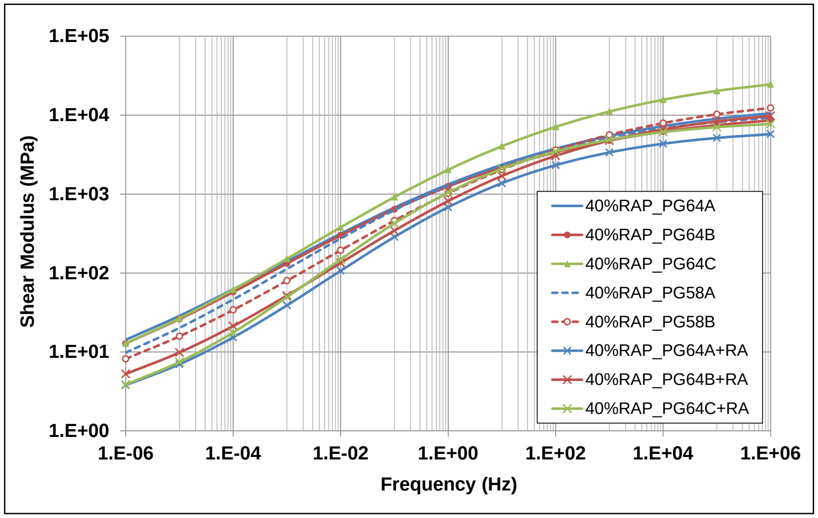


Figure 23. Shear Modulus Master Curves of FAM Mixes With 40% RAP Binder Replacement

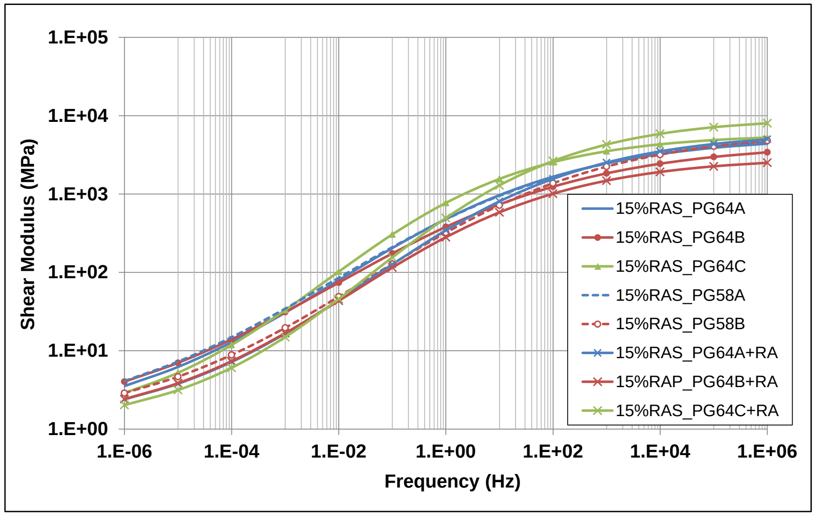


Figure 24. Shear Modulus Master Curves of FAM Mixes With 15% RAS Binder Replacement

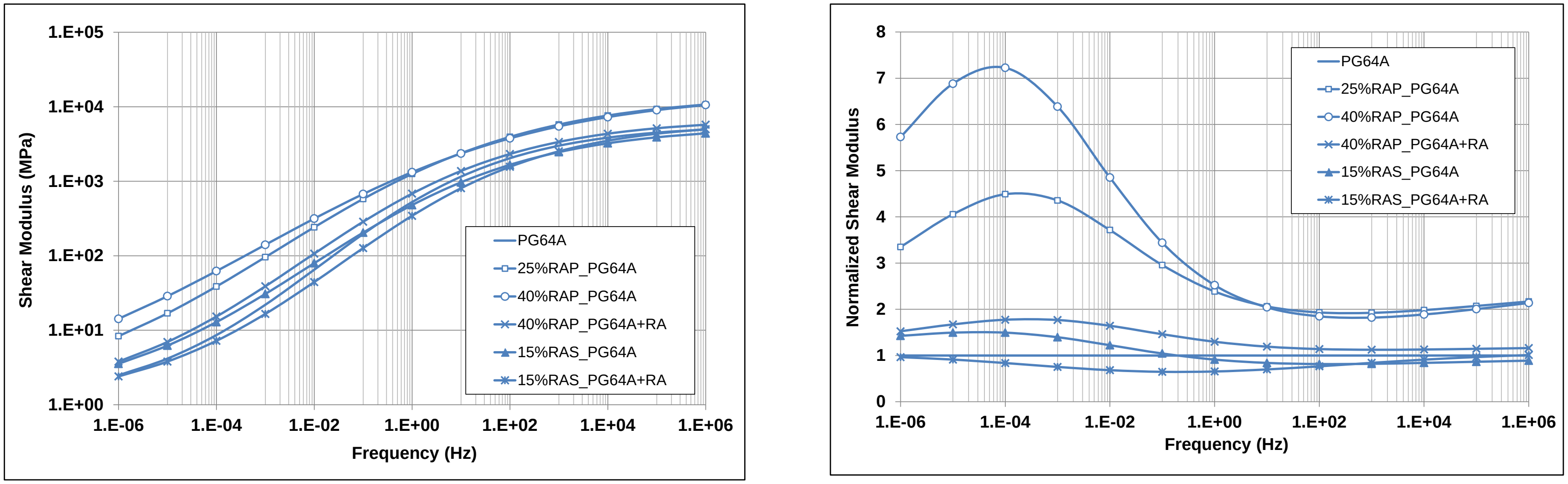


Figure 25. Shear and Normalized Modulus Master Curves of FAM Mixes for PG 64-16A

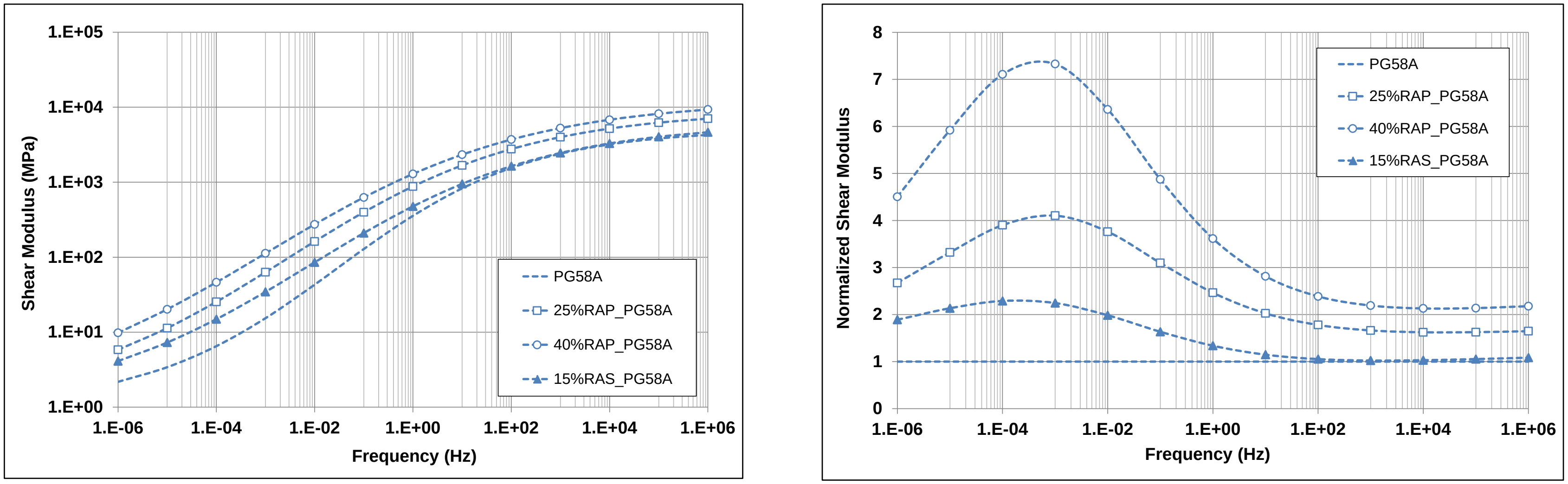


Figure 26. Shear and Normalized Modulus Master Curves of FAM Mixes for PG 58-22A

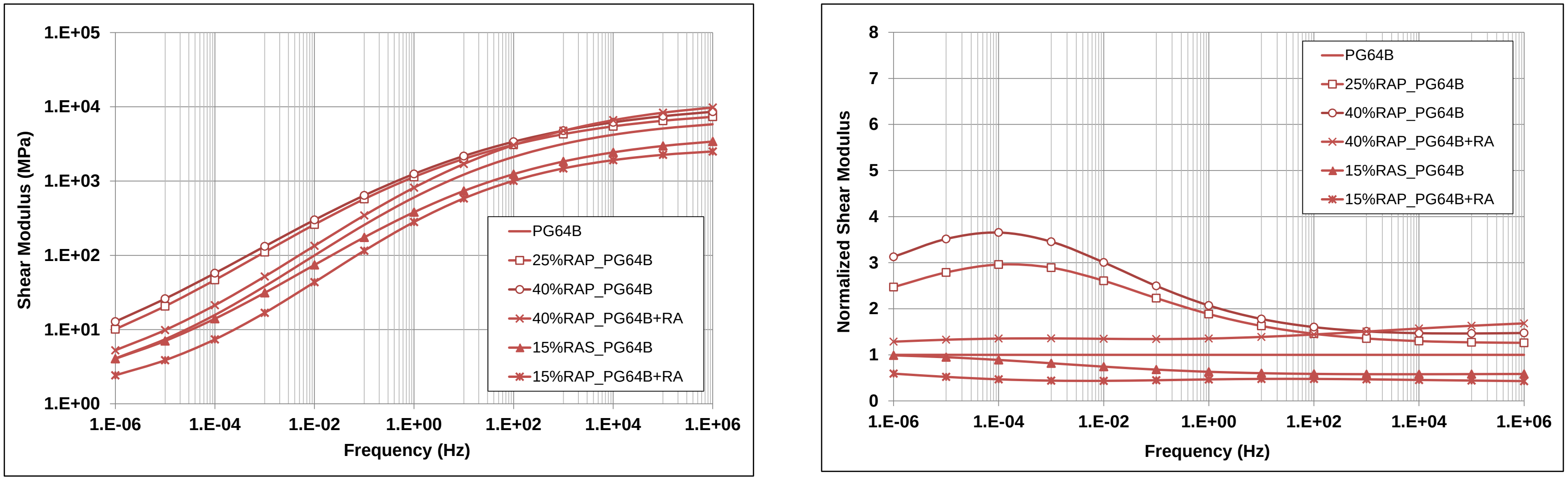


Figure 27. Shear and Normalized Modulus Master Curves of FAM Mixes for PG 64-16B

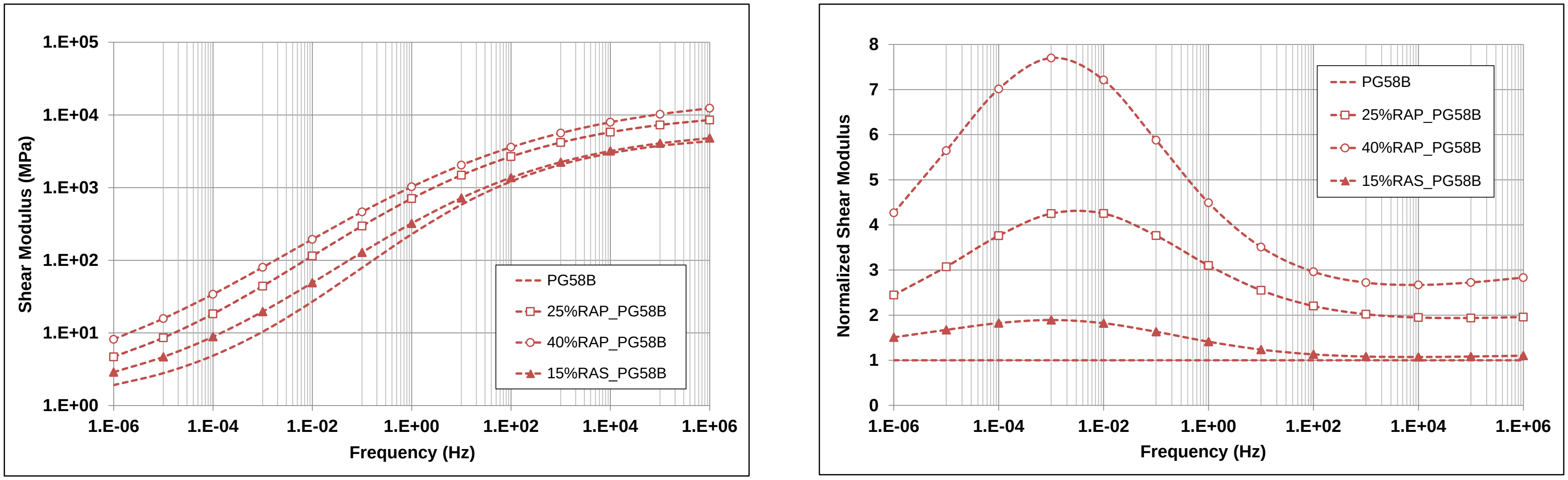


Figure 28. Shear and Normalized Modulus Master Curves of FAM Mixes for PG 58-22B

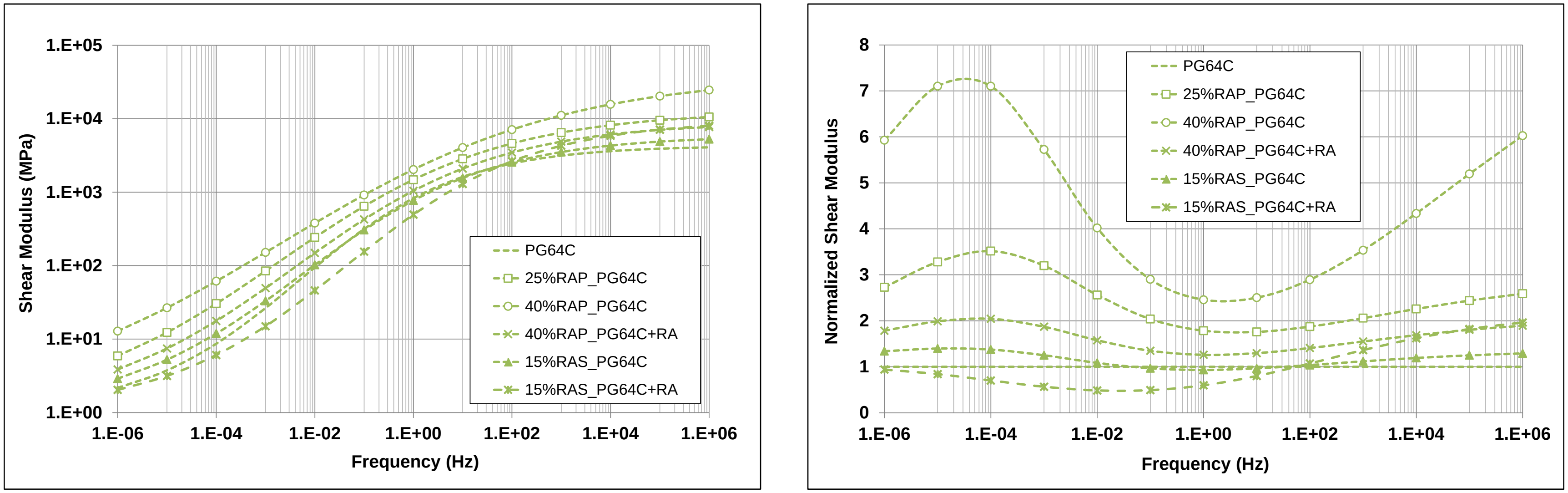


Figure 29. Shear and Normalized Modulus Master Curves of FAM Mixes for PG 64-16C

The following observations were made:

- The differences in shear moduli between the different control mixes were consistent with the differences in binder grade. Minor differences were noted between the binders with the same grade but from different refineries; this was attributed to the slight differences between the air-void contents of each specimen and potentially to the binder (i.e., crude oil) source. Mixes produced with PG 58 binders were less stiff than the mixes produced with PG 64 binders, as expected.

- Adding RAP to the mix increased the stiffness of all the mixes at all frequencies, as expected. The mixes with 40% binder replacement were correspondingly stiffer than those with the 25% binder replacement, especially at the lower testing frequencies. The normalized plots show that 25% and 40% RAP binder replacement caused respective stiffness increases up to 4.5 times and 7.5 times that of the virgin binder. The variation between the different mixes and binder grades was less apparent when compared to the mixes without RAP binder replacement.

- Adding RAS to the mixes appeared to have little effect on the shear moduli, supporting the observations and findings in section 6.3.2 that the RAS binder did not fully blend with the virgin binder and that differences in performance between the virgin and blended binders are attributable to differences in the effective binder content and to air-void content (see figures 17 and 18).

- The shear moduli of the FAM mixes with RA were lower than those of the corresponding mixes without the rejuvenator, as expected. The effect of the RA was more noticeable in the mixes containing RAP than in the mixes containing RAS.

6.3.4 Analysis of Variance.

The analysis of variance (ANOVA) approach was used to statistically identify the significance level of influential factors, which include the virgin binder source and grade, percentage of RAP and RAS binder replacement, and use of an RA.

The ANOVA was performed using the complex shear modulus (G*) values at 0.001 Hz, 1.0 Hz, and 1000 Hz frequencies at the reference temperature of 20°C as the dependent variables, and using binder source, binder grade, percent binder replacement, and use of the RA as the independent variables. The choice of $G^*_{0.001\text{ Hz}}$, $G^*_{1\text{ Hz}}$, and $G^*_{1000\text{ Hz}}$ as the dependent variables eliminated any potential bias caused by frequency and temperature.

The null hypothesis for the analysis was that the mean shear modulus was the same for all independent variable categories (i.e., the sample means of $G^*_{0.001\text{ Hz}}$ would be equal regardless of the amount of binder replacement). A significance level of 0.01 was used in the analysis (i.e., any variable with a p-value larger than 0.01 was considered to be statistically insignificant).

The ANOVA results are listed in table 12. Based on the p-values for the significant variables, the amount of reclaimed asphalt material used was the most significant factor influencing shear modulus at the three defined testing frequencies. The use of the RA was the next most significant factor. Asphalt binder source and binder grade had the least influence on the shear moduli of the evaluated FAM mixes at the selected frequencies. It should be noted that binders from just three CA refineries were assessed in this study; additional testing on different binder grades sourced from a larger geographical selection of refineries may increase the significance of binder grade and source.

Table 12. Results From ANOVA

Variable	Type	$G^*_{0.001\ Hz}$		$G^*_{1\ Hz}$		$G^*_{1000\ Hz}$	
		F-value	p-value	F-value	p-value	F-value	p-value
% Binder Replacement	0% 25% RAP 40% RAP 15% RAS	135.789	2.52e-15	121.726	1.63e-14	47.579	1.3e-08
Binder Source	Refinery A Refinery B Refinery C	0.217	0.806	15.859	5.77e-06	9.204	0.000434
Binder Grade	PG 64-16 PG 64-16 PG 58-22	2.920	0.064	1.043	0.361	0.174	0.841182
RA Effect	No RA With RA	91.360	1.68e-12	69.448	9.58e-11	15.319	0.000298

6.3.5 Comparing Asphalt Binder and FAM Mix Test Results.

Figures 30 through 32 show the relationship between the shear moduli of extracted asphalt binders and the corresponding shear moduli of the FAM mixes at frequencies of 0.1 Hz, 1.0 Hz, and 10 Hz (at the 20°C reference temperature), obtained from frequency sweep testing. These frequencies were selected since loading frequencies beyond this range are not typical on in-service pavements. Reasonable correlations (r^2 values) were observed between the asphalt binder stiffnesses and the FAM mix stiffnesses at these three frequencies. Discrepancies between the two measured stiffnesses may be an indication that complete blending of the virgin and reclaimed asphalt binders was not achieved in the FAM mix, but was forced during the chemical extraction and recovery. Although these preliminary results appear promising, only a limited number of tests were completed, and additional testing will be required before firm conclusions can be drawn.

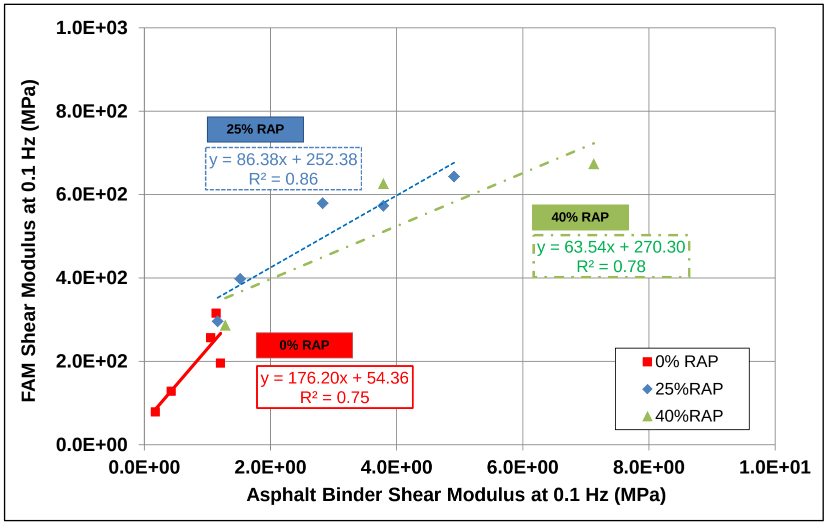


Figure 30. Comparison of Asphalt Binder and FAM Mix Shear Modulus (0.1 Hz at 20°C)

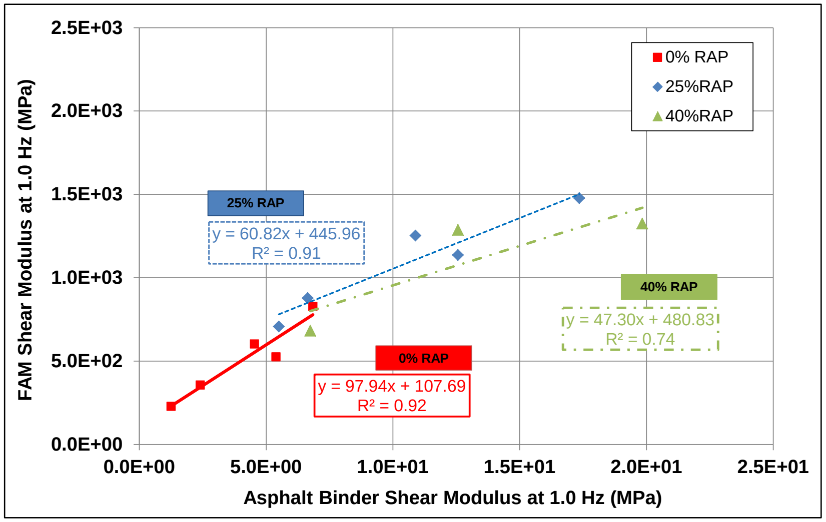


Figure 31. Comparison of Asphalt Binder and FAM Mix Shear Modulus (1.0 Hz at 20°C)

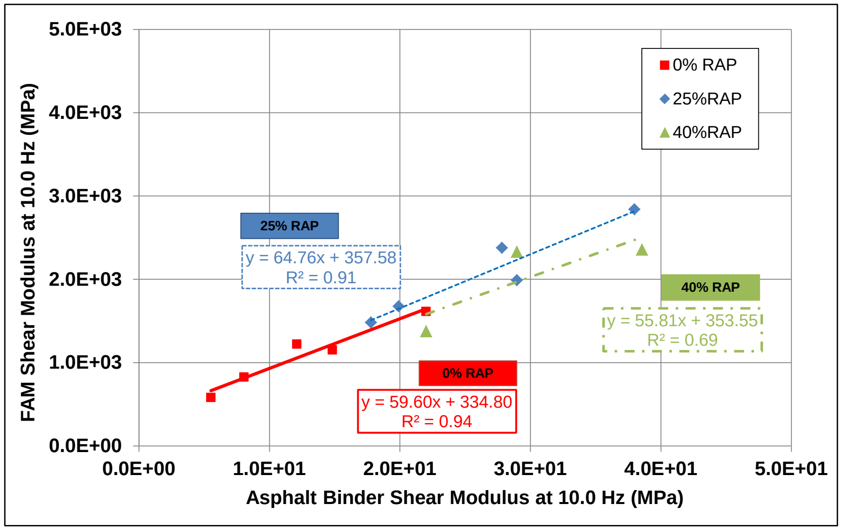


Figure 32. Comparison of Asphalt Binder and FAM Mix Shear Modulus (10 Hz at 20°C)

6.4 PHASE 1c TEST SUMMARY.

Based on the findings from this phase of the study, FAM mix testing is considered to be a potential appropriate alternative procedure to extraction and recovery for evaluating the properties of blended asphalt binder in mixes containing relatively high quantities of RAP and RAS. Further testing on a wider range of asphalt binder grades, asphalt binder sources, and RAP and RAS sources is recommended to confirm this conclusion and to develop models for relating binder properties determined from FAM mix testing to those determined from conventional performance-grade testing. Chemical analyses of blended binders may provide additional insights for interpreting test results and warrant further investigation.

Notable observations and findings from this phase of the study include the following:

- Preliminary testing of FAM mixes indicated that this approach appears to be repeatable (consistent results on multiple specimens by the same operator) and reproducible (consistent results by different operators), and produces apparently representative results for characterizing the performance-related properties of blended binders at binder replacement rates up to 40 percent and possibly higher. Although some experimentation with materials passing the 4.75 mm and 1.18 mm (#4 and #16) sieves was carried out, use of materials passing the 2.36 mm (#8) sieve is recommended to facilitate specimen preparation and to minimize variability in the results.

- Asphalt binder extracted and recovered from RAS could not be tested according to AASHTO M 320 due to its very high stiffness. The RAS binder was not sufficiently workable to mold specimens for testing in a DSR or in a BBR.

- The effect of RAP in increasing the stiffness of blended binders was dependent primarily on the asphalt binder grade and, to a lesser extent, by the source of asphalt binder.

- Statistical analyses of the test results indicate that asphalt binder grade and source, RAP and RAS content, and RA all had an influence on FAM mix stiffness, as expected. RAP and RAS content followed by the use of an RA had the most significant influence.

- The FAM mixes containing RAS showed similar stiffnesses to the corresponding control mixes (i.e., containing no reclaimed materials), suggesting that the RAS binder did not effectively blend with the virgin binder at the temperatures and mixing durations used in this study.

- The influence of RAs on reducing the blended binder and FAM mix stiffnesses was evident. Additional testing (beyond the scope of this study) is required to evaluate the long-term behavior of mixes produced with RAs to determine whether the benefits are limited to production and early life, or whether they extend through the design life of the layer.

- Reasonable correlations were observed between the stiffnesses of extracted blended binders and the stiffnesses of the corresponding FAM mixes at testing frequencies ranging from 0.1 Hz to 10 Hz. Discrepancies between the two measured stiffnesses may indicate that complete blending of the virgin and reclaimed asphalt binders was not achieved in the FAM mix, but was forced during the chemical extraction and recovery. The chemical solvent used in the extraction process also may have influenced the RAP binder properties. These factors warrant further investigation.

Based on the results of testing the RAS materials, RAS was not included in further phases of this study.

7. PHASE 2a: MIX DESIGN AND SPECIMEN PREPARATION.

The FAA has a set of standards and guidelines for materials and methods used in the construction of airport pavements [2], which covers Marshall and Superpave gyratory mix design methods for hot mix asphalt (HMA) used in the surface course of airfield pavements subjected to aircraft loading with gross weight greater than 12,500 pounds (5,670 kg). The mix design process discussed in this section followed the FAA P-401 Superpave mix design method [2].

7.1 EXPERIMENT DESIGN.

Table 13 summarizes the sampling and testing factorial for the materials assessed in Phase 2 of this UCPRC study. This factorial equates to a total of six different mixes. Note that mixes containing RAS were not tested based on the concerns identified during preliminary testing in Phase 1c (see section 6.3).

Table 13. Experimental Design Factors and Factorial Levels for Phase 2

Factor	Factorial Level	Details
Asphalt binder grade	3	PG 64-22 PG 58-28 PG 76-22 PM
Aggregate type	1	Granitic
RAP source	3	New York (NY) California (CA) Alabama (AL)
RAP content (by binder replacement)	3	0% (all three binders tested) 25% (2 binders [PG 64-22, PG 76-22 PM] and 3 RAP sources) 40% (1 [PG 58-28] and 1 RAP source [NY])
Anti-stripping agent (type and content)	1	Amine-based chemical (0.75% by weight of virgin binder used in the mix)

7.2 MIX DESIGN.

The FAA P-401 Superpave mix design [2] covers four primary steps, namely:

1. Material selection (aggregate and asphalt binder)
2. Selection of aggregate structure

3. Determination of optimum binder content
4. Controlling for asphalt mix moisture susceptibility

7.2.1 Material Selection.

7.2.1.1 Virgin Aggregate.

Granitic aggregates meeting the requirements specified in FAA P-401 [2] (as tested by the aggregate supplier) were sampled from four stockpiles at an aggregate quarry near Watsonville, CA. The aggregate gradations for each stockpile (tested by the UCPRC) are shown in table 14. Oven-dried aggregates were sieved to single sizes (ranging from 19 mm [3/4 in.] to 0.075 mm [#200]). Appropriate quantities of aggregates per size were batched according to the mix design gradations (see section 7.2.2) to obtain the specified mix volumetric properties.

Table 14. Phase 2: Gradation, Specific Gravity, and Absorption of Virgin Aggregate

Sieve Size		Stockpiles (% Passing)			
mm	in./mesh	3/4 x 1/2	1/2 x #4	1/4 x #10	Sand
25.4	1	100	100	100	100
19.0	3/4	85	100	100	100
12.5	1/2	27	95	100	100
9.50	3/8	10	61	100	100
4.75	#4	4	6	64	100
2.36	#8	3	4	8	86
1.19	#16	0	0	4	59
0.60	#30	0	0	3	38
0.30	#50	0	0	0	20
0.15	#100	0	0	0	9
0.075	#200	0	0	2	5

7.2.1.2 Asphalt Binders.

The FAA P-401 specification [2] states that the initial PG of asphalt binder must be consistent with that specified by the local state department of transportation for interstate highway projects in the vicinity of the airport. Adjustment of the initial grade (bumping) is required as listed in table 15. The low PG grade of the binder must not be higher (warmer) than -22°C since this may increase the chance of block cracking. The elastic recovery must be higher than 70% for PM binders.

Table 15. The FAA Guidance for Binder Performance Grade Adjustment

Aircraft Gross Weight (lb/kg)	High-Temperature Adjustment to Binder Grade (All Pavement Types)
≤12,500/5,670	--
<100,000/45,360	1 Grade
≥100,000/45,360	2 Grade

Note: Typically, rutting is not a problem on airport pavements. However, at airports with a history of stacking on the end of runways and taxiway areas, rutting has occurred due to the slow speed of loading on the pavement. If rutting has been observed or it is anticipated that stacking may occur during the design life of the project, then grade bumping should be applied for the top 5 in. (125 mm) of paving at the end of runways and taxiways as follows for aircraft tire pressures between:

- 100 and 200 psi (0.7 and 1.4 MPa), increase the high temperature by one grade. Do not adjust the low-temperature grade.
- >200 psi (1.4 MPa), increase the high temperature by two grades. Do not adjust the low-temperature grade.

Using these guidelines, two unmodified asphalt binders (PG 64-22 and PG 58-28) and one PM binder (PG 76-22 PM) were used in this phase of the UCPRC study. All binder grades were supplied by one local refinery in northern CA (Refinery A in Phase 1). The PG 58-28 binder was the same as that used for the base binder in the production of the PM binder. The high, intermediate, and low PG temperatures for the three binders were determined in accordance with AASHTO M 320 [78] and the results are shown in table 16.

7.2.1.3 Anti-Stripping Agent.

A commercial amine-based, liquid anti-stripping agent meeting the FAA P-401 specifications [2] was used in this study to meet moisture resistance specifications.

Table 16. The PG Results of Asphalt Binder

Critical Temperature	Aging Condition	Test Parameter	PG 58-28	PG 64-22	PG 76-22 PM
High	Unaged	$G^*/\sin\delta \geq 1.00$ kPa	59.7	66.5	80.1
High	RTFO-aged	$G^*/\sin\delta \geq 2.20$ kPa	60.4	67.8	82.5
Intermediate	RTFO-aged	$G^* \times \sin\delta \leq 5000$ kPa	16.5	22.7	14.3
Low	RTFO-aged	$S(60) \leq 300$ MPa[1]	184 (at -18°C)	176 (at -12°C)	54 (at -12°C)
Low	PAV-aged	m-value ≥ 0.30[1]	0.35 (at -18°C)	0.34 (at -12°C)	0.43 (at -12°C)

[1] Values correspond to testing performed at 10°C warmer than PG grade temperature.

7.2.1.4 Reclaimed Asphalt Pavement.

The current FAA P-401 specification [2] does not allow the use of RAP in HMA used in surface layers on runways, taxiways, and aprons. It is, however, permitted in mixes used in lower layers or shoulders. These mixes may contain up to 30% RAP by weight of the mix, but the mix must still meet the requirements specified for HMA with no reclaimed material. RAP must have a consistent gradation with a maximum size less than 38 mm (1.5 in.). Mixes containing more than 20% RAP by weight of the mix must use a one-grade softer binder (both high and low PG temperatures). RAS is currently not permitted in any asphalt mixes used on airport pavements.

RAP materials were obtained from sources in three states, New York, California, and Alabama, and these are referred to as NY, CA, and AL respectively in the test results in this report. The NY RAP materials were sampled at two different times (April 2015 and December 2015). The majority of the mixes containing NY RAP were made with materials sampled in April 2015. The AL RAP was fractionated into coarse, (passing the 9.5 mm (3/8 in.) sieve and retained on the 2.36 mm (#8) sieve) and fine (passing the 2.36 mm (#8) sieve) sizes.

Gradation and asphalt binder content of the RAP aggregates were determined using both extraction and recovery (AASHTO T 164 [78] and ASTM D 1856 [83]) and ignition oven (AASHTO T 308 [90]) tests. The gradations (AASHTO T 30 [84]), specific gravities, and absorption for the fine and coarse aggregates (AASHTO T 85 [94] and AASHTO T 84 [95]) were determined for both recovered and burned aggregates. The NY RAP materials sampled in December 2015 were tested using extraction and recovery only.

Gradations and binder contents for the recovered and burned aggregates are listed in tables 17 and 18, respectively. Gradations are illustrated in figures 33 to 36. For all three RAP sources, the burned aggregates were slightly finer than the recovered aggregates; this was expected, since the ignition oven can result in degradation of the aggregates, which generates more fine material. The NY RAP had the finest gradation followed by the CA RAP and the AL RAP. Based on the NY and CA RAP gradations, the two AL RAP samples were combined into a single sample in a 70% coarse to 30% fine RAP ratio.

Gradations of the three RAP sources are compared in figure 37, which shows that the range of particle size distributions was achieved and were representative of typical expected variability from different RAP sources.

Table 17. The RAP Gradations and Binder Contents (Chemical Extraction)

Gradation (% Passing)						
Sieve Size		NY			AL	
mm	in./mesh	April 2015	December 2015	CA	Retained #8	Passing #8
25.4	1	100	100	100	100	100
19.0	3/4	100	100	100	100	100
12.5	1/2	100	100	100	100	100
9.50	3/8	100	100	96	93	100
4.75	#4	90	89	74	55	100
2.36	#8	63	65	56	22	100
1.19	#16	47	51	43	16	82
0.60	#30	35	39	33	12	57
0.30	#50	23	25	22	7	32
0.15	#100	14	16	13	5	17
0.075	#200	9	11	8	3	9
Asphalt Binder Content (%)						
Total mix		6.30	5.62	4.51	2.73	6.23
Mass of dry aggregate		6.73	5.96	4.57	2.81	6.64

Table 18. The RAP Gradations and Binder Contents (Ignition Oven)

Gradation (% Passing)					
Sieve Size		NY		AL	
mm	in./mesh	April 2015	CA	Retained #8	Passing #8
25.4	1	100	100	100	100
19.0	3/4	100	100	100	100
12.5	1/2	100	100	99	100
9.50	3/8	100	97	93	100
4.75	#4	91	74	54	100
2.36	#8	63	55	22	100
1.19	#16	49	44	17	83
0.60	#30	37	34	13	60
0.30	#50	25	24	8	36
0.15	#100	17	18	6	23
0.075	#200	12	12	4	15
Asphalt Binder Content (%)					
Total mix		7.19	5.75	2.85	6.89
Mass of dry aggregate		7.75	6.10	2.93	7.40

Binder contents in the RAP are illustrated in figure 38. The ignition oven method resulted in higher binder contents than those obtained by solvent extraction for all the RAP sources. This was attributed to not all the binder in the RAP being extracted by the chemical solvent [37 and 41]. The NY RAP had the highest binder content followed by the CA RAP and the AL RAP.

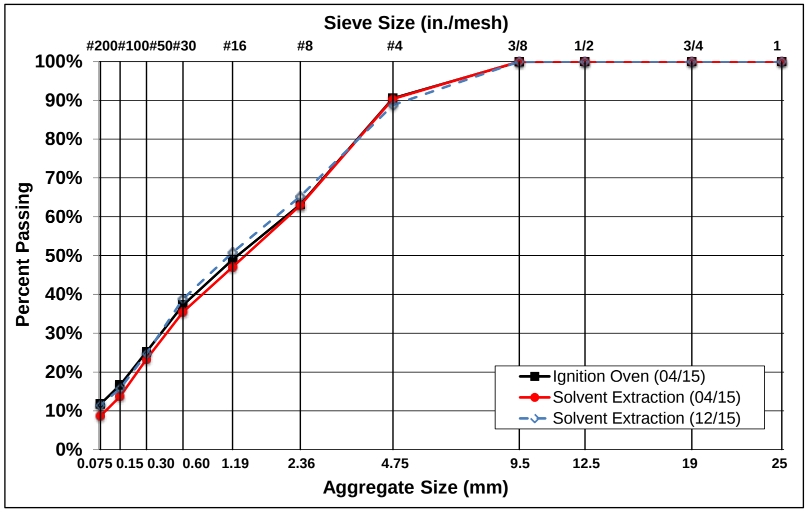


Figure 33. Gradations of NY RAP

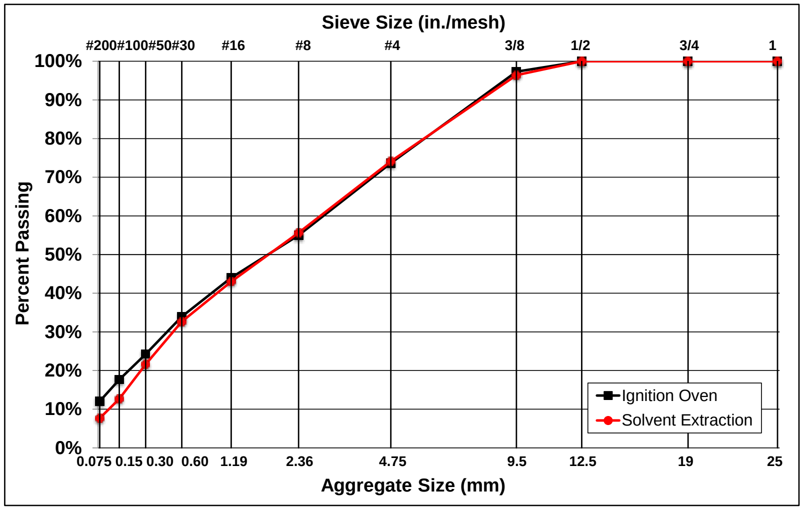


Figure 34. Gradations of CA RAP

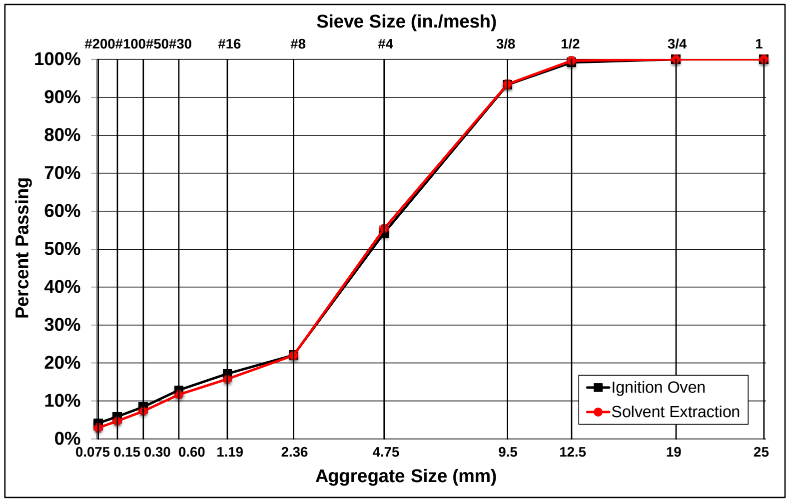


Figure 35. Gradations of AL Coarse RAP

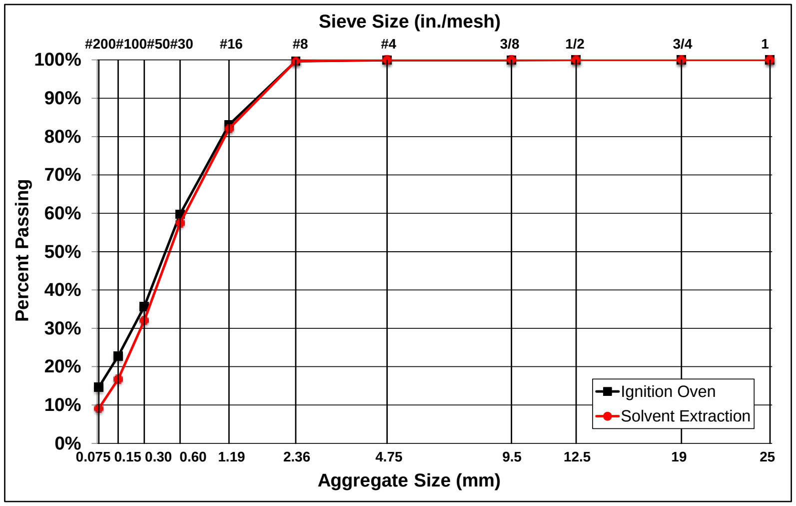


Figure 36. Gradations of AL Fine RAP

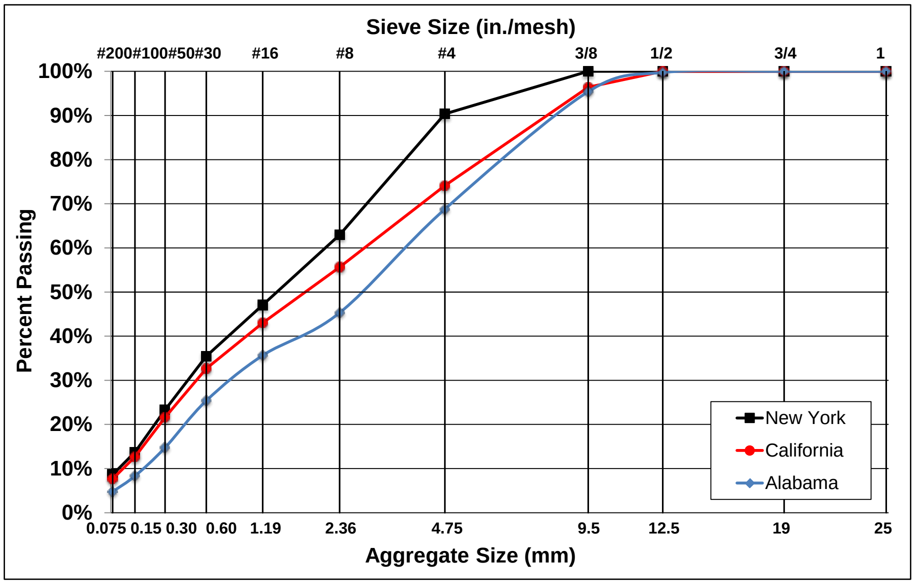


Figure 37. Comparison of RAP Aggregate Gradations by Solvent Extraction

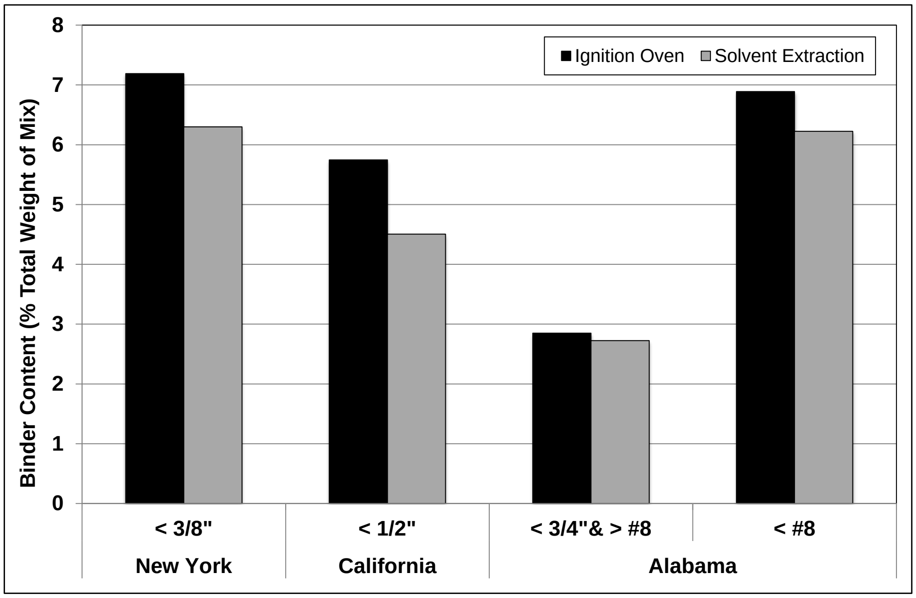


Figure 38. The RAP Asphalt Binder Contents

Bulk specific gravity and absorption of burned and recovered RAP aggregates are shown in figures 39 and 40, respectively. Bulk specific gravity was highest for the NY RAP and lowest for the AL RAP. Burned aggregates generally had higher bulk specific gravities than extracted aggregates (coarse AL RAP was the exception). This was attributed to the different gradations. Extracted aggregates generally had higher absorptions than burned aggregates (coarse AL RAP was again the exception).

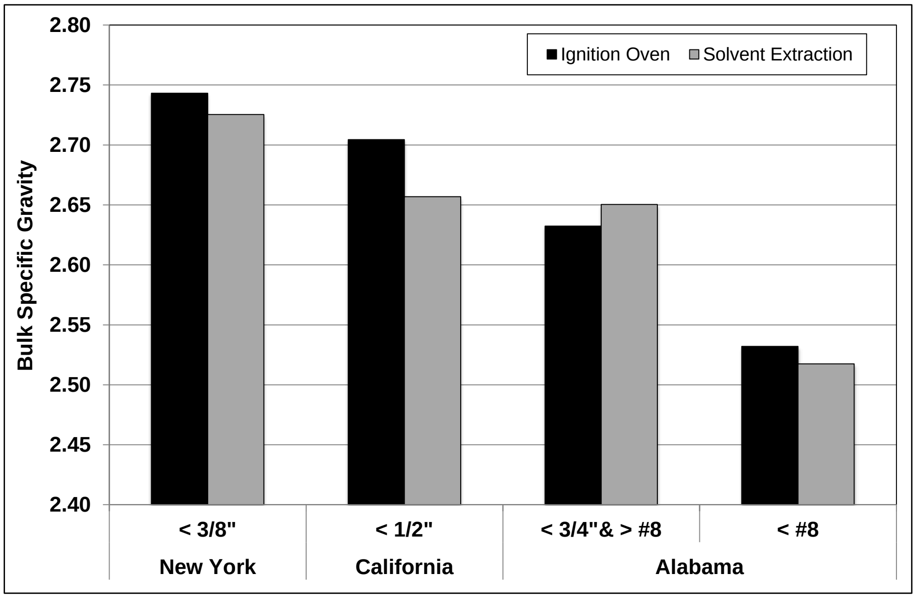


Figure 39. Bulk Specific Gravity of RAP Aggregates

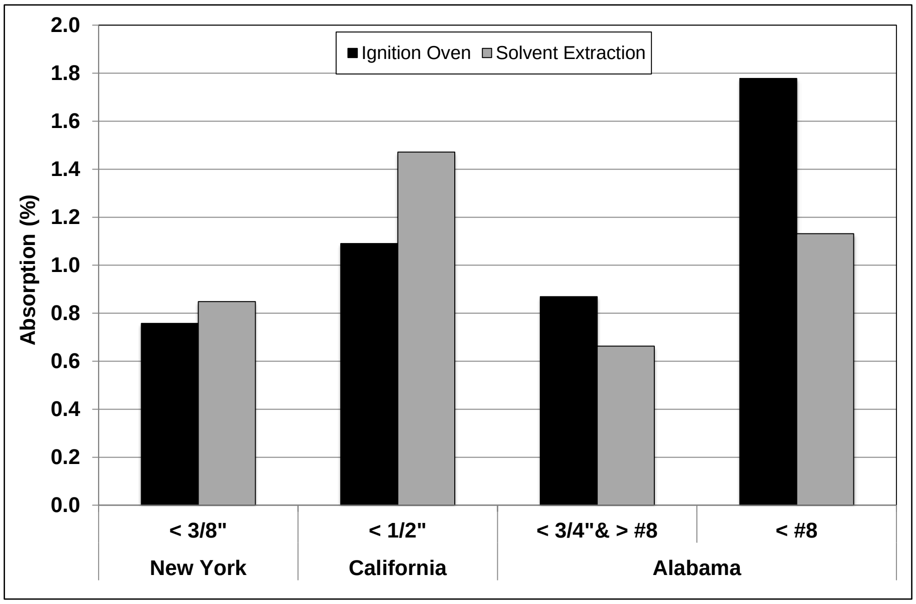


Figure 40. Absorption of RAP Aggregates

7.2.2 Selection of Aggregate Structure.

The aggregate gradation for airfield mix designs must be selected based on the FAA P-401 gradations [2] specified in table 19. Gradation-1 is a 3/4-in. (19-mm) coarser gradation mix and is typically used in thicker lifts of asphalt concrete. Gradation-2 is a 1/2-in. (12.5-mm) mix typically used in thinner lifts or where a smoother, less permeable mix is required. Gradation-3 can only be used for leveling course, airfield shoulders, and roadways. The maximum aggregate size may not be greater than one-quarter of the lift thickness. For this study, a number of trial formulations were evaluated to select an appropriate gradation that met the specified individual size ranges as well as the volumetric requirements, primarily VMA.

Table 19. The P-401 Aggregate Gradations for Asphalt Mixes [2]

Sieve Size		Gradation (% Passing)		
mm	in./mesh	Gradation-1	Gradation-2	Gradation-3
25.4	1	100	--	--
19.0	3/4	76-98	100	--
12.5	1/2	66-86	79-99	100
9.50	3/8	57-77	68-88	79-99
4.75	#4	40-60	48-68	58-78
2.36	#8	26-46	33-53	39-59
1.19	#16	17-37	20-40	26-46
0.60	#30	11-27	14-30	19-35
0.30	#50	7-19	9-21	12-24
0.15	#100	6-16	6-16	7-17
0.075	#200	3-6	3-6	3-6
Asphalt Binder Content (%)				
Stone or gravel		4.5-7.0	5.0-7.5	5.5-8.0
Slag		5.0-7.5	6.5-9.5	7.0-10.5

Four trial gradations of the virgin aggregate were assessed, as shown in table 20 and in figure 41. All the gradations were selected to fall within the FAA P-401 specified gradation limits [2].

Table 20. Virgin Aggregate Trial Gradations for Mix Design

Sieve Size		Gradation (% Passing)			
mm	in./mesh	Trial #1	Trial #2	Trial #3	Trial #4
25.4	1	100	100	100	100
19.0	3/4	87	96	96	96
12.5	1/2	76	84	84	84
9.50	3/8	67	75	75	75
4.75	#4	50	55	48	55
2.36	#8	36	40	28	35
1.19	#16	27	28	18	20
0.60	#30	19	19	12	12
0.30	#50	13	11	8	7
0.15	#100	11	7	6	6
0.075	#200	5	4	3	3

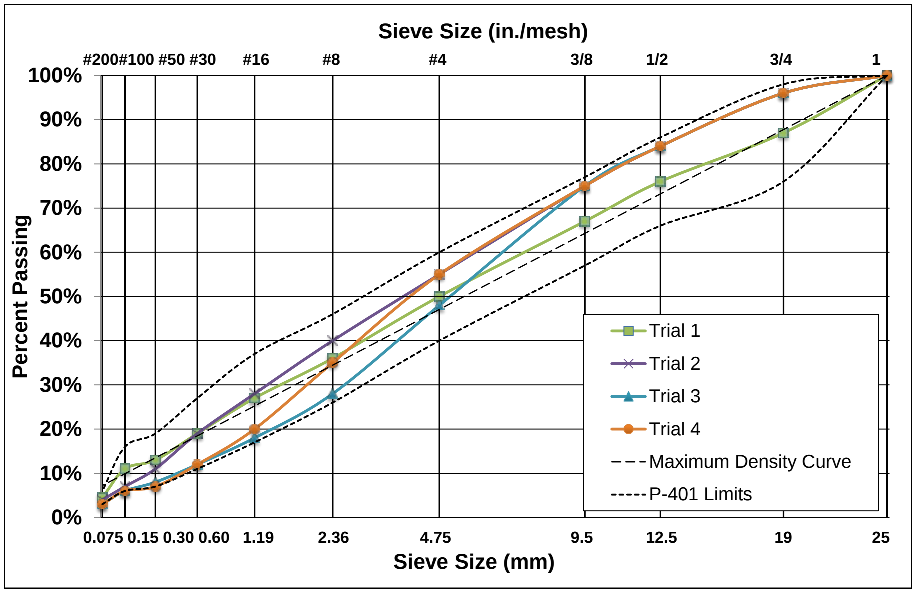


Figure 41. Gradation Curves for Trial Aggregate Structures

7.2.3 Determination of Optimum Binder Content.

The current FAA P-401 specification requires that the optimum asphalt binder must be determined by preparing asphalt mixes at different binder contents and then compacting them to the number of gyrations specified based on the gross weight of aircraft and tire pressure [2] (table 21). The heaviest aircraft traffic was selected for this study, and therefore trial mixes were compacted to 75 gyrations. The specification requires that the optimum binder content of the mix should correspond to a 3.5% air-void content in the compacted specimens [2]. The specification has a minimum requirement for VMAs (see table 22), but no requirements for VFA or DP [2].

Although three grades of asphalt binder were used in this study, the control mix design was only conducted on mixes prepared with PG 64-22 binder. It was assumed that the binder grade would not significantly change the mix volumetrics, given that the binder viscosities of the three asphalt binders were relatively similar at the mixing and compaction temperatures.

Table 21. The P-401 Required Number of Compactor Gyrations and Target Air-Void Content

Test Properties	Pavements Designed for Aircraft Gross Weight ≥60,000 lb or Tire Pressure ≥100 psi	Pavements Designed for Aircraft Gross Weight <60,000 lb or Tire Pressure <100 psi
Number of compactor gyrations	75	50
Target air-void content (%)	3.5	3.5

Table 22. Minimum P-401 Required VMA

Aggregate Gradation (see table 19)	Minimum VMA (%)
Gradation-1	14
Gradation-2	15
Gradation-3	16

Asphalt mixes were prepared at an estimated optimum binder content of 5% (close to the lower limit of the recommended binder content for Gradation-1 in table 19). After short-term aging of the loose mix for 2 hours at the compaction temperature (AASHTO R 30 [88]), the mixes were compacted to 75 gyrations at 600 kPa (87 psi) pressures using a Superpave gyratory compactor (AASHTO T 312 [91]). The air-void content and VMA of the compacted specimens were calculated based on the volumetric equations provided in AASHTO R 35 [87], but modified for a design air-void content of 3.5%, as specified in FAA P-401 [2] (the design air-void content for highway pavements is typically 4.0%). Table 23 shows the measured and estimated volumetrics at the design air-void content. Based on the estimated VMA values, Trial Gradation #3, shown in bold in table 23 and featured in figure 42, was selected as the design aggregate structure. Table 24 provides the bulk specific gravity (dry), apparent specific gravity, and absorption for the fine and coarse fractions of the selected gradation (i.e., Trial #3).

Table 23. Volumetrics of Mixes Prepared With Different Gradations

Gradation	Binder Content (%)	Air-Void Content (%)	VMA (%)	Estimated VMA at 3.5% Air Voids
Trial #1	5	1.1	10.2	10.3
Trial #2	5	3.5	12.6	12.5
Trial #3	**5**	**6.1**	**14.4**	**14.6**
Trial #4	5	6.6	15.3	15.5

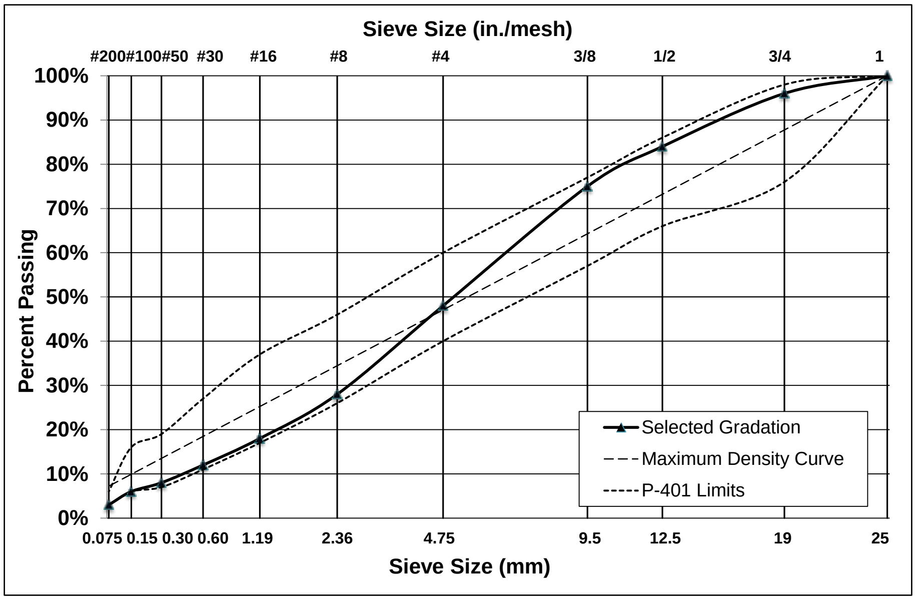


Figure 42. Gradation Curve for Selected Trial #3 Aggregate Structure

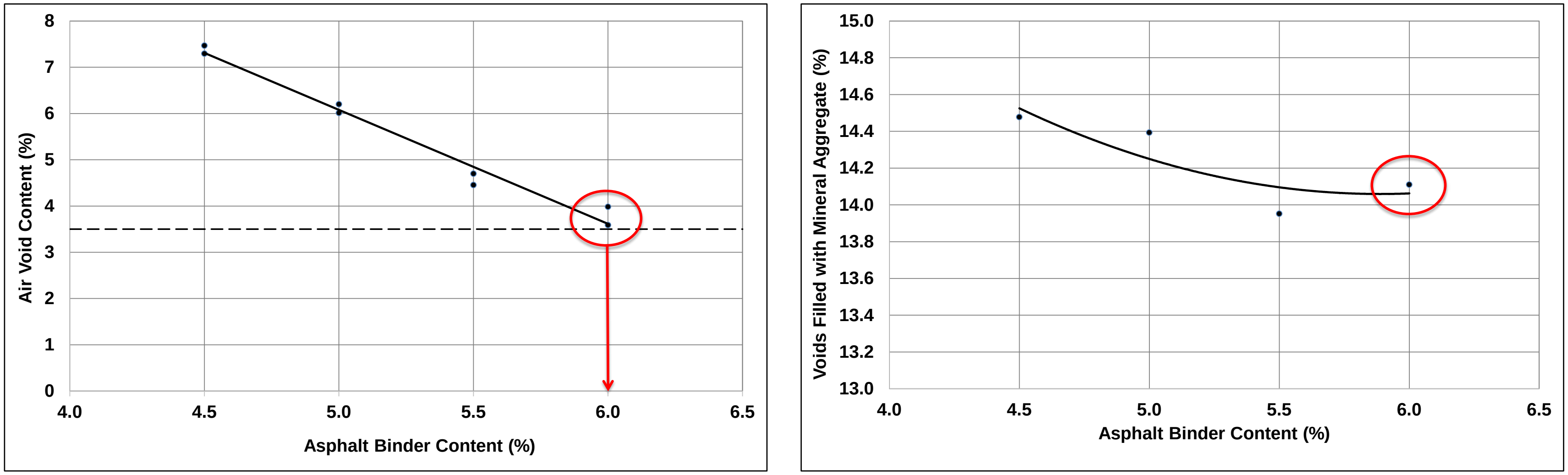
Table 24. Specific Gravity and Absorption Values in the Selected Gradation

Property	Fine Aggregate	Coarse Aggregate
Bulk specific gravity (dry)	2.690	2.720
Bulk specific gravity (SSD[1])	2.743	2.763
Apparent specific gravity	2.841	2.843
Absorption (%)	1.988	1.592

[1] Saturated surface dry

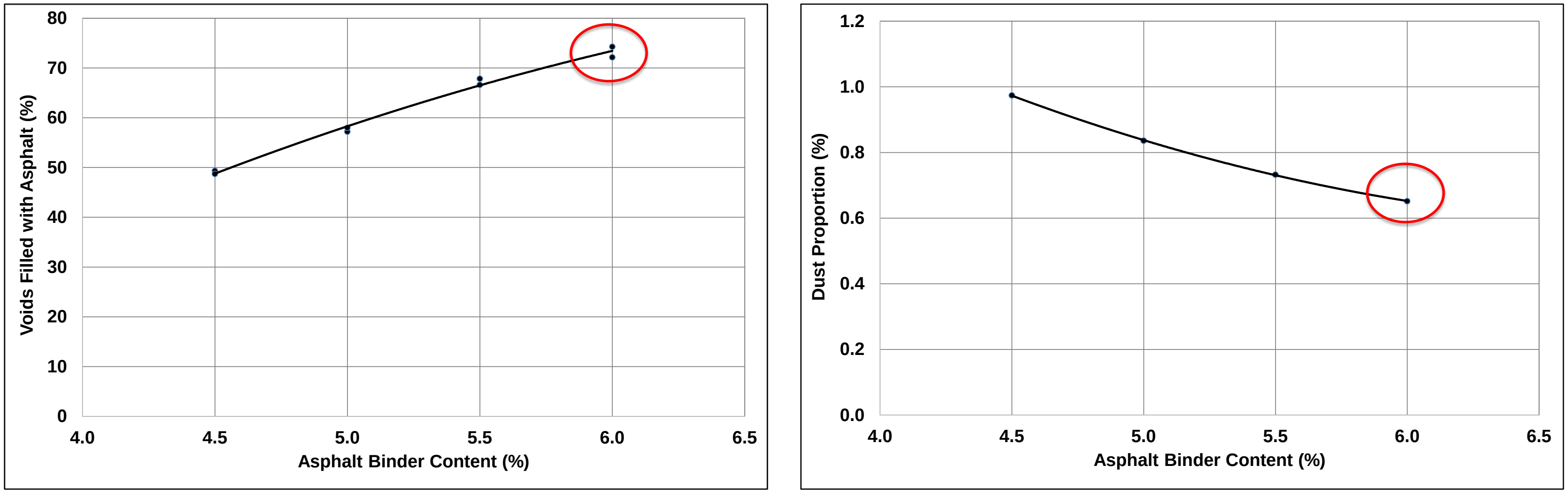
Asphalt mixes were then prepared at four different binder contents (4.5%, 5.0%, 5.5%, and 6.0%) to determine the optimum binder content for the selected aggregate gradation (i.e., Trial #3). The loose mixes were aged for 2 hours at the compaction temperature followed by compaction with 75 gyrations. Bulk specific gravity, VMA, VFA, and DP values were calculated for each mix prepared at the different binder contents. Although the FAA P-401 specification [2] does not have limits for VFA and DP, they are required by most state departments of transportation and were therefore considered in all mix volumetric calculations in this study.

Figure 43 shows the relationship between binder content and volumetrics. The optimum binder content to achieve the FAA P-401 design 3.5% air-void content was 6.0%. VMA, VFA, and DP at 6.0% binder content were verified and the results are listed in table 25.



Asphalt Binder Content vs Air-Void Content

Asphalt Binder Content vs VMA



Asphalt Binder Content vs VFA

Asphalt Binder Content vs DP

Figure 43. Changes in Mix Volumetrics With Different Asphalt Binder Contents

Table 25. Asphalt Mix Volumetrics at Optimum Binder Content

Mix Volumetrics	Values (%)
Asphalt binder content	6.0
Air-void content	3.5
VMA	14.1
VFA	74.0
DP	0.65

7.2.4 Controlling for Mix Moisture Susceptibility.

The FAA P-401 specification requires that the TSR of the asphalt mix (based on AASHTO T 283 [96]) shall not be less than 75 when tested at a 70% to 80% saturation level [2]. A liquid anti-stripping agent can be used to remedy moisture susceptibility problems.

TSR tests were conducted on prepared specimens to check moisture sensitivity. The results are shown in figure 44 and indicate that the TSR of the mix was 78, which was close to the minimum limit of 75. Since the moisture sensitivity was considered to be marginal, a mix with an amine liquid anti-stripping agent was prepared (0.75% by weight of asphalt binder) and tested. The results showed a considerable improvement in TSR. All mixes tested in this study were therefore treated with the anti-stripping agent.

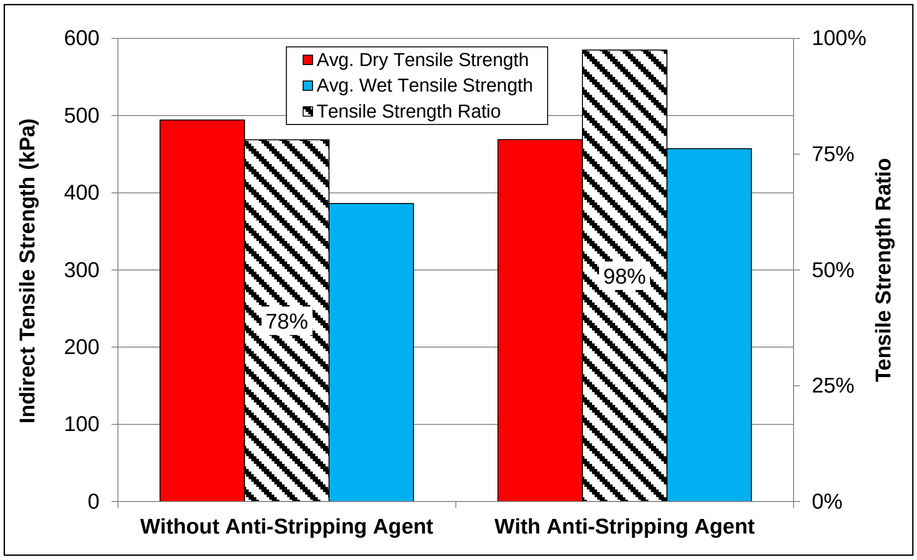


Figure 44. Average IDT Strength and TSR
(Control mix with PG 64-22 binder before and after adding RA.)

7.3 MIX DESIGN: MIXES CONTAINING RAP.

The focus of this study was to compare the properties and performance of a control mix (i.e., containing no RAP) with those of mixes containing 25% and 40% RAP by binder replacement. To facilitate this comparison, the combined gradations and binder contents of the RAP mixes were kept as close as possible to the gradation and binder content of the control mix. This was achieved by first calculating the quantity of RAP material that would provide the required binder replacement and then adjusting the gradation of the virgin aggregate so that the combined gradation of virgin aggregate and RAP aggregate was as close as possible to the target gradation of the control mix while still meeting the FAA P-401 volumetric requirements [2]. Mixes containing 25% RAP were prepared with the same PG 64-22 virgin asphalt binder used in the mix design of the control mix. Mixes containing 40% RAP were prepared with the PG 58-28 virgin asphalt binder to compensate for the stiffening effect of the higher RAP binder content. When calculating the mix volumetrics, the properties of the RAP determined from both ignition oven and solvent extraction tests were used.

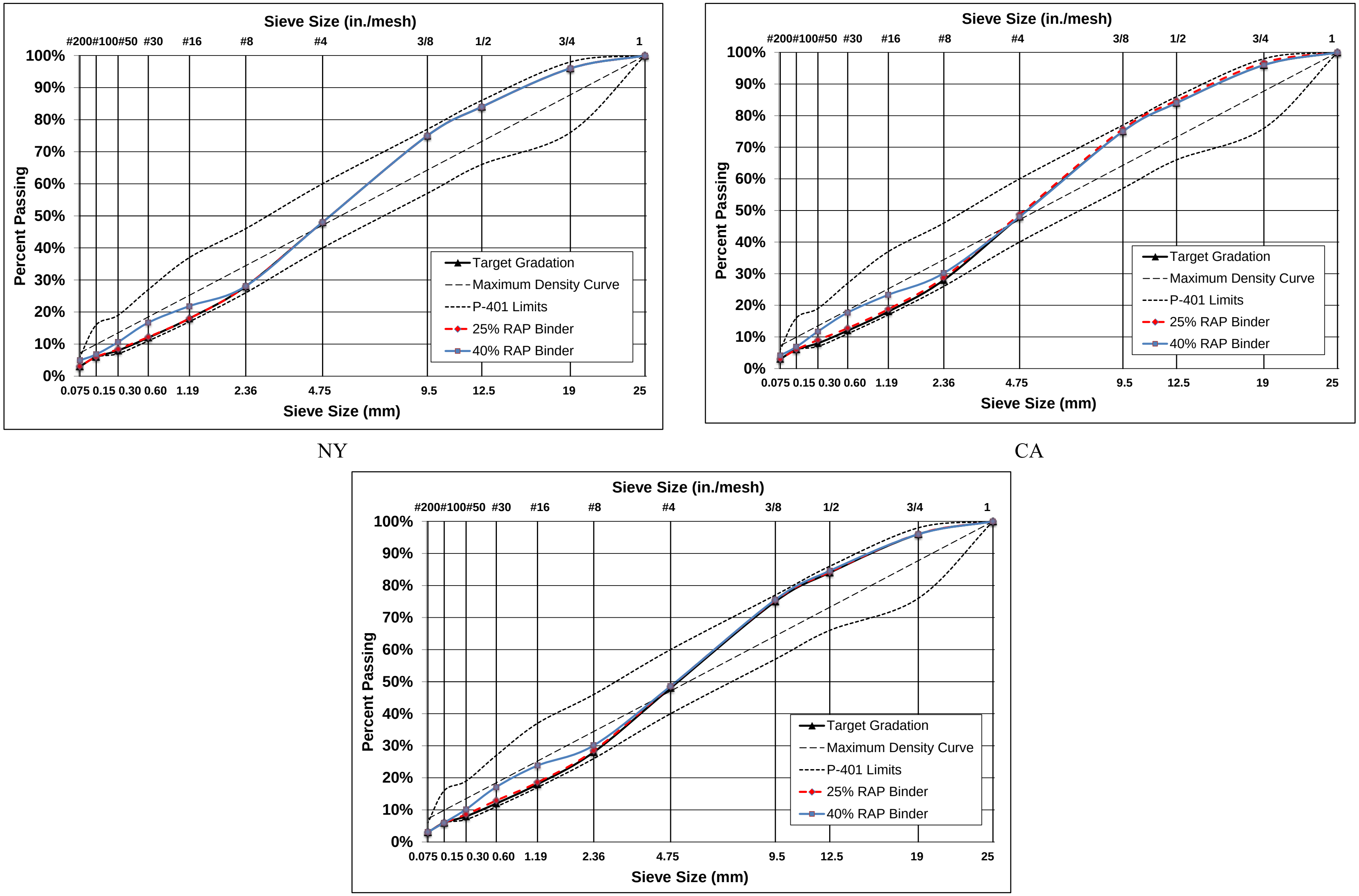
Gradations of the three mixes containing 25% and 40% of each RAP source are shown in figure 45. The gradations of the mixes with 25% RAP were identical to the target gradation. However, the gradation of the 40% RAP mixes were slightly coarser (but still within the FAA P-401 gradation limits) as a result of the higher RAP contents. Only limited adjustment of the grading was possible if all the FAA P-401 specification requirements were to be met.

Figures 46 through 49 show the air-void content, VMA, VFA, and DP for the 25% and 40% RAP mixes.

The difference in volumetrics resulting from the two binder content determination processes (ignition oven and solvent extraction) was negligible. The mix with 25% NY RAP and 6.0% total binder content met the volumetric criteria specified in FAA P-401 [2] (i.e., air-void content and VMA). However, the air-void contents of the mixes with 25% CA and AL RAP were lower than the FAA P-401 specified value of 3.5%, and therefore the total binder content for these two mixes was lowered to 5.5%. The volumetric criteria for both mixes were met at this binder content. The reduction in binder content was achieved by reducing the quantity of virgin binder; the quantities of RAP and virgin aggregate were not altered. These adjustments to the virgin binder content therefore effectively increased the RAP binder replacement rate to 27% for the CA and AL RAP mixes.

7.4 FINE AGGREGATE MATRIX MIX DESIGN.

The binder content and aggregate gradations determined in the mix designs described previously were used as the basis for the FAM mix design. Sample preparation followed the process described in section 6.1.5. The binder contents of the FAM mixes were determined using the ignition oven test (AASHTO T 308 [90]) as it was considered to provide a more accurate indication of the total binder content than solvent extraction. Binder contents and gradations of the RAP aggregates were determined by both ignition oven and by extraction and recovery to identify which method provided the better estimation of the amount of available binder in the RAP materials to mobilize and effectively blend with the virgin binder. The binder content results are shown in figure 50 and based on these results solvent extraction and recovery was selected as the most appropriate method. RAP gradations are shown in figures 51 through 53. The gradations of the burned RAP aggregates were finer than the recovered RAP aggregate, consistent with other studies that have shown that the very fine portion (≤0.075 mm [#200]) can be burned off in the process.



NY

CA

AL

Figure 45. Aggregate Gradations of Mixes With 25% and 40% RAP

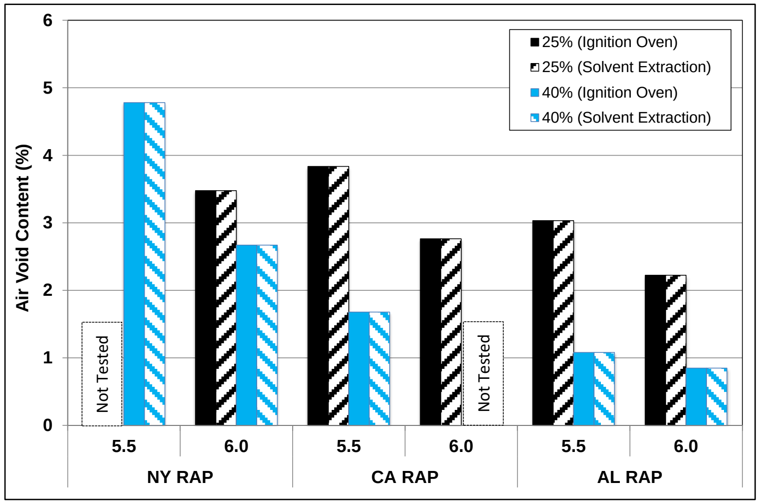


Figure 46. Air-Void Contents

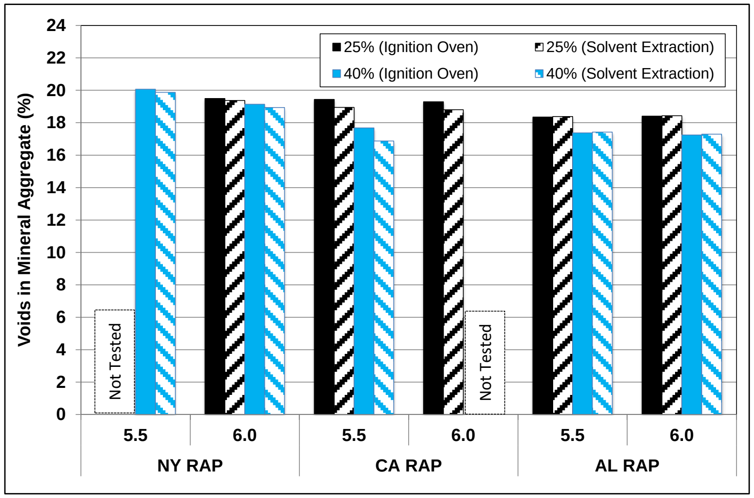


Figure 47. Voids in Mineral Aggregates

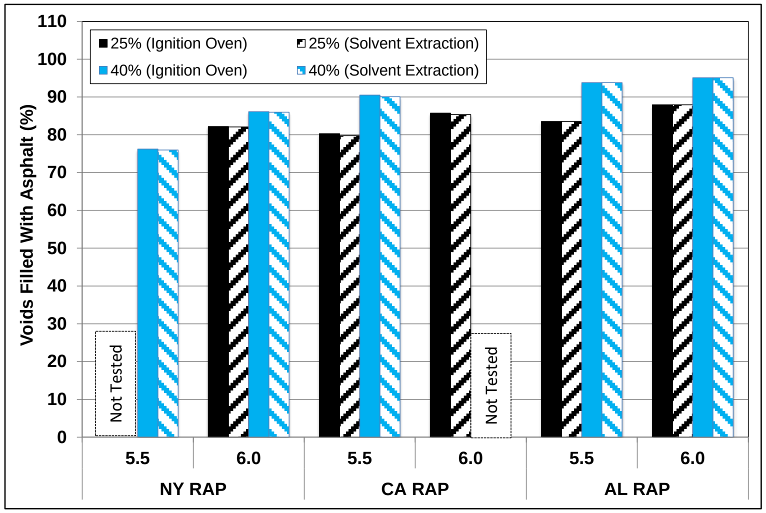


Figure 48. Voids Filled With Asphalt

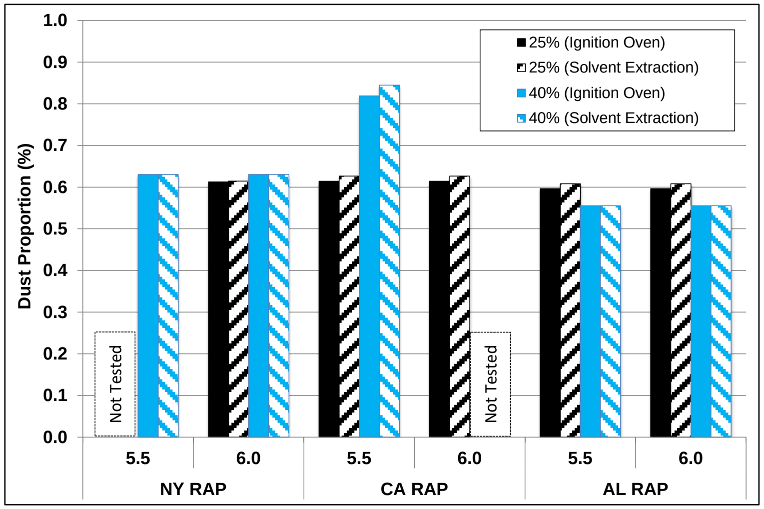


Figure 49. Dust Proportion

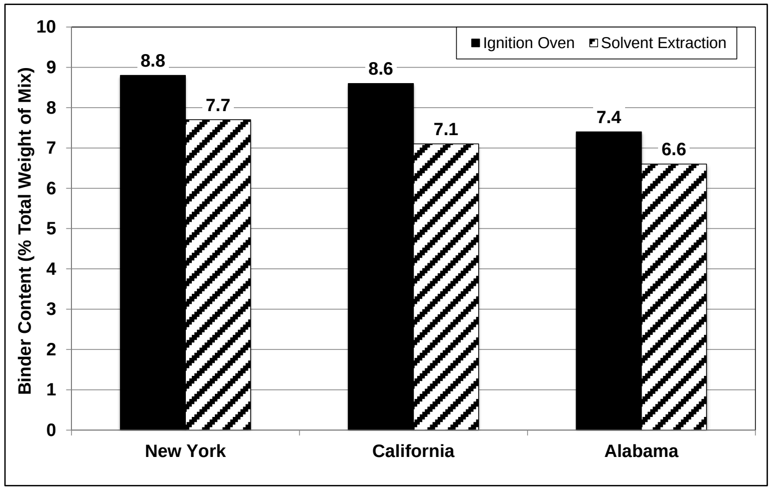


Figure 50. Binder Contents of Fine RAP Materials

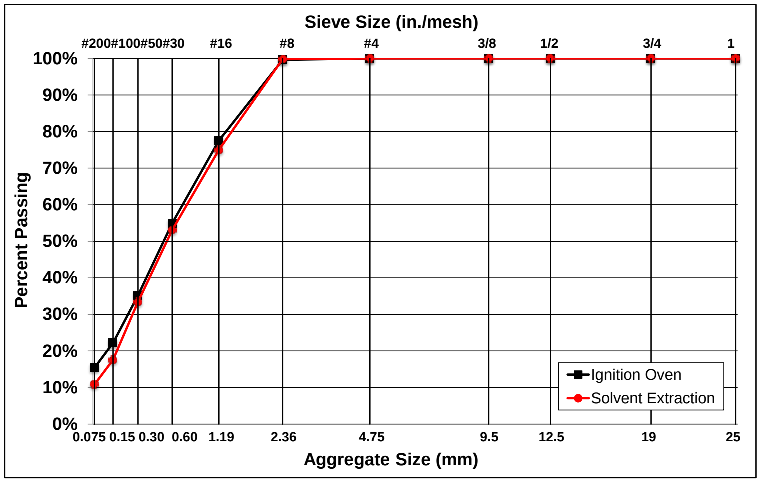


Figure 51. Fine Aggregate Gradations of NY RAP

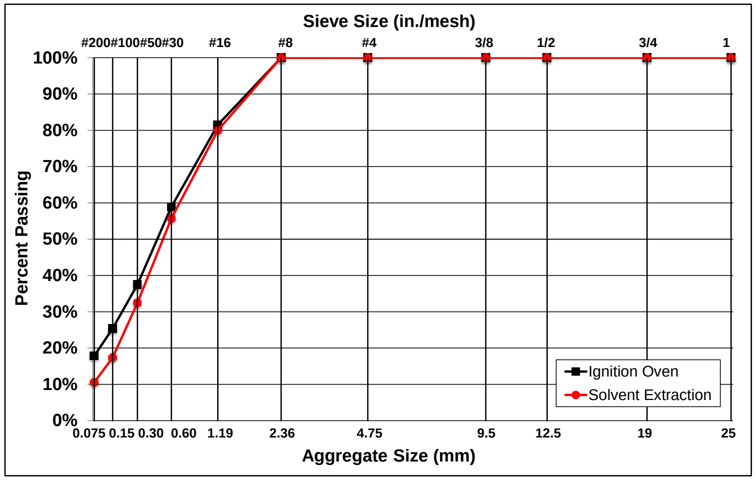


Figure 52. Fine Aggregate Gradations of CA RAP

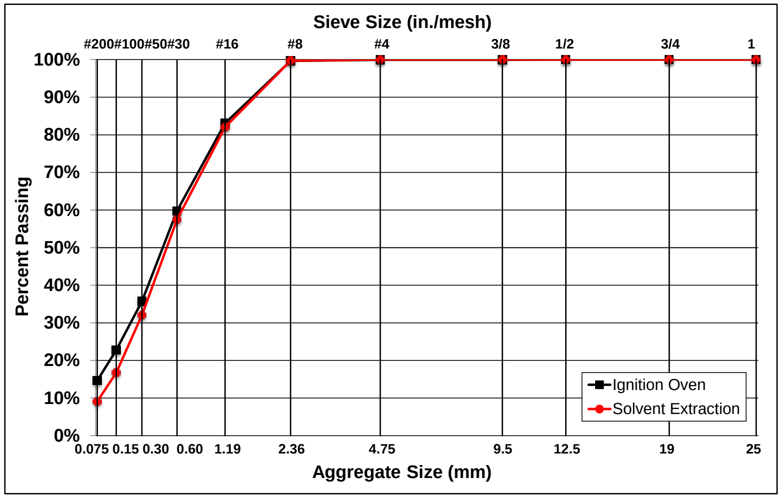


Figure 53. Fine Aggregate Gradations of AL RAP

The optimum binder content of the FAM mix was found to be 10.7% by weight of the mix. The aggregate gradation and asphalt binder content of the FAM mixes was the same for all mixes. The quantities of RAP required to meet the target binder replacement were first determined, and then the quantity of virgin binder and the quantity and gradation of virgin aggregates were adjusted to preserve the target gradation and binder content. The gradations for each of the FAM mixes are listed in table 26.

Table 26. The RAP Aggregate and Virgin Aggregate Gradations

Sieve Size		FAM Mix Type Gradation (% Passing)				
mm	in./mesh	Control	25% NY RAP	25% CA RAP	25% AL RAP	40% NY RAP
2.36	#8	100	100	100	100	100
1.19	#16	64	54	54	50	38
0.60	#30	43	33	34	31	26
0.30	#50	29	26	27	26	26
0.15	#100	21	22	26	25	26
0.075	#200	11	8	11	12	3

7.5 MIX DESIGN SUMMARY.

Based on the mix design results described above, 10 different asphalt mixes were considered for further evaluation of performance-related properties (table 27). The mix identification codes listed in the table are used in sections 8 and 9 when discussing the performance of the mixes.

Table 27. Asphalt Mixes Selected for Further Evaluation

Mix #	Mix Identification Code	Virgin Binder Grade	RAP Binder Replacement (%)	RAP Source
1	64-0RAP	PG 64-22	0	Control
2	64-25RAP-NY		25	NY
3	64-25RAP-CA		25	CA
4	64-25RAP-AL		25	AL
5	58-0RAP	PG 58-28	0	Control
6	58-40RAP-NY		40	NY
7	76-0RAP	PG 76-22 PM	0	Control
8	76-25RAP-NY		25	NY
9	76-25RAP-CA		25	CA
10	76-25RAP-AL		25	AL

The experimental plan did not include testing of all possible combinations of binder grade, RAP source, and RAP content, for the following reasons:

- PG 58-28 mixes with 25% RAP binder replacement were not considered based on the findings of other studies cited in the literature review, which indicated that using softer binders to compensate for stiffness increases associated with the addition of RAP was not justified in mixes with RAP contents of 25% and lower.

- PG 58-28 mixes with 40% RAP binder replacement from the CA and AL sources were not included given that the FAA P-401 grading and volumetric property specifications [2] could not be met.

- PG 64-22 and PG 76-22 PM mixes with 40% RAP from any of the sources were not considered given that the FAA P-401 grading and volumetric property specifications [2] could not be met.

7.6 SPECIMEN PREPARATION.

7.6.1 Fine Aggregate Matrix Mixes.

FAM mixes were prepared according to the procedure described in section 6.1.5. The asphalt binder mixing temperatures were determined from temperature-viscosity charts provided by the refineries. Virgin aggregates were heated to 15°C (27°F) higher than the corresponding asphalt binder mixing temperature, while RAP materials were preheated to 110°C (230°F) for 60 minutes. FAM mixes were short-term aged for 2 hours at their corresponding compaction temperatures (obtained from the virgin binder temperature-viscosity charts) before compaction.

7.6.2 Full-Graded Mixes for Performance-Related Testing.

Full-graded mixes with the predetermined gradations, RAP contents, and binder contents were short-term aged in loose form for 4 hours at 135°C (275°F) according to AASHTO R 30 [88] and then heated further to the required compaction temperatures prior to compaction. Mixes were compacted (rolling wheel for fatigue beams, gyratory for all other specimens) to the required air-void contents and then cored/cut to the dimensions specified for each test.

8. PHASE 2b: ASPHALT BINDER AND FAM MIX TESTING RESULTS.

This section summarizes the test results of the asphalt binder and FAM mix testing. Tests on the asphalt binder included PG and shear modulus. Tests on the FAM mixes included air-void content and shear modulus.

8.1 ASPHALT BINDER TEST RESULTS.

8.1.1 Asphalt Binder PG.

The performance grade of the virgin binders and recovered RAP binders were determined following the testing procedure explained in section 4.1.2. The PG criteria and values for the virgin and extracted RAP binders are listed in tables 28 and 29, respectively.

Table 28. Performance Grade Results of Virgin Binders

Critical Temperature	Aging Condition	Test Parameter	Binder PG Grading		
			58-28	64-22	76-22 PM
High	Unaged	G*/sinδ ≥1.00 kPa	59.7	66.5	80.1
High	RTFO-aged	G*/sinδ ≥2.20 kPa	60.4	67.8	82.5
Intermediate	RTFO-aged	G* x sinδ ≤5000 kPa	16.5	22.7	14.3
Low	RTFO-aged	S(60) ≤300 MPa[1] m-value ≥0.30[1]	184 (at -18°C)	176 (at -12°C)	54 (at -12°C)
Low	PAV-aged		0.35 (at -18°C)	0.34 (at -12°C)	0.43 (at -12°C)

[1] Values correspond to testing performed at 10°C warmer than PG grade temperature.

Table 29. Performance Grade Results of Recovered RAP Binders

Critical Temperature	Aging Condition	Test Parameter	RAP Binder		
			NY	CA	AL
High	Unaged	G*/sinδ ≥1.00 kPa	91.1	106	>118
High	RTFO-aged	G*/sinδ ≥2.20 kPa	92.0	108	>118
Intermediate	RTFO-aged	G* x sinδ ≤5000 kPa	26.6	48.3	58.2
Low	RTFO-aged	S(60) ≤300 MPa[1] m-value ≥0.30[1]	216 (at -12ºC)	476 (at -6ºC)	166 (at -6ºC)[1]
Low	PAV-aged	S(60) ≤300 MPa[1] m-value ≥0.30[1]	0.31 (at -12ºC)	0.20 (at -6ºC)	0.28 (at -6ºC)[1]

[1] Values correspond to testing performed at 10°C warmer than PG grade temperature.

The high PG limit of the extracted and recovered binder from the AL RAP was not determined since the procedure could not be performed at temperatures higher than 120°C, the limit of the range of the DSR used in this study. The grades of the extracted binders from the three RAP sources were notably different; therefore, they were considered to be appropriately representative of different RAP sources, which would provide insights with regard to the influence of RAP binder source and grade on the properties of composite binders and the mixes produced with them. Studies into the influence of the chemical solvent used in the extraction process were beyond the scope of this study, but that influence warrants further investigation.

Recovered RAP binders were blended with different virgin binders to simulate 25% and 40% binder replacement. The binders were then short-term aged in an RTFO and tested in a DSR (25-mm parallel plate with 1-mm gap setting) to measure the influence of the RAP binder on the high PG limits of the virgin binder. RTFO aging was considered appropriate since the blending of RAP and virgin binders mostly occurs during mixing, storage, and paving operations. The following blended binders were evaluated:

- PG 64-22 binder with 25% RAP binder replacement (all three RAP sources)
- PG 58-28 binder with 40% RAP binder replacement (NY RAP source only)
- PG 76-22 PM binder with 25% RAP binder replacement (all three RAP sources)

Figure 54 shows the high PG limit of the RTFO-aged virgin and blended binders. The following observations were made:

- The influence of RAP binder on the high PG limit of the virgin and PM binders was inconsistent.
- Adding NY RAP binder to the PG 64-22 binder resulted in a slight reduction (1.4°C) in the high PG limit of binder, which was unexpected given that adding RAP binder to virgin binder generally results in an increase in binder stiffness. This was attributed in part to the apparent relatively unaged condition of the NY RAP (i.e., limited long-term aging of the binder) and likely lower initial PG of the original binder (e.g., PG 58-34).
- The high PG limit of the PG 64-22 binder increased by 3.3°C and 7.5°C with the addition of CA and AL RAP, respectively.
- Adding NY, CA, and AL RAP to the PG 76-22 PM binder reduced the high PG limit by 11.8°C, 4.5°C, and 3.4°C, respectively. This was also unexpected, but was attributed in part to potential dilution of the polymer modification by the addition of the unmodified RAP binder and/or to potential alteration of the polymer cross-linking structure. Additional research into the compatibility of the different binders and the influence of the chemical solvents used in the RAP binder extraction was beyond the scope of this study but these warrant further investigation.

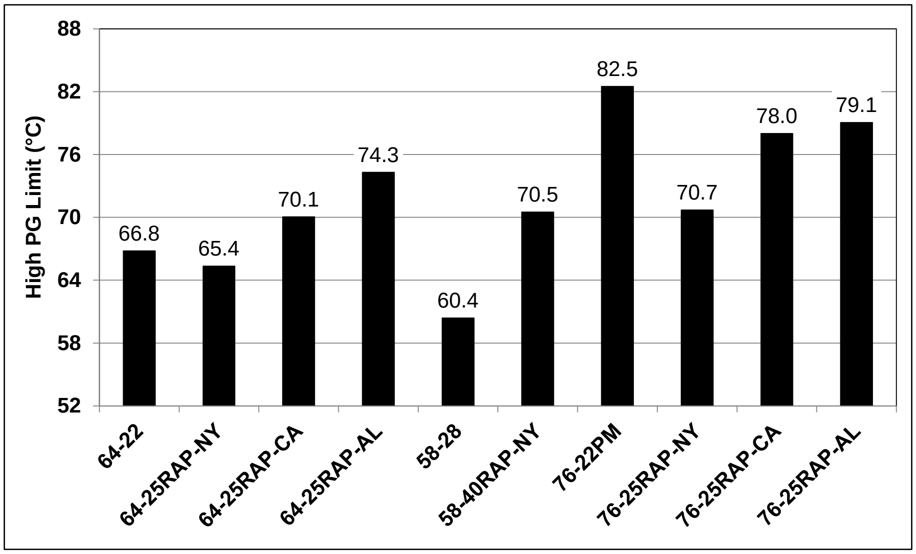


Figure 54. High PG Limit of RTFO-Aged Virgin and Blended Binders

8.1.2 Asphalt Binder Shear Modulus.

The RTFO-aged virgin binders, extracted RAP binders, and blended binders were tested with a DSR (8-mm parallel plate with 2-mm gap setting) to measure the shear moduli of the binders at three temperatures (4°C, 20°C, and 40°C) and a range of frequencies (0.1 to 100 Hz). The sigmoidal function parameters (equation 1) and activation energy terms for the Arrhenius shift factor equation (equation 3) used to plot the master curves are provided in table 30.

Table 30. Shear Modulus Master Curve Parameters

RAP Binder Replacement (%)	Binder Identification	Master Curve Parameters				
		δ	α	β	γ	E_a (kJ/mol)
0	64-22	-2.92	8.10	-1.31	-0.41	192,136
	58-28	-4.05	9.42	-1.12	-0.37	181,941
	76-22 PM	-0.72	6.00	-0.56	-0.42	180,555
25	64-25%RAP-NY	-1.80	6.56	-1.37	-0.52	194,634
	64-25%RAP-CA	-0.79	5.39	-1.67	-0.61	200,091
	64-25%RAP-AL	-1.15	5.45	-1.65	-0.60	200,103
	76-25%RAP-NY	-1.10	6.07	-0.82	-0.46	184,114
	76-25%RAP-CA	-0.43	5.16	-1.11	-0.53	191,348
	76-25%RAP-AL	-3.61	8.85	-1.30	-0.31	200,288
40	58-40%RAP-NY	-1.57	6.39	-1.31	-0.48	192,941

Figure 55 shows the shear modulus master curves, and figure 56 shows the modulus curves normalized to the corresponding control binder for the 10 binders evaluated.

The following observations were made:

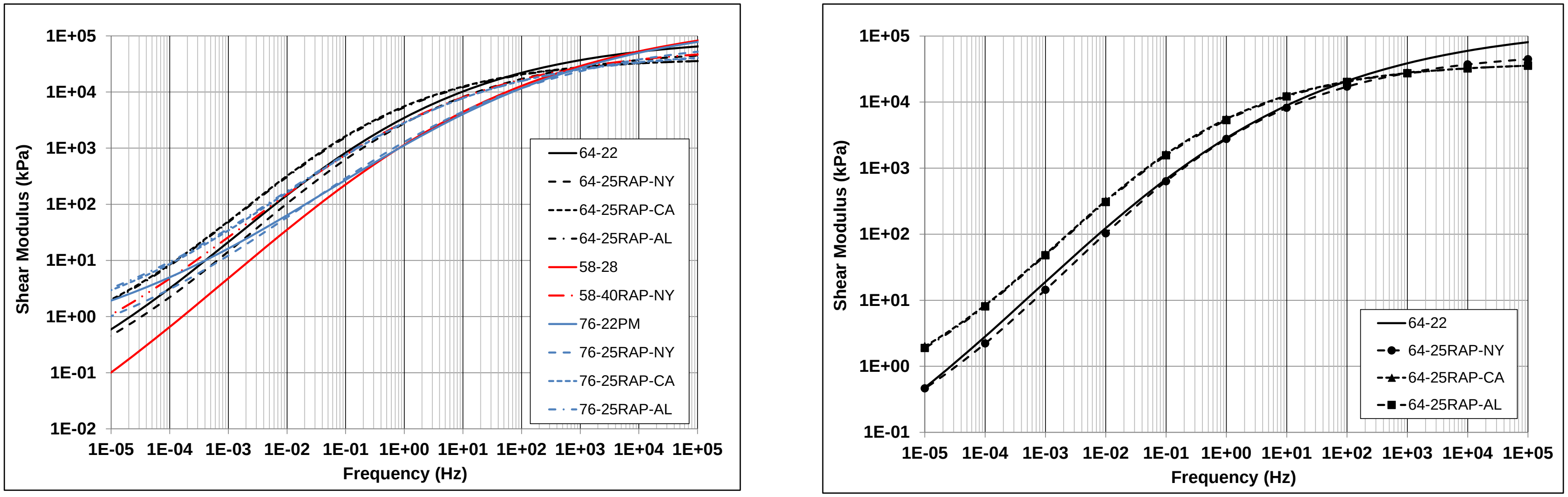
- The modulus of the PG 58-28 virgin binder was the lowest (at frequencies ≤1 Hz), as expected. Adding 40% RAP binder from the NY source increased the stiffness considerably through most of the frequency range.

- The PG 64-22 binder with 25% binder replacement from the CA and AL RAP sources had the highest moduli through most of the testing frequency range.

- The RAP binder from those two sources had a similar influence in terms of change of stiffness. The PG 64-22 binder with 25% NY RAP binder had lower moduli than the control binder, as expected based on the results of the PG testing.

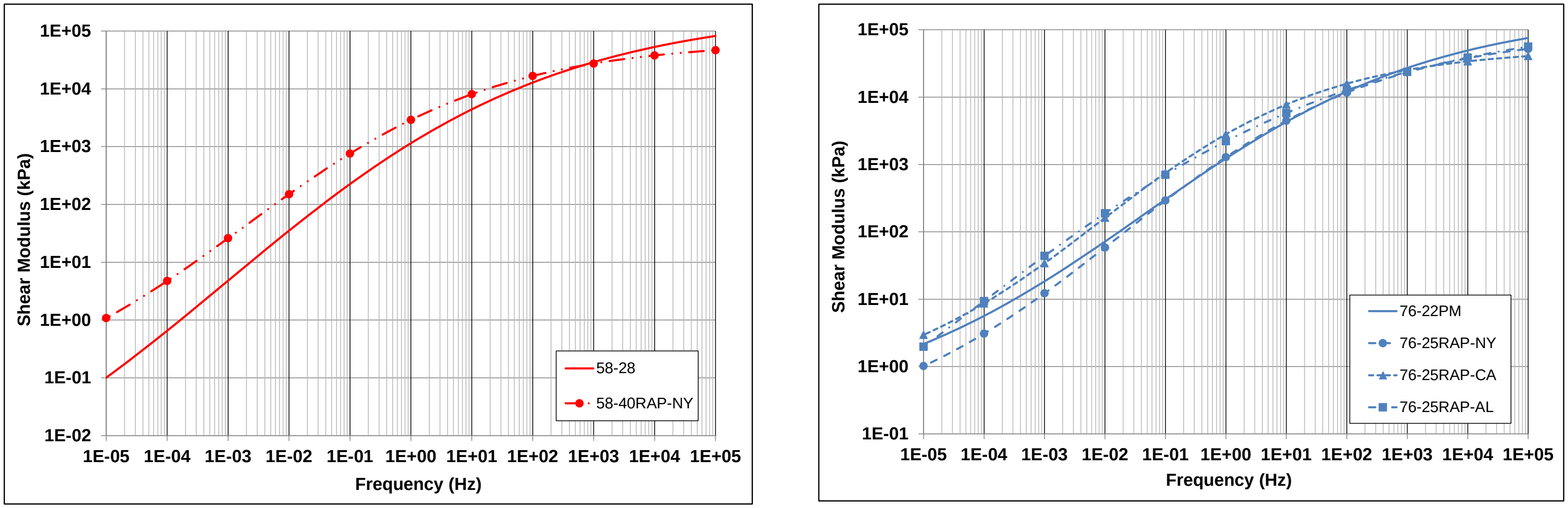
- The PG 76-22 PM control binder was notably stiffer than the PG 64-22 and PG 58-28 control binders at lower frequencies (corresponding to higher temperatures), but merged with the PG 58-28 binder curve at intermediate and higher temperatures, as expected (i.e., the polymer increases stiffness at higher temperatures, but adds flexibility at lower temperatures). Adding 25% CA and AL RAP binder to the PG 76-22 PM binder increased the stiffness of the binder, consistent with the results of the PG 64-22 binder. Adding RAP binder from the NY source reduced the stiffness.

- The master curves of all binders merged at high frequencies (>1000 Hz, representing colder temperatures), regardless of the virgin binder grade, RAP source, or the quantity of RAP binder added.



All binders

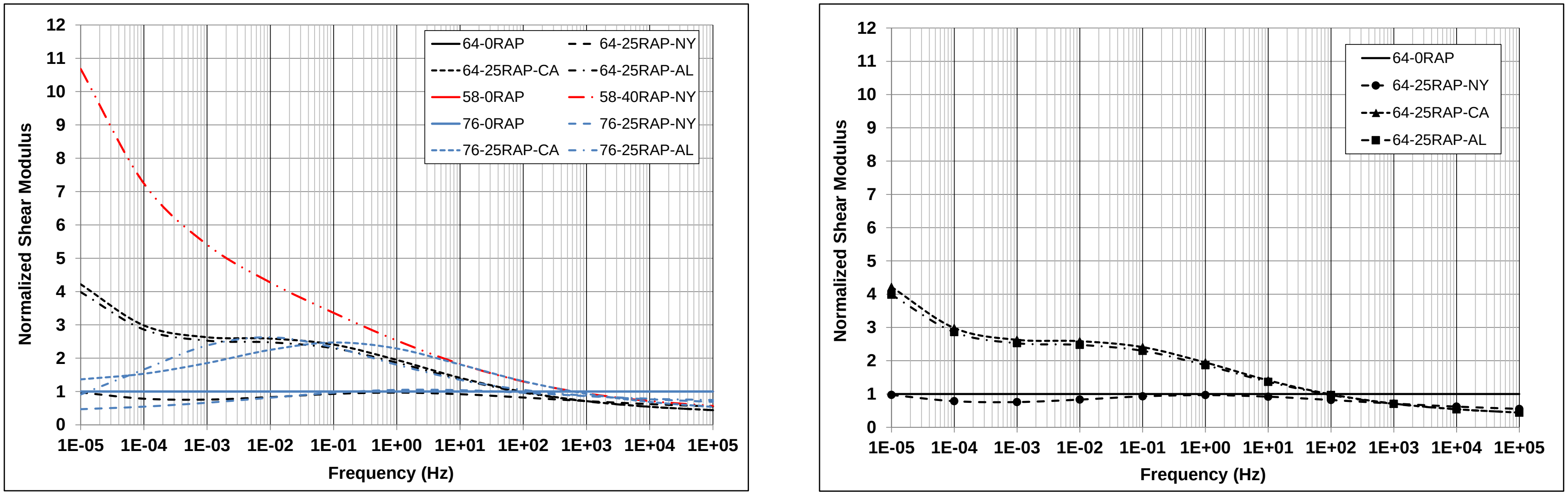
PG 64-22 binders



PG 58-28 binders

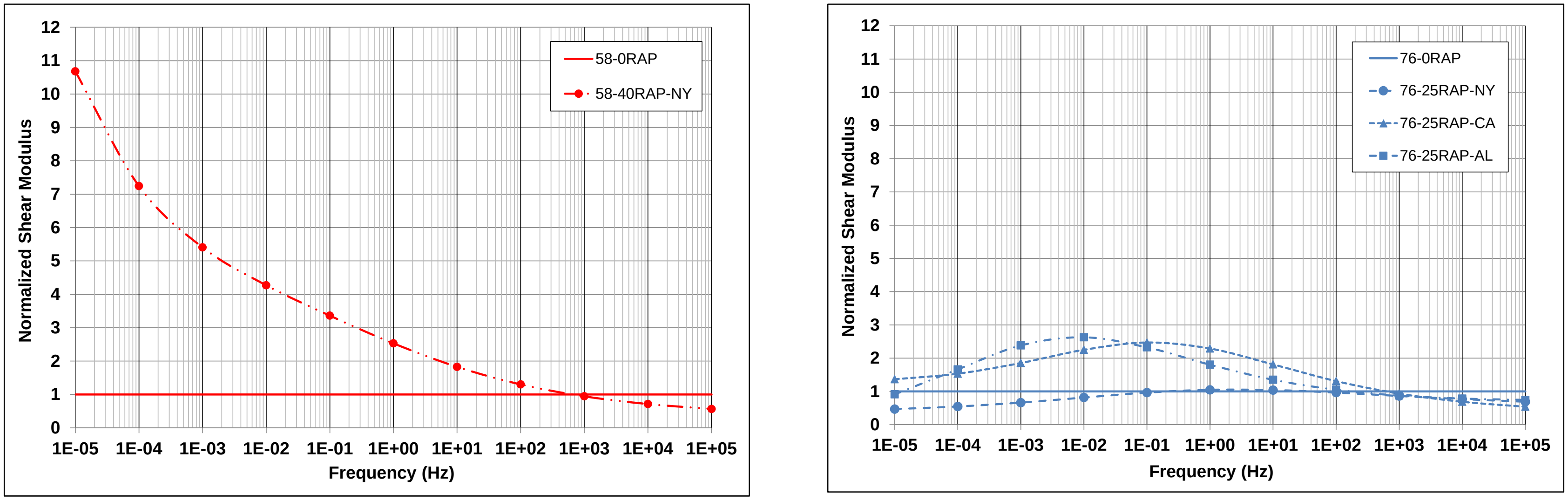
PG 76-22 PM binders

Figure 55. Shear Moduli Master Curves for Asphalt Binders at 20°C



All binders

PG 64-22 binders



PG 58-28 binders

PG 76-22 PM binders

Figure 56. Normalized Shear Moduli Master Curves for Asphalt Binders at 20°C

8.2 FINE AGGREGATE MATRIX MIX TEST RESULTS.

FAM mix specimens were prepared and tested according to the procedures described in section 6.2 and the mix design described in section 7.4. A total of 10 FAM mixes were evaluated.

8.2.1 Fine Aggregate Matrix Mix Air-Void Content.

Air-void contents of the FAM mix specimens were determined by measuring the maximum theoretical specific gravity of the mix (AASHTO T 209 [89]) and bulk specific gravity of the SSD specimen (AASHTO T 166 [92]). Figure 57 summarizes the air-void contents measured on the specimens (average of six specimens per mix). The air-void contents ranged between 9.1% and 11.8%, which were within the target range and considered acceptable for this study. Air-void contents were considered in all test result analyses.

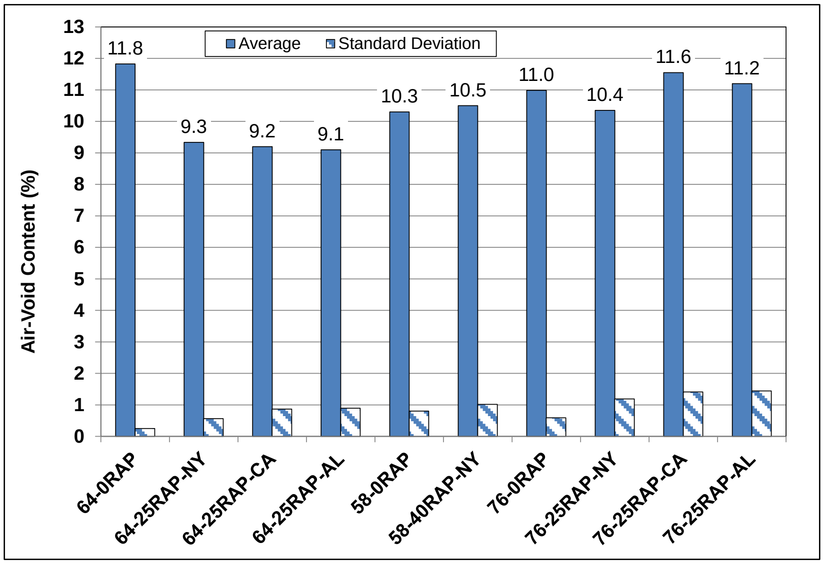
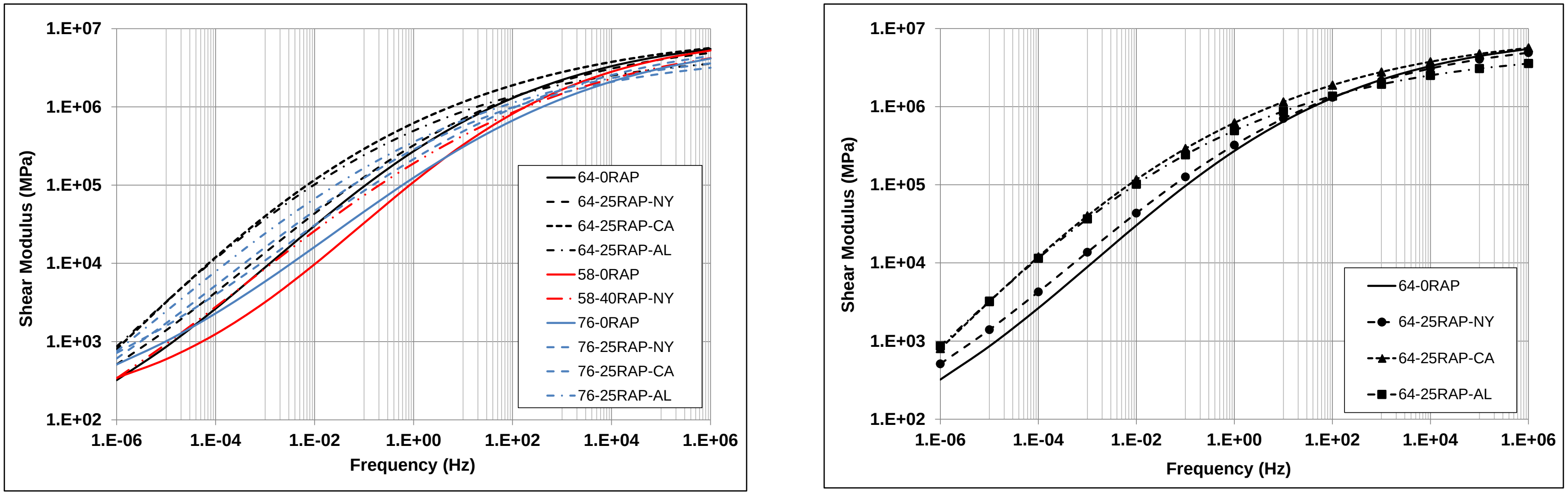


Figure 57. Air-Void Contents of FAM Mixes

8.2.2 Fine Aggregate Matrix Mix Characterization.

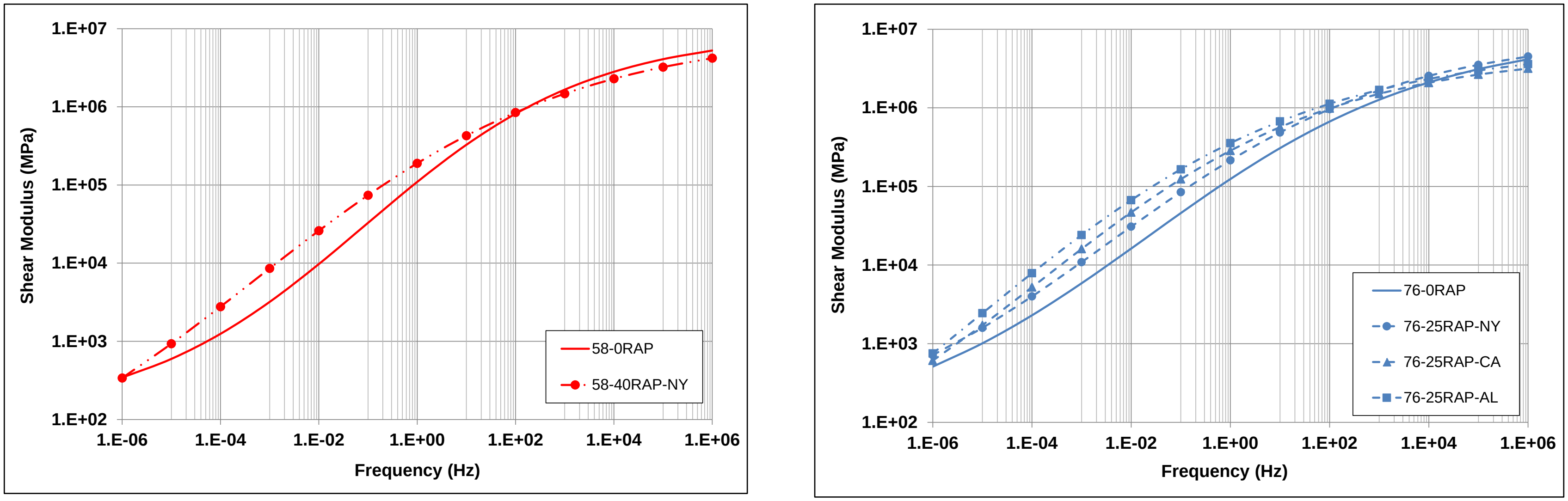
FAM mix specimens were testing using a DMA fitted to a DSR to measure the shear modulus (G*) at three temperatures (4°C, 20°C, and 40°C) and over a range of frequencies from 0.1 Hz to 25 Hz under strain control conditions. A strain amplitude of 0.002% was selected to ensure that specimens were tested within the LVE region of the mix. A sigmoidal function (equation 1) and an Arrhenius shift factor (equation 3) were used to shift the measured moduli to the reduced frequency domain and to construct shear modulus master curves for each mix. The estimated parameters are provided in table 31.

The shear modulus master curves for the FAM mixes at different RAP binder replacement and virgin binder grades are shown in figure 58. Master curves normalized to the corresponding control mixes are shown in figure 59.



All FAM mixes

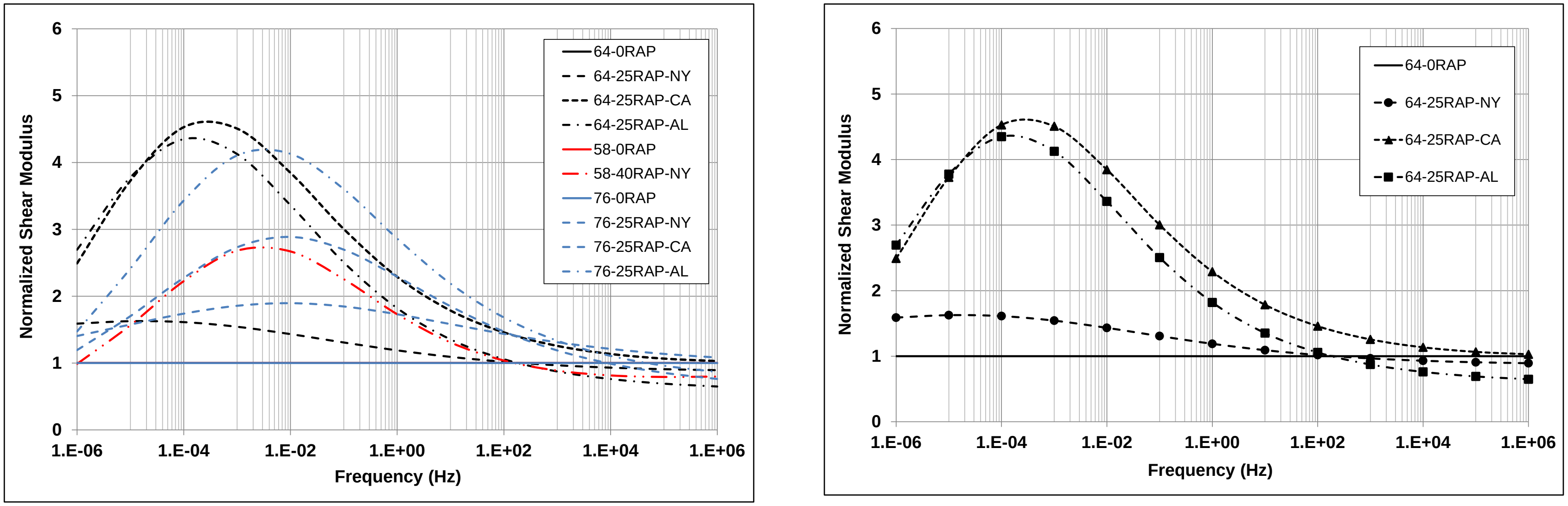
PG 64-22 FAM mixes



PG 58-28 FAM mixes

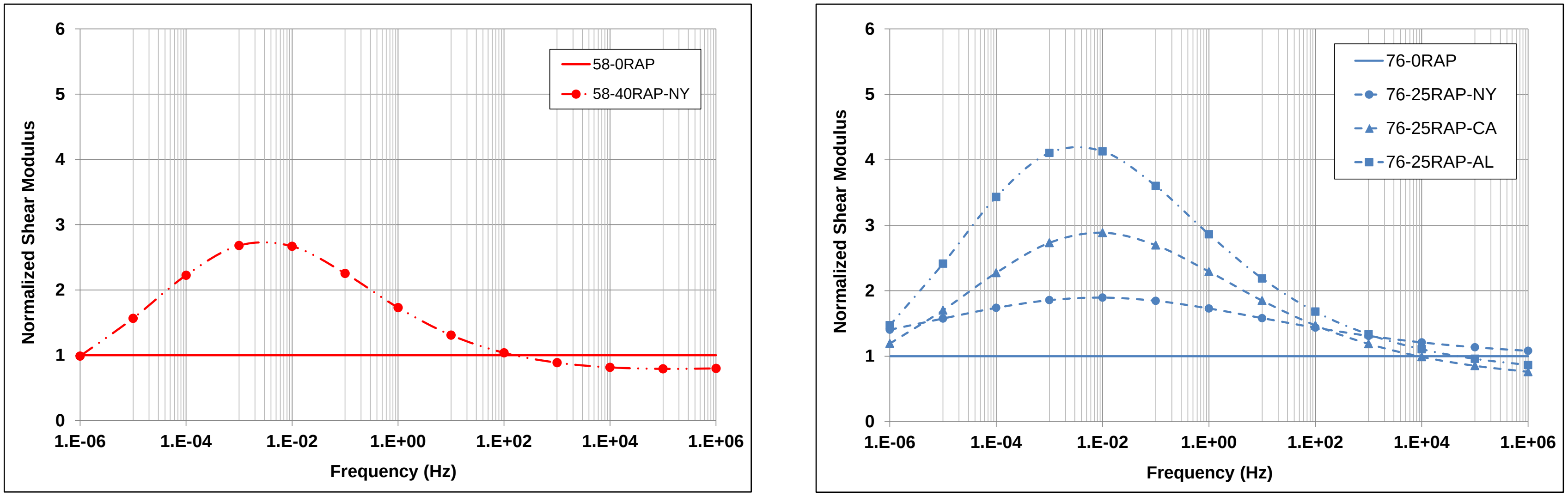
PG 76-22 PM FAM mixes

Figure 58. Shear Moduli Master Curves for FAM Mixes at 20°C



All FAM mixes

PG 64-22 FAM mixes



PG 58-28 FAM mixes

PG 76-22 PM FAM mixes

Figure 59. Normalized Shear Moduli Master Curves for FAM Mixes at 20°C

Table 31. Master Curve Parameters for Determining the FAM Mix Shear Modulus

RAP Binder Replacement (%)	FAM Mix Identification[1]	Master Curve Parameters				
		δ	α	β	γ	E_a (kJ/mol)
0	64-22	1.11	5.85	-1.04	-0.37	204,052
	58-28	2.02	4.92	-0.46	-0.43	182,937
	76-22 PM	1.78	5.17	-0.58	-0.35	195,405
25	64-25%RAP-NY	1.13	5.77	-1.14	-0.35	207,550
	64-25%RAP-CA	-1.37	8.36	-1.79	-0.29	216,933
	64-25%RAP-AL	-0.72	7.45	-1.81	-0.31	226,856
	76-25%RAP-NY	1.65	5.28	-0.83	-0.34	206,826
	76-25%RAP-CA	0.92	5.78	-1.29	-0.34	211,854
	76-25%RAP-AL	-0.14	6.94	-1.51	-0.30	221,915
40	58-40%RAP-NY	0.59	6.37	-1.02	-0.31	201,955

[1] Note that the mix identifications were not changed to reflect the effective 27% binder replacement rates in the CA and AL mixes.

The following observations were made:

- The results were generally consistent with the observations made about the binder test results. Differences were attributed to the variances in the degree of blending between the virgin and RAP binders when mixed prior to binder testing, and the degree of blending when the virgin binder was mixed with the virgin and RAP aggregates. Possible influences of the solvent on the properties of the extracted and recovered blended binder may have also had an effect on overall results.

- The shear modulus of the PG 58-28 mix was the lowest (at frequencies ≤1 Hz), as expected. Adding 40% RAP binder from the NY source increased the stiffness of the mix up to about three times that of the control at low and intermediate frequencies.

- The PG 64-22 mixes with 25% binder replacement from the CA and AL RAP sources had the highest moduli through most of the testing frequency range. The two sources had a similar influence in terms of change of stiffness (up to five times stiffer than the control mix, at about 0.0001 Hz). The PG 64-22 mix with 25% NY RAP binder had similar moduli to the control binder. Although the virgin binder content was slightly lower in the CA and AL RAP mixes than in the NY RAP mix (73% versus 75%—see discussion on binder content determination in section 7.3), comparison with the binder testing results (where all three binder samples were prepared with 75% virgin binder content) indicate that this binder content difference did not significantly influence the results and that the RAP binder properties had the biggest influence on the shear modulus.

- The PG 76-22 PM control mix was notably stiffer than the PG 64-22 and PG 58-28 mixes at lower frequencies (corresponding to higher temperatures), but merged with the PG 64-22 mix curve at an intermediate frequency (~10 Hz) and with the PG 58-28 mix curve at a higher frequency (~100 Hz) (corresponding to colder temperatures). The differences between the PG 76-22 PM mix and the PG 64-22 and PG 58-28 mixes were less distinct here than they were in the binder testing results. Adding 25% CA and AL RAP binder to the PG 76-22 PM mix had only a marginal effect on mix stiffnesses. Adding RAP binder from the NY source reduced the stiffness. The same conclusions with regard to effective virgin binder content of the PG 64-22 CA and AL RAP mixes discussed above are also relevant to the PG 76-22 PM mixes.

- The master curves of all binders merged at high frequencies (>1000 Hz, representing colder temperatures), regardless of the virgin binder grade, RAP source, or the quantity of RAP binder added.

8.3 PHASE 2b TESTING SUMMARY.

Key observations from this phase of the study include the following:

- The degree of change in PG grade after the addition of RAP binder varied depending on the virgin binder grade and the RAP source. This was attributed to various factors including but not limited to the degree of aging of the RAP binder, the original PG grade of the RAP binder, and the extent of the “dilution” of the polymer in PM binders.

- Using RAP binder to replace a portion of the virgin binder always increased the stiffness of the binder, but the degree of increase was dependent on the RAP source.

- The results from FAM mix testing were consistent with the results from binder testing. Differences were attributed to the variances in the degree of blending during preparation of the binders (stirred with a glass rod in a glass beaker) and preparation of the FAM mixes (standard laboratory mixing process), and to possible effects of the chemical solvent on the properties of the extracted and recovered binder. The slightly higher effective RAP binder contents of the CA and AL RAP mixes did not appear to influence the results.

- The FAM mix test results further supported the use of this testing approach as an appropriate procedure for evaluating the properties of blended asphalt binder in mixes containing relatively high quantities of RAP.

9. PHASE 2b: MIX TESTING RESULTS.

This section summarizes the test results on full-graded mixes. Tests included air-void content, stiffness (dynamic modulus and flexural modulus), rutting performance (flow number, APA, and Hamburg-Wheel Track), and cracking performance (beam fatigue).

9.1 EXPERIMENT DESIGN.

Table 32 lists the test methods and brief details about the test parameters used to conduct performance-related testing on full-graded asphalt mixes in this study. The test results are discussed in sections 9.2 through 9.9.

Table 32. Phase 2b Asphalt Mix Tests Performed

Test	Specification	Replicates	Air-Void Content (%)	Test Variables
Stiffness • AMPT[1] dynamic modulus	AASHTO TP 79 [97]	2	7.0 ±1.0	1 temperature sequence (4°C, 25°C, 40°C) 1 frequency sequence (10, 1, 0.1, 0.01 Hz) 1 stress level[2]
Stiffness • Beam flexural frequency sweep	AASHTO T 321 [98]	2	6.0 ±0.5	3 temperatures (10°C, 20°C, 30°C) 2 strain levels (100 µstrain at 10, 20°C; 200 µstrain at 30°C)
Rutting Performance • AMPT flow number	AASHTO TP 79 [97]	2	7.0 ±1.0	1 temperature (52°C) 1 deviator stress (600 kPa [70 psi]) 1 contact stress (30 kPa [4 psi])
Rutting Performance • APA[3]	AASHTO T 340 [99]	3	7.0 ±1.0	1 temperature (64°C) 1 hose pressure (1700 kPa [250 psi]) 1 wheel load (113 kg [250 lb])
Moisture Sensitivity • Hamburg Wheel-Track	AASHTO T 324 [100]	4	7.0 ±1.0	1 temperature (50°C) 1 bath condition (with water bath)
Cracking Performance • Beam fatigue	AASHTO T 321 [98]	3	6.0 ±0.5	1 temperature (20°C) 3 strain ranges (dependent on mix)

[1] AMPT - asphalt mix performance tester
[2] Deviator stress controlled by software to get 75 to 125 µstrain (strain levels) peak-to-peak axial strain.
[3] Testing performed by FAA at the National Airport Pavement and Materials Research Center (NAPMRC).

9.2 SPECIMEN PREPARATION.

The following process was followed to prepare asphalt mix specimens for performance-related testing.

1. Add liquid anti-stripping agent to virgin asphalt binder at a dosage of 0.75% by the weight of total binder (including virgin binder and RAP binder) used in the mix.

2. Heat the aggregates, asphalt binder, and RAP to the specified mixing temperatures obtained from the viscosity-temperature charts provided by the binder supplier (150°C [302°F] for PG 64-22 and PG 58-28 asphalt binders, 165°C [329°F] for the PG 76-22 PM binder). Heat the aggregates to 15°C (27°F) higher than the mixing temperature of the binder for 4 hours. Heat the RAP to 110°C (230°F) higher than the mixing temperature

of the binder for 1 hour (use a shorter heating period to eliminate possible undesired aging of asphalt binders).

3. After heating, mix the asphalt binder, aggregates, and RAP in a mechanical mixer to achieve a uniform mix with well-coated aggregates.

4. Short-term age the loose mix at 135°C (275°F) for 4 hours (note that the duration of short-term aging for mix testing specimens is different from that for mix design testing, which specifies 2 hours at the representative compaction temperature (AASHTO R 30 [88]).

5. Increase the loose mix temperature to the compaction temperature. In this study, compaction temperatures were chosen from temperature-viscosity charts provided by the refinery (140°C [284°F] for PG 64-22 and PG 58-28 and 142°C [288°F] for PG 76-22 PM).

6. Compact the mix in a Superpave gyratory compactor to produce specimens for dynamic modulus, flow number, Hamburg Wheel-Track, and APA tests. Compact additional mix under a rolling wheel compactor to produce specimens for beam flexural stiffness and beam fatigue tests. The target air-void contents were:

    - 7 ±1.0% for dynamic modulus, flow number, Hamburg Wheel-Track and APA tests.

    - 6 ±0.5% for beam flexural stiffness and fatigue tests.

7. Core or extract and trim asphalt mix specimens from the compacted cylinders and beams to the desired dimensions for testing.

8. Measure the air-void content of the prepared specimens according to AASHTO T 269 [93], using the bulk specific gravities of the saturated surface-dry compacted specimen (determined according to AASHTO T 166 [92]) and the theoretical maximum specific gravity of each mix (determined according to AASHTO T 209 [89]).

9. Seal and store dry samples for testing.

9.3 EFFECT OF RAP ON MIX STIFFNESS DYNAMIC MODULUS.

9.3.1 Specimen Air-Void Contents.

Average specimen air-void contents are summarized in figure 60.

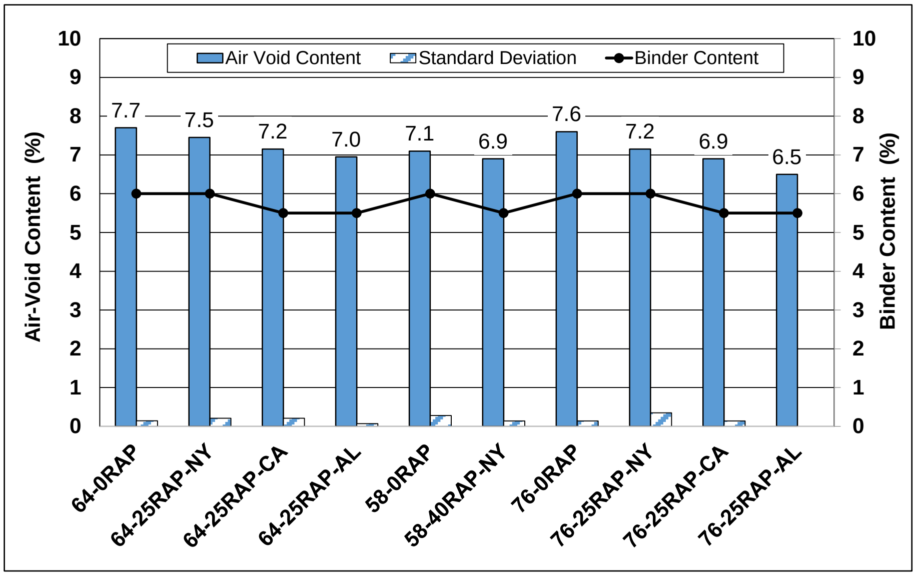


Figure 60. Average Air-Void Contents of Dynamic Modulus Specimens

Air-void contents ranged between 6.5% and 7.7%, with all specimens within the allowable range. There was very little variation in the air-void contents of the replicate specimens in each mix, indicating that specimen compaction was satisfactory. The mixes had fixed binder contents, as discussed in section 7.3 (i.e., 5.5% for mixes containing RAP from the CA and AL sources, and 6.0% for the other mixes).

9.3.2 Test Results.

Table 33 lists the sigmoidal function parameters and activation energy term in the Arrhenius shift factor equations (equations 1 and 3 in section 4.1.2.3) that were used to develop dynamic modulus master curves.

Table 33. Dynamic Modulus Master Curve Parameters

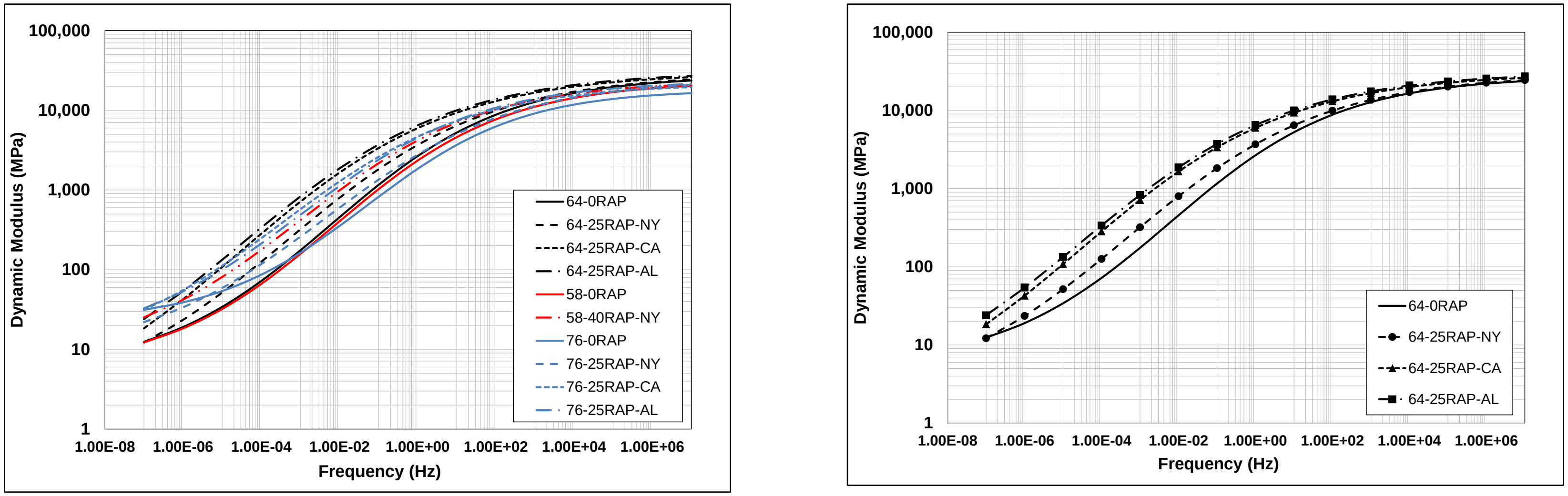
RAP Binder Replacement (%)	Mix Identification	Master Curve Parameters				
		δ	α	β	γ	E_a (kJ/mol)
0	64-0RAP	0.70	3.73	-0.99	0.45	200,000
	58-0RAP	0.73	3.64	-0.98	0.46	200,000
	76-0RAP	0.50	2.92	-0.66	0.50	200,000
25	64-25RAP-NY	0.28	4.18	-1.30	0.39	200,000
	64-25RAP-CA	-0.01	4.48	-1.68	0.37	200,000
	64-25RAP-AL	0.15	4.37	-1.68	0.37	200,000
	76-25RAP-NY	1.34	2.92	-0.66	0.50	200,000
	76-25RAP-CA	0.91	3.48	-0.99	0.42	200,000
	76-25RAP-AL	0.85	3.49	-1.44	0.42	200,000
40	58-40RAP-NY	0.88	3.48	-1.29	0.43	200,000

Figure 61 shows the dynamic shear modulus master curves, and figure 62 shows the master curves normalized to the corresponding control mix for the ten mixes evaluated. The normalized values were obtained by dividing the stiffness of each mix with binder replacement by the corresponding value of the control mix. The following observations were made:

- The results were consistent with those recorded during FAM mix testing (discussed in section 8.2.2).

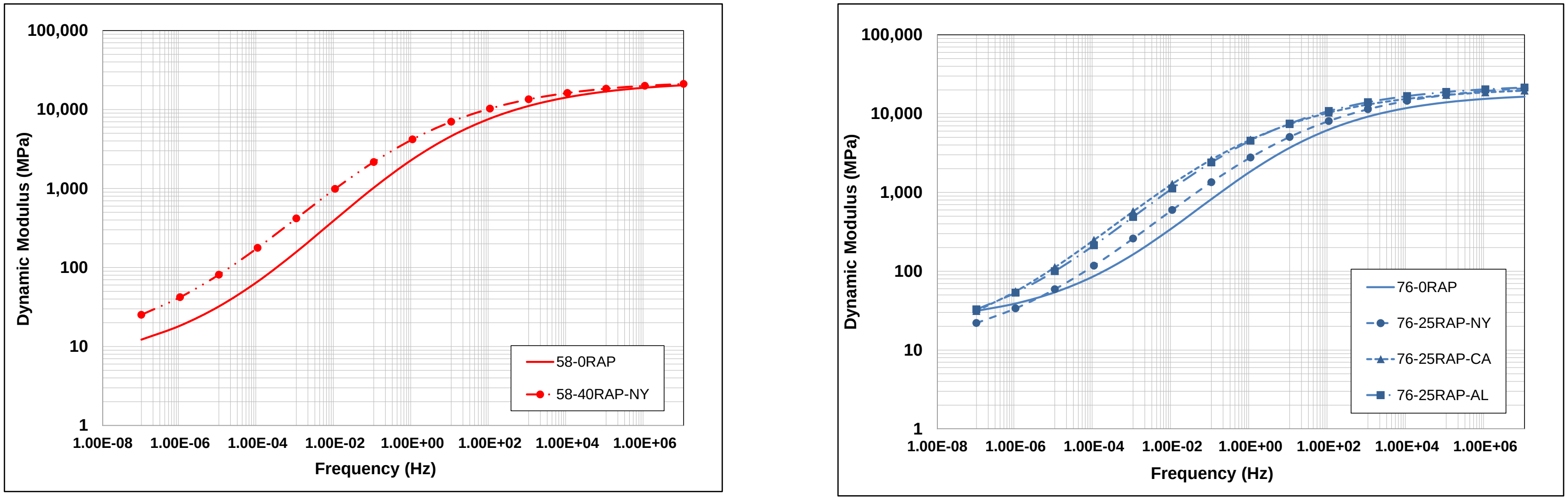
- The PG 64-22 and PG 58-28 control mixes had similar stiffnesses throughout the testing frequency range. The PG 76-22 PM control mix had a notably higher stiffness than the other control mixes at testing frequencies less than 0.001 Hz, and slightly lower stiffness at higher testing frequencies. Incorporation of RAP into the mixes always resulted in an increase in stiffness when compared to the corresponding control mix without RAP, as expected.

- The normalized graphs show that the differences in modulus occurred mainly between 0.00001 Hz and 100 Hz for all mixes. Of the PG 64-22 mixes, those with 25% CA and RAP were the stiffest, followed by the mix with 25% NY RAP. This was again attributed in part to the apparent relatively unaged condition of the NY RAP (i.e., limited long-term aging of the binder) and likely lower initial PG grading of the original binder (e.g., PG 58-34). Adding 25% NY, CA, and AL RAP resulted in modulus increases up to 1.7, 4.0, and 4.8 times, respectively, over the corresponding control mixes. The largest differences were observed at frequencies around 0.001 Hz.



All mixes

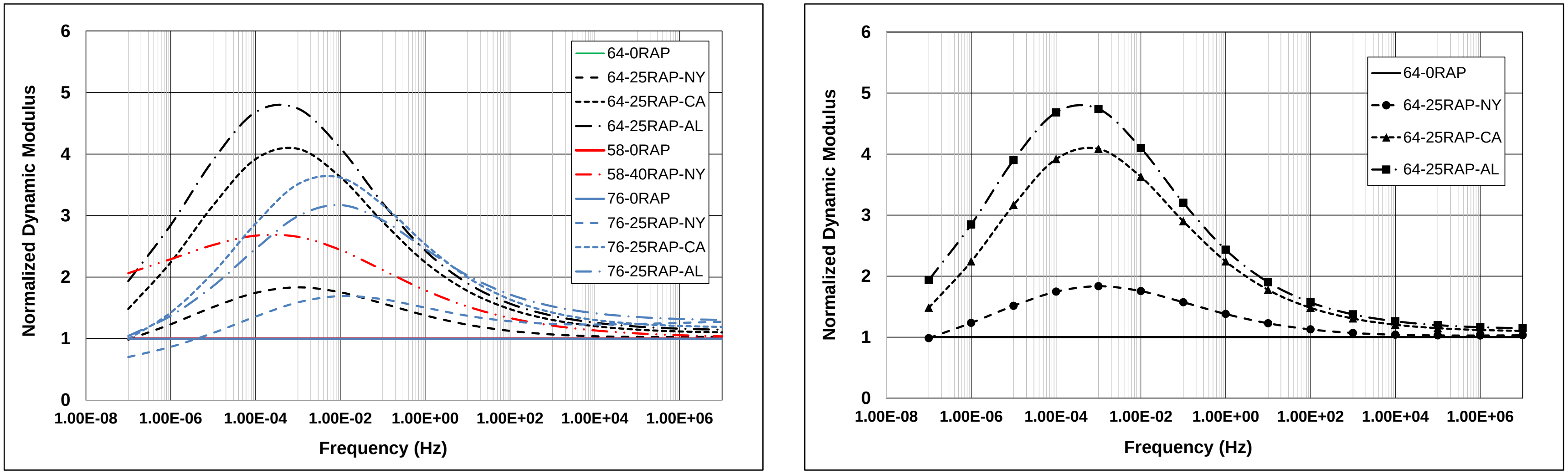
PG 64-22 mixes



PG 58-28 mixes

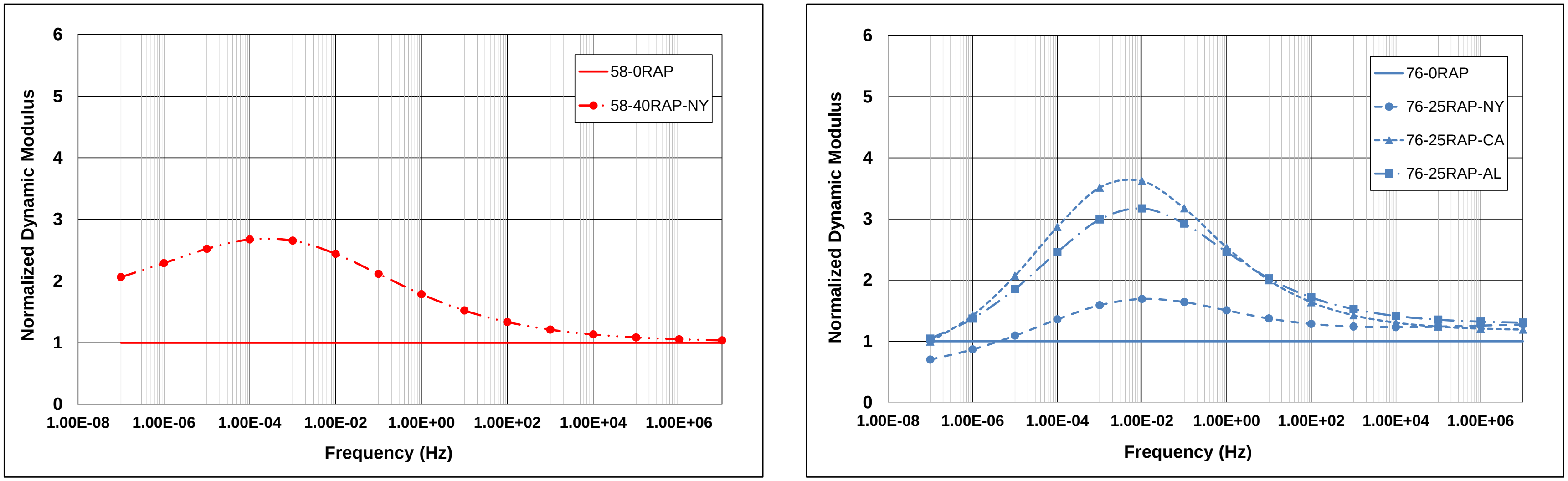
PG 76-22 PM mixes

Figure 61. Dynamic Modulus Master Curves for Full-Graded Mixes



All mixes

PG 64-22 mixes



PG 58-28 mixes

PG 76-22 PM mixes

Figure 62. Normalized Dynamic Modulus Master Curves for Full-Graded Mixes

- Of the PG 76-22 PM mixes, those with 25% CA and 25% AL RAP had the highest stiffnesses, followed by the mixes with 25% NY RAP, which is consistent with the observations for the PG 64-22 mixes. Adding 25% RAP from the NY, CA, and AL sources resulted in modulus increases of up to 1.5, 3.1, and 3.5 times, respectively, over the corresponding control mixes. The largest differences were observed at frequencies between 0.005 Hz and 0.01 Hz. This difference in behavior compared to the PG 64-22 and PG 58-28 mixes was attributed mostly to the effect of the polymer modification.

- Comparing the 40% NY RAP mix (PG 58 binder) with the 25% NY RAP mixes (PG 64 and PG 76 binders) shows that the mix with 40% RAP had a marginally higher stiffness over the frequency range, indicating some stiffening by the RAP binder despite using the softer virgin base binder. Adding 40% NY RAP to the PG 58-28 mixes increased the modulus by up to 2.7 times over the control mix. The largest differences were also observed at frequencies around 0.001 Hz.

The addition of 25% RAP had a larger influence on the modulus of the PG 64-22 mixes than on the PG 76-22 PM mixes, indicating the dominating effect of the polymer modification. Figure 63 summarizes the dynamic modulus of the ten mixes at three frequencies in the middle of the testing range (0.01 Hz, 1.0 Hz, and 100 Hz).

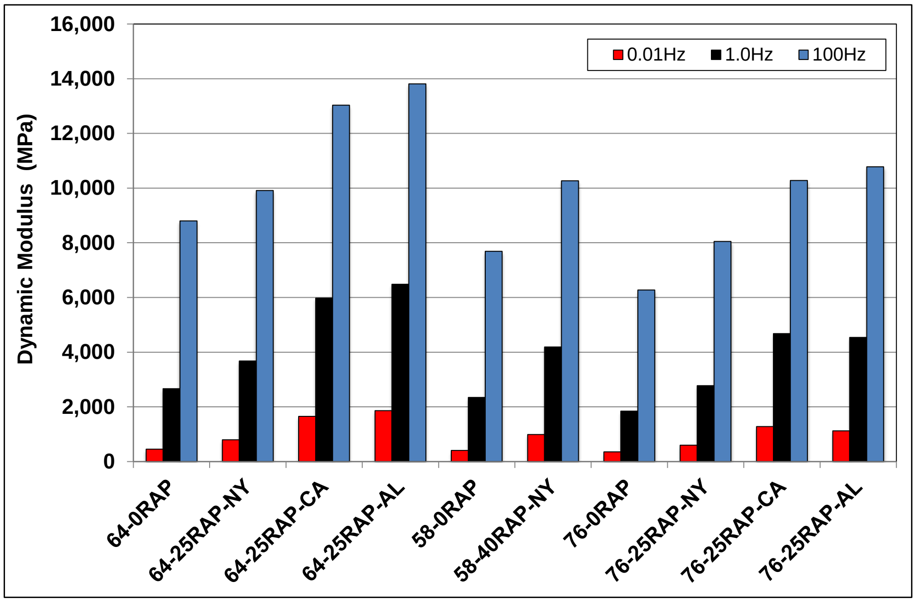


Figure 63. Comparison of Dynamic Modulus at Three Frequency Levels at 20°C

The following observations were made, further supporting the above discussion:

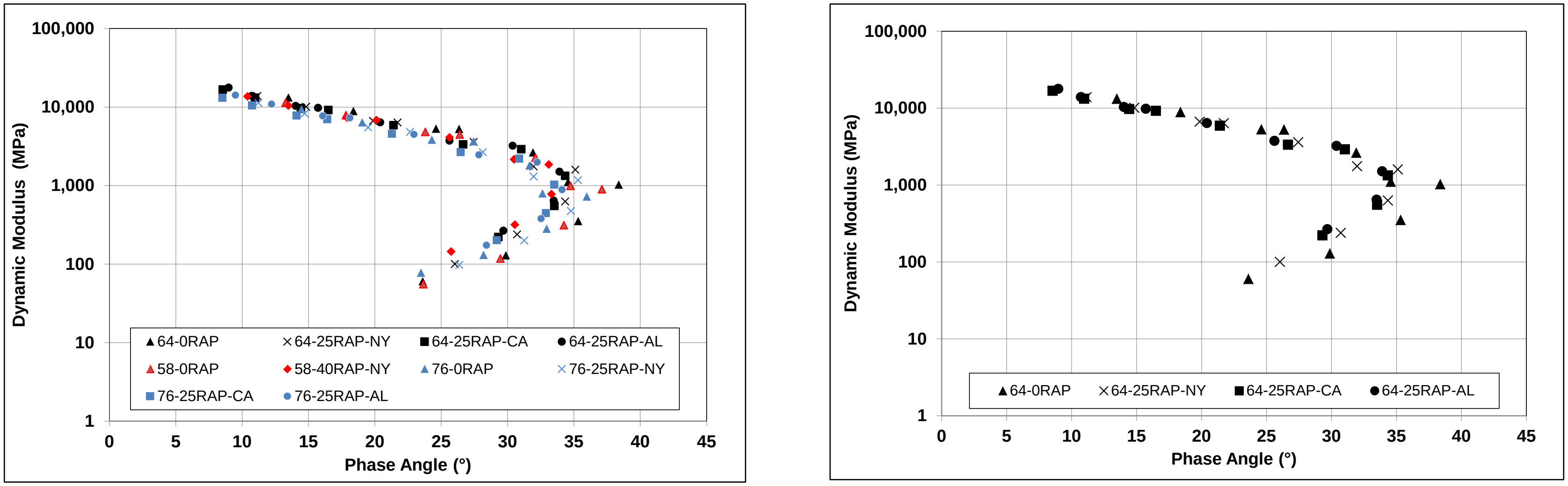
- The PG 64-22 mixes had the highest stiffnesses across the three frequencies and the PG 76 mixes had the lowest stiffness. Similar trends were observed across all the mixes.

- The effect of the addition of RAP was clearly evident at all frequencies. The CA and AL RAP mixes were stiffer than the NY RAP mixes.

- The stiffnesses of the PG 58-28 mix with 40% NY RAP were similar to the PG 64-22 mix with 25% NY RAP, but lower than the PG 64-22 mixes with CA and AL RAP, indicating the compensating effect of using a softer binder for the higher RAP content.

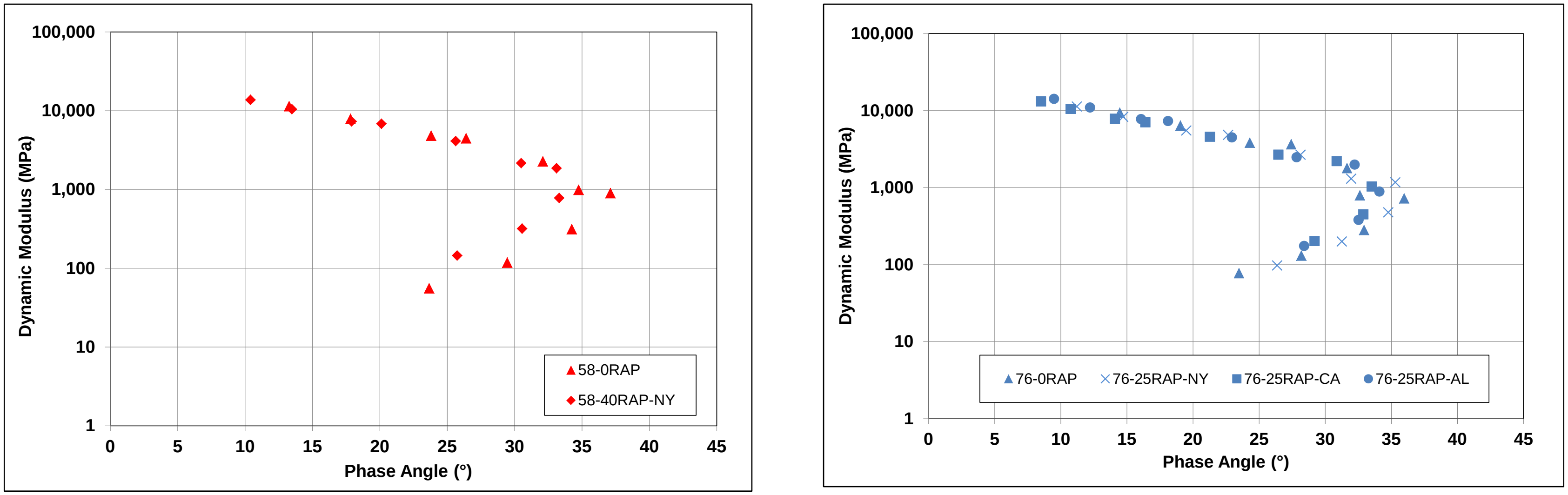
- Although the virgin binder content was slightly lower in the CA and AL RAP mixes than in the NY RAP mix, 73% versus 75% (see discussion on binder content determination in section 7.4), the trends in the testing results were consistent with the FAM mix testing results and binder testing results (where all three binder samples were prepared with 75% virgin binder content), further supporting the observation that this slightly higher binder content did not significantly influence the results and that the RAP binder properties had the biggest influence.

Figure 64 shows Black diagrams illustrating the relationship between stiffness and phase angle for each mix for all testing temperatures and frequencies. Phase angle trends were similar across all mixes. At stiffnesses above 1000 MPa, the phase angles of the different mixes were essentially the same. At stiffnesses below 1000 MPa, corresponding mixes showed slightly more spread, with phase angles of the RAP mixes generally higher than those of the control mixes, indicating the less elastic behavior of the RAP mixes.



All mixes

PG 64-22 mixes



PG 58-28 mixes

PG 76-22 PM mixes

Figure 64. Phase Angle Black Diagrams for Full-Graded Mixes

9.4 EFFECT OF RAP ON MIX STIFFNESS FLEXURAL MODULUS.

9.4.1 Specimen Air-Void Contents.

The average air-void content and standard deviation of the beams produced for each mix are summarized in figure 65. Beam air-void contents in seven of the mixes were within the target range. Beam air-void contents in the remaining three mixes (i.e., 64-25RAP-AL, 76-25RAP-CA, and 76-25RAP-AL) were slightly below the target range, but researchers decided to continue with testing these beams due to the limited availability of materials and time constraints for compacting additional beams. Variation in air-void content between beams from the same mix was larger than that achieved with the gyratory-compacted specimens but was still acceptable, indicating that consistent compaction was achieved. Any potential influences of air-void content were considered during analysis of the results.

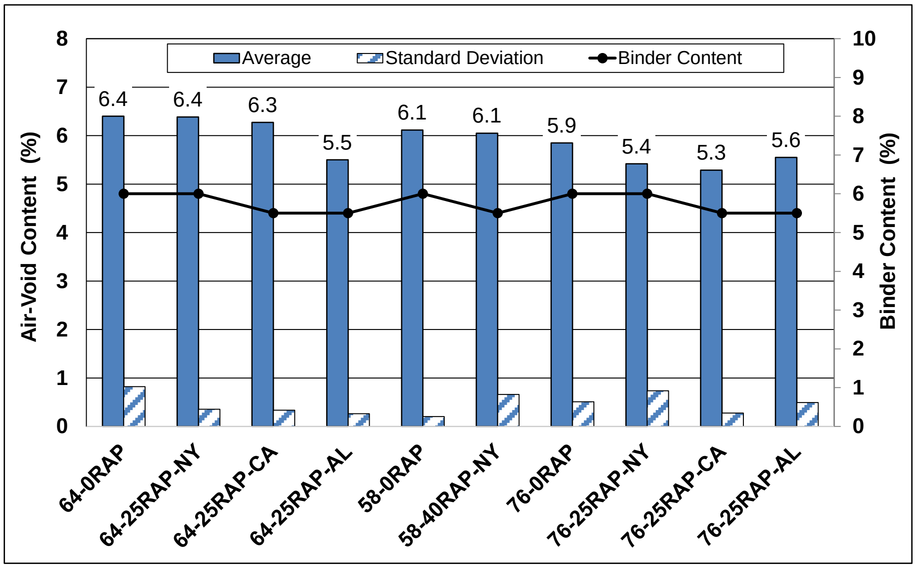


Figure 65. Average Air-Void Contents of Flexural Frequency Sweep Specimens

9.4.2 Test Results.

Four-point bending frequency sweep tests were conducted to measure the stiffness (flexural modulus) of the beams under different frequencies and various loading rates. Two replicates were tested at temperatures of 10°C, 20°C, and 30°C and over frequencies of 15, 10, 5, 2, 1, 0.5, 0.2, 0.1, 0.05, 0.02, and 0.01 Hz. Tests were performed in strain-control mode. A sigmoidal function similar to that used to determine the FAM mix shear modulus and dynamic modulus was used to construct the flexural modulus master curve at a reference temperature of 20°C. The shift factor equation used for generating the master curves is shown in equation 4. Table 34 shows the sigmoidal function parameters and the shift factor equation constant used for the evaluated mixes.

$$Log\ a_T(T) = C \times (T - T_r) \qquad (4)$$

where:

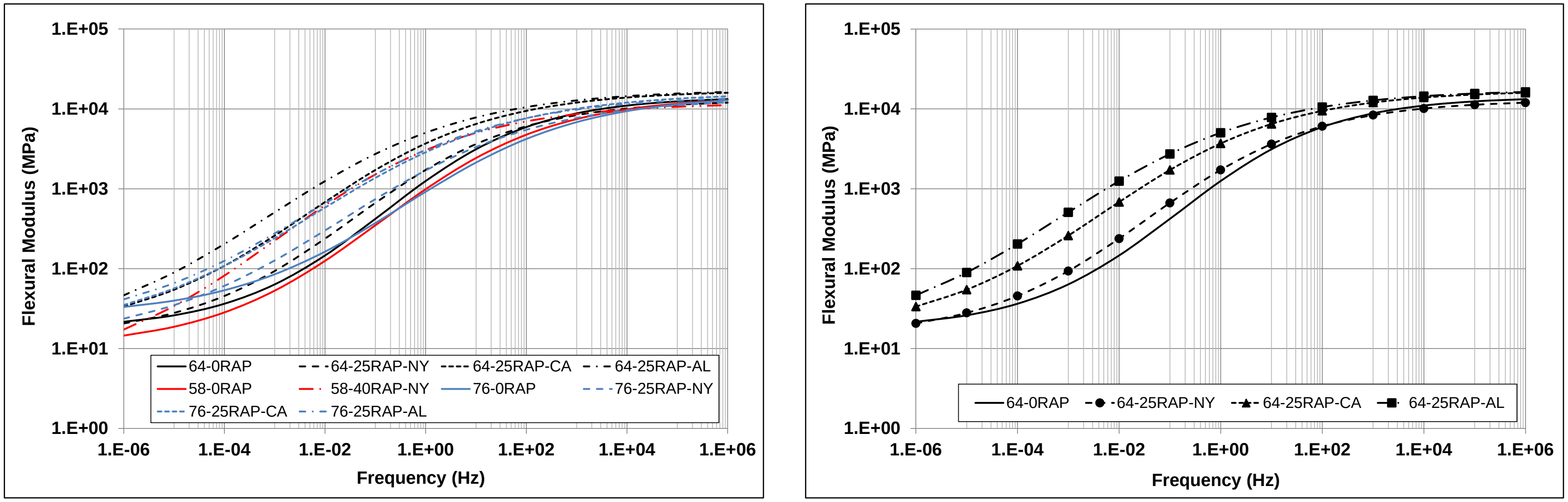
$a_T(T)$ is the shift factor value for Temperature T(°K),
C is the shift factor constant,
T_r is the reference temperature, and
T is the testing temperature (°C).

Table 34. Phase 2 Flexural Modulus Master Curve Parameters

RAP Binder Replacement (%)	Mix Identification	Master Curve Parameters				
		δ	α	β	γ	E_a (kJ/mol)
0	64-0RAP	0.70	3.51	-0.78	-0.58	-0.12
	58-0RAP	1.23	2.79	-0.54	-0.70	-0.14
	76-0RAP	1.48	2.56	-0.33	-0.67	-0.13
25	64-25RAP-NY	1.14	2.97	-0.88	-0.61	-0.13
	64-25RAP-CA	1.18	3.06	-1.28	-0.55	-0.14
	64-25RAP-AL	1.06	3.18	-1.58	-0.51	-0.15
	76-25RAP-NY	1.08	3.06	-0.86	-0.52	-0.14
	76-25RAP-CA	1.15	3.05	-1.13	-0.51	-0.14
	76-25RAP-AL	1.24	2.93	-1.19	-0.52	-0.14
40	58-40RAP-NY	0.67	3.41	-1.56	-0.53	-0.12

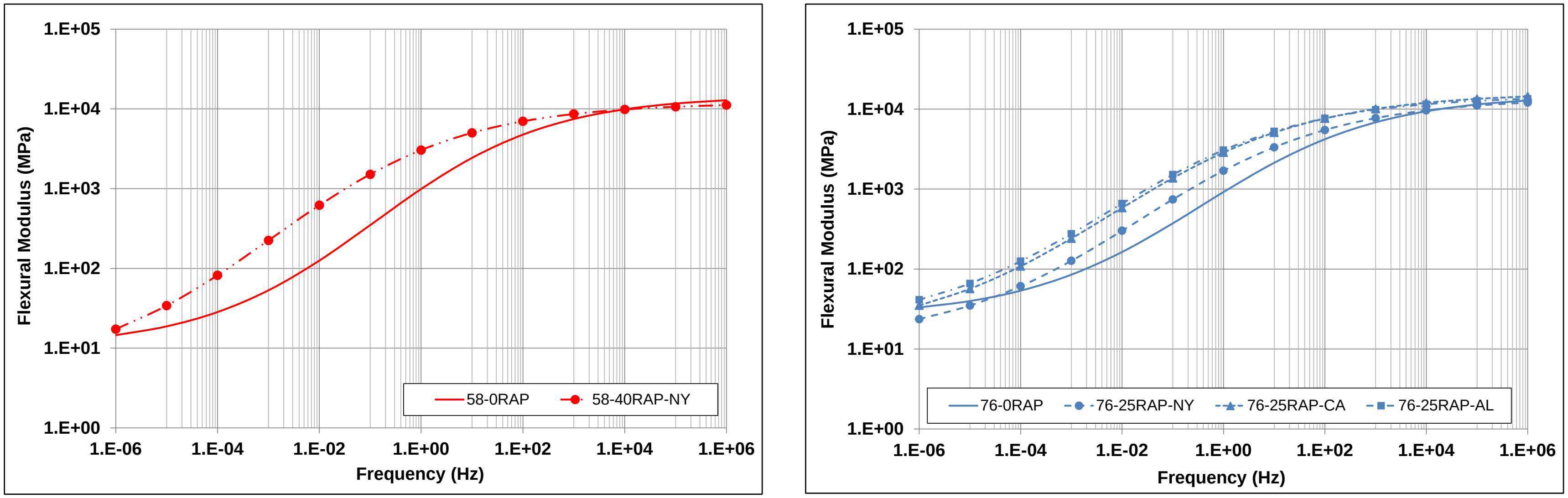
Figure 66 shows the flexural modulus master curves for the different mixes. Figure 67 shows the modulus curves normalized to those of the control mix. The normalized values were obtained by dividing the stiffness of each mix with binder replacement by the corresponding value of the control mix. The following observations were made:

- The results were consistent with the results from the asphalt mix performance tester (AMPT) dynamic modulus testing discussed in this section.
- The master curves of all the mixes merged at high frequencies (>1000 Hz, corresponding to colder temperatures).
- The stiffnesses of the three control mixes varied between the frequencies, as expected. At the lower frequencies, corresponding to warmer temperatures, the PG 76-22 PM mix had the highest stiffness, and the PG 58-28 mix had the lowest stiffness. Mix stiffnesses were the same at a frequency of 0.1 Hz; but at higher frequencies (1.0 Hz through 1000 Hz, corresponding to decreasing temperatures), the PG 64-22 mix had the highest stiffness, and the PG 76-22 PM mix had the lowest stiffness. This is consistent with the effect of the polymer increasing stiffness at higher temperatures, but providing additional flexibility at lower temperatures.



All mixes

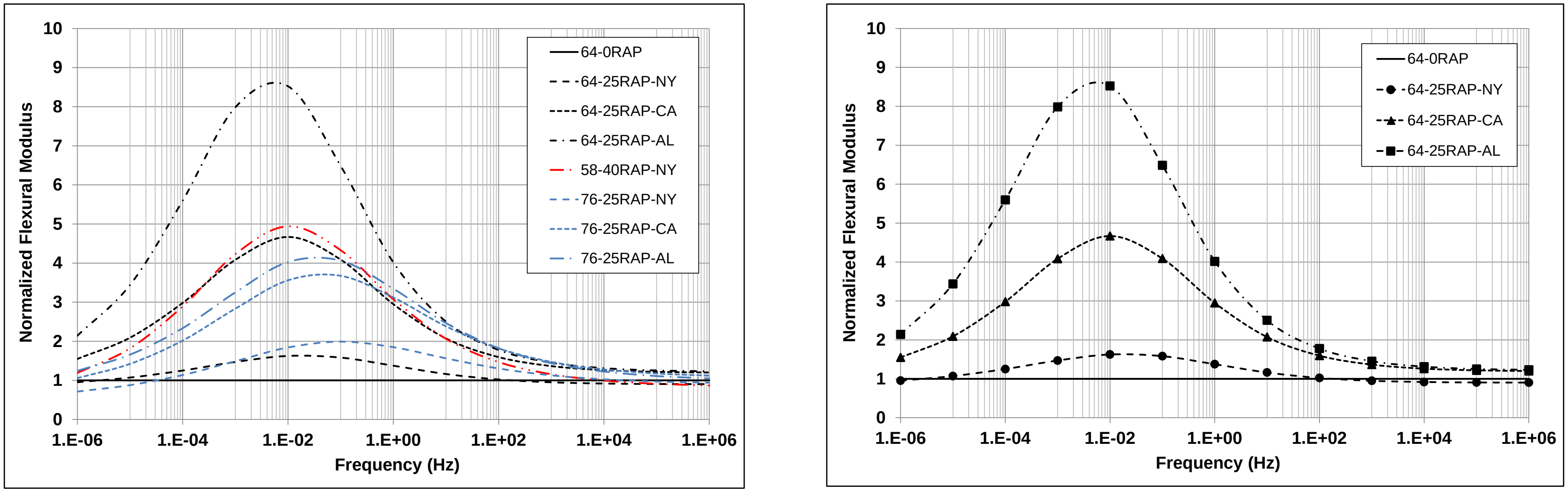
PG 64-22 mixes



PG 58-28 mixes

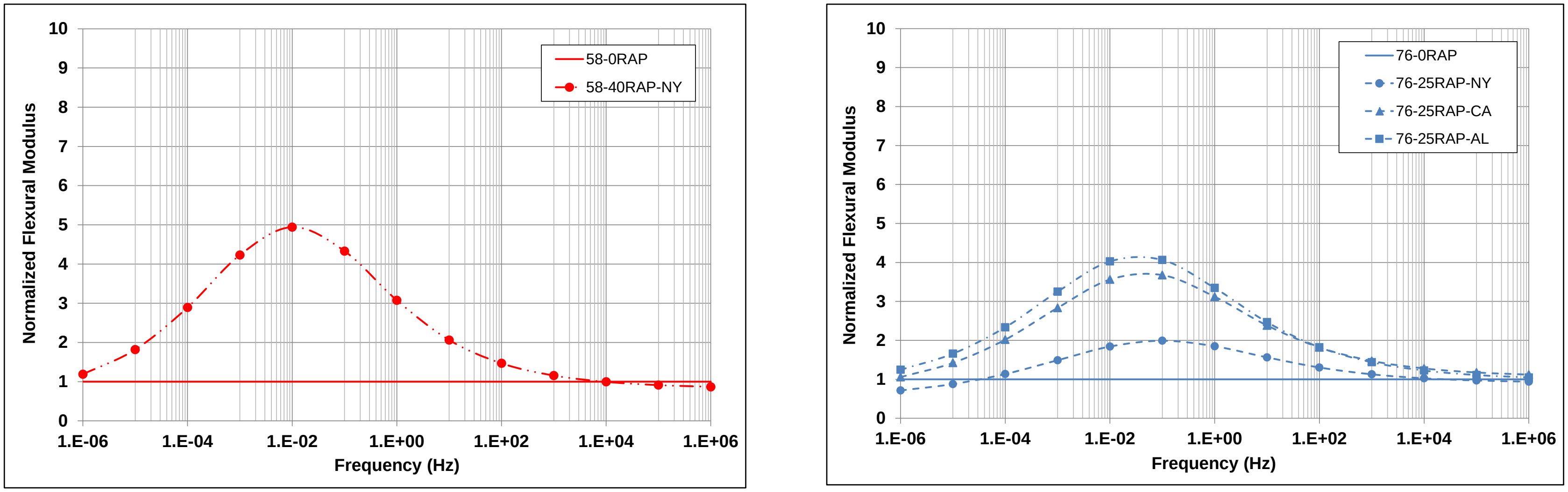
PG 76-22 PM mixes

Figure 66. Flexural Modulus Master Curves for Full-Graded Mixes



All mixes

PG 64-22 mixes



PG 58-28 mixes

PG 76-22 PM mixes

Figure 67. Normalized Flexural Modulus Master Curves for Full-Graded Mixes

- Adding RAP to the mixes always resulted in an increase in stiffness when compared to the corresponding control mix without RAP, as expected.

- The normalized master curves show that the differences in modulus occurred mainly between 0.00001 Hz and 100 Hz, which is consistent with AMPT dynamic modulus results.

- The PG 64-22 mix with 25% AL RAP had the highest stiffness of all the mixes over the full range of frequencies, which is consistent with AMPT dynamic modulus results.

- Of the PG 64-22 mixes, the one with 25% AL RAP was the stiffest, followed by the mix with 25% CA RAP and then the mix with 25% NY RAP. Adding 25% CA and AL RAP increased the stiffness of the mix by up to 6 times and 11 times that of the control, respectively. Adding 25% NY RAP increased the flexural stiffness by up to 2.5 times that of the control.

- The stiffnesses of the PG 58-28 control mix and the mix with 40% NY RAP merged at the higher and lower frequencies, corresponding to the coldest and warmest temperatures. The stiffening effect of the RAP occurred primarily in the 0.001 Hz to 10 Hz frequency range. The greatest increase in stiffness was about six times that of the control mix, at a frequency of 100 Hz.

- Of the PG 76-22 PM mixes, those with 25% CA and 25% AL RAP had similar high stiffnesses (up to 4 times that of the control) compared to the mix with 25% NY RAP (up to 2 times that of the control), which is consistent with the observations for the PG 64-22 mixes and with the AMPT dynamic modulus results. The largest differences were observed at frequencies between 0.005 Hz and 0.01 Hz. The smaller difference between the behavior of the PG 76-22 PM mixes and the PG 58-28 and PG 64-22 mixes was again attributed to the effect of the polymer modification. Results from the two PG 76-22 PM mixes with air-void contents marginally lower than the target 5.5% did not appear to differ from the general trend.

- Comparing the 40% NY RAP mix (PG 58 binder) with the 25% NY RAP mixes (PG 64 and PG 76 binders) showed that the mix with 40% RAP had a higher stiffness over the frequency range, indicating the stiffening effect of the RAP despite using the softer binder. This observation differed from the AMPT dynamic modulus results, where the softer binder compensated somewhat for the increase in stiffness caused by the higher RAP content.

9.5 EFFECT OF RAP ON RUTTING PERFORMANCE USING REPEATED LOAD TRIAXIAL.

9.5.1 Specimen Air-Void Contents.

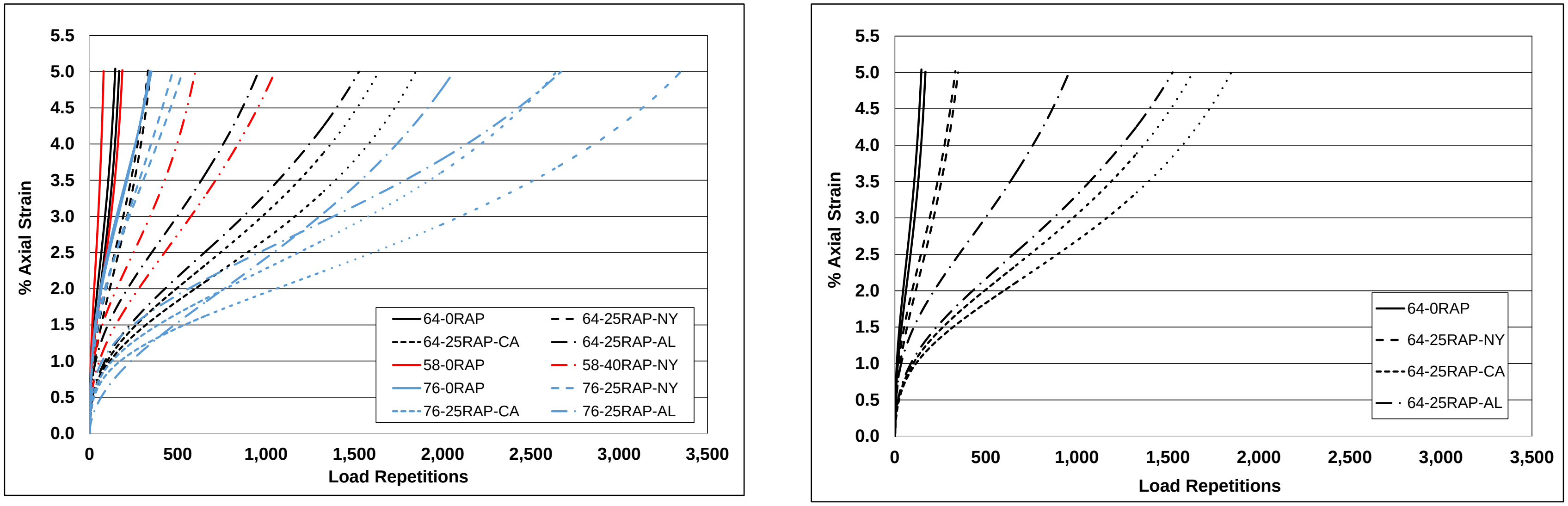
The same mix specimens used to assess dynamic modulus were also used to assess rutting performance using the flow number test setup in an AMPT. Specimen air-void contents ranged between 6.5% and 7.7% (see figure 68), with all specimens within the allowable range.

9.5.2 Test Results.

All tests were conducted at 52°C with 30 kPa contact stress and 600 kPa deviator stress in an unconfined configuration. The results were analyzed in terms of axial strain and flow number (i.e., the number of load repetitions to the start of tertiary flow as determined by the AMPT software), both of which are measures of expected cumulative permanent deformation. Figure 68 shows the development of axial strain versus loading cycles for both specimens in each mix. The following observations were made:

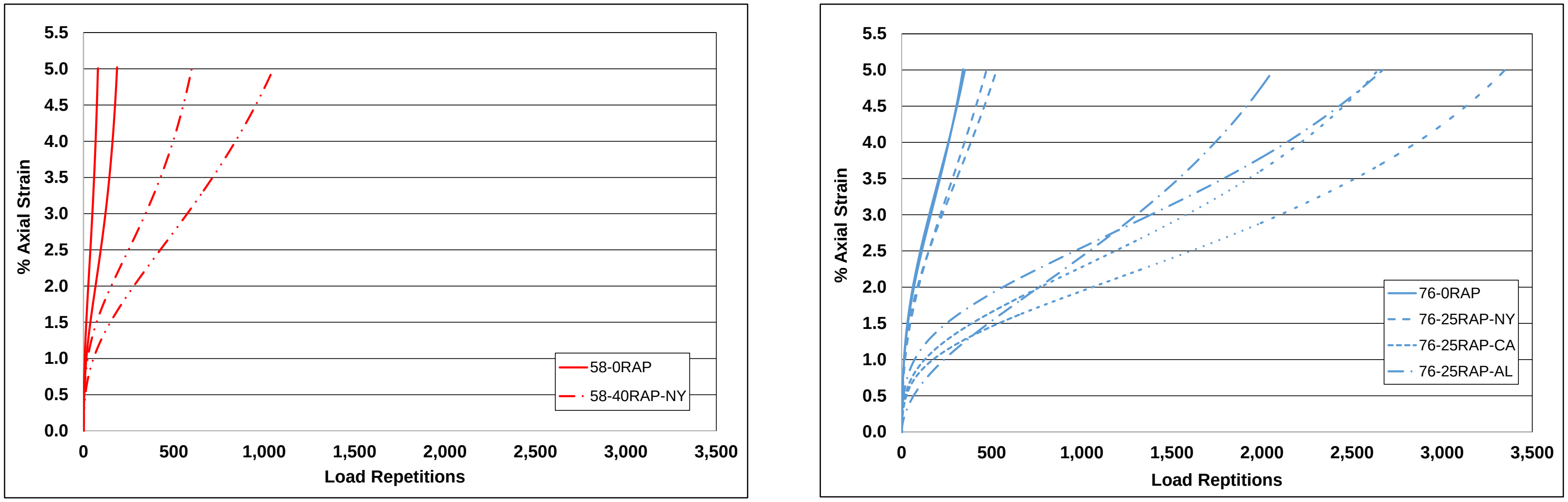
- Variability between specimens in the same mix was considered acceptable for repeated load tests. Results in terms of ranking of performance were consistent with the stiffness measurements discussed in section 9.4.
- Adding RAP to the mixes improved the rutting resistance properties, as shown by the increase in stiffness and consequent decrease in the rate of change in permanent deformation.
- Performance varied across the different RAP sources, with the RAP sourced in CA generally showing the most potential improvement in rutting performance, followed by the AL RAP and then by the NY RAP.
- The control mix with PG 76-22 PM binder had the lowest increase in cumulative permanent strain (the best rutting resistance) followed by the control mixes with PG 64-22 binder, as expected. The mixes with PG 58-28 binder had a much faster development of permanent deformation compared to the other control mixes. Adding 40% RAP to the PG 58-28 mix resulted in a notable improvement in rutting performance.

Figures 69 and 70 show the average number of load repetitions required to reach 3% axial strain and the flow number, respectively, at a testing temperature of 52°C for all mixes. Error bars show the differences between the two replicates. Binder content and air-void content are shown on the plots for reference purposes. The flow numbers of the RAP mixes after normalizing to the corresponding control mixes are shown in figure 71 to better illustrate the influence of the RAP on performance.



All mixes

PG 64 mixes



PG 58 mixes

PG 76 mixes

Figure 68. Percent Axial Strain vs Load Repetitions

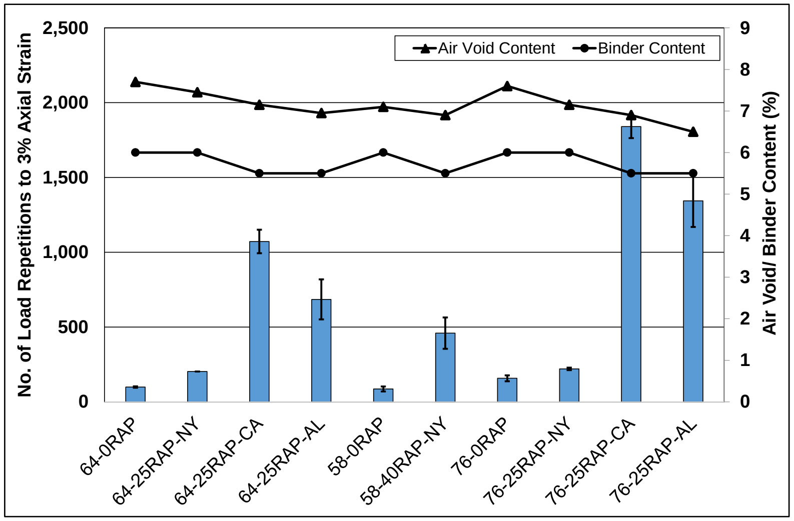


Figure 69. Average Number of Load Repetitions to Reach 3% Axial Strain at 52°C

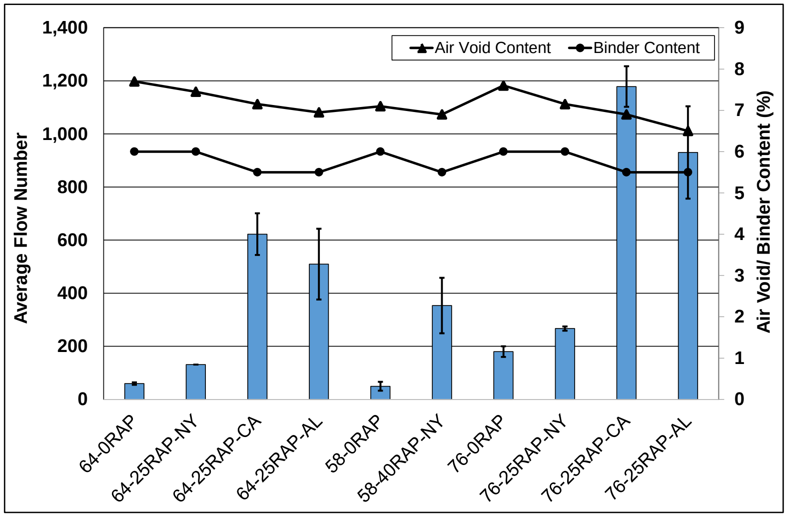


Figure 70. Average Flow Number at 52°C

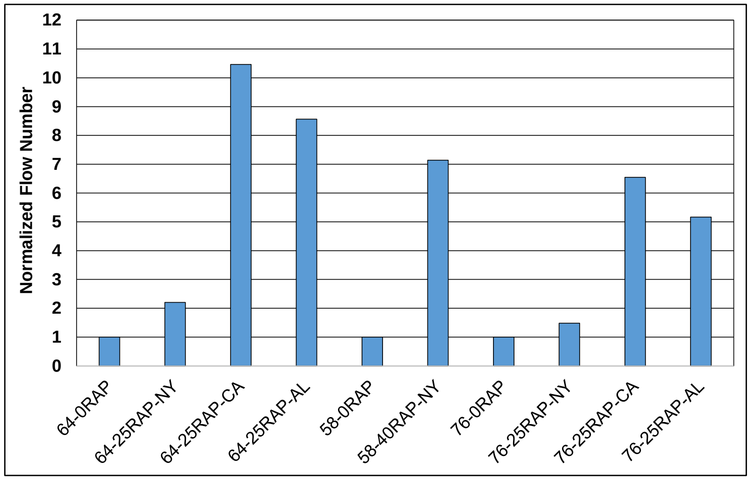


Figure 71. Normalized Flow Number

9.6 EFFECT OF RAP ON RUTTING PERFORMANCE USING APA.

APA testing was carried out at the FAA William J. Hughes Technical Center according to AASHTO T 340 [99] on gyratory-compacted specimens. Hose pressure was set at 250 psi (1700 kPa) and load was set at 250 lb (113 kg). The testing temperature was maintained at 64°C (147°F). Mixes were considered to have failed if the rut depth exceeded 10 mm at 4000 loading cycles.

9.6.1 Specimen Air-Void Contents.

Specimen air-void contents ranged between 6.3% and 7.4%%, with all specimens within the allowable range (figure 72). There was very little variability between the specimens in each mix.

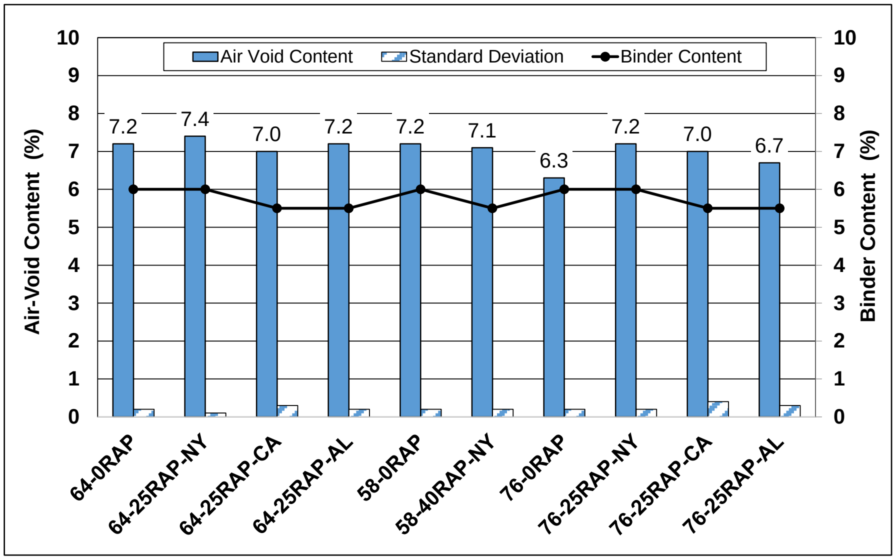


Figure 72. Average Air-Void Contents of APA Specimens

9.6.2 Test Results.

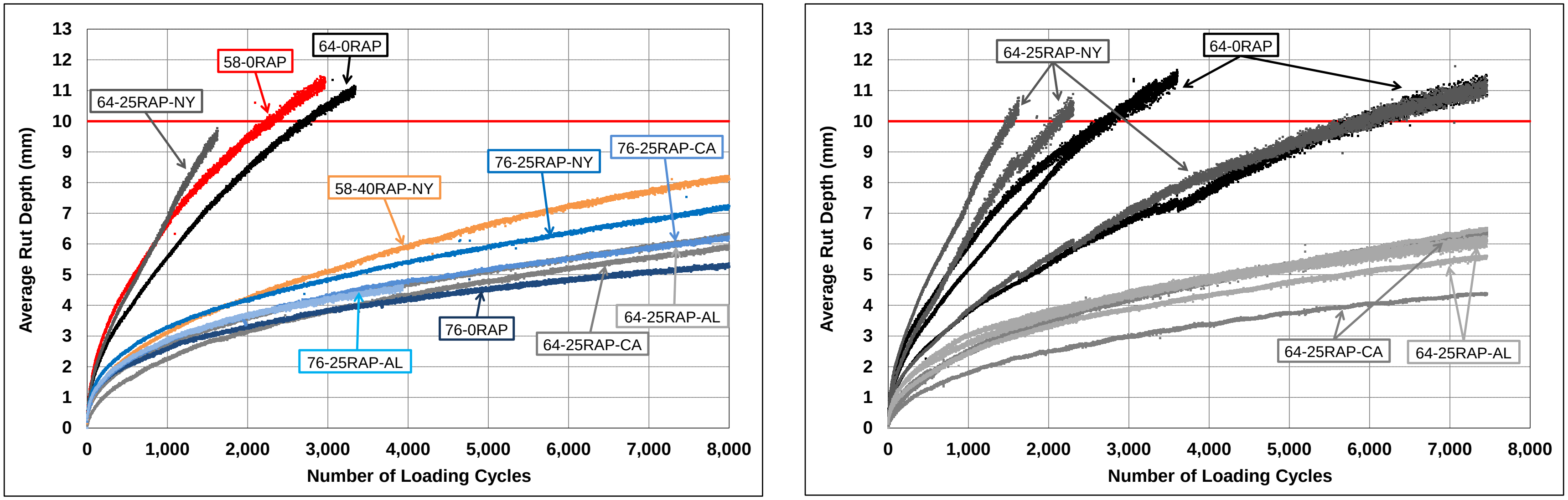
The APA test results are summarized in figure 73. A technical problem with the equipment resulted in the PG 76-22 PM mix with 25% AL RAP testing being terminated after approximately 4000 loading cycles. This incident was unlikely to influence the interpretation of the results, given that this was the point at which failure was assessed. The following observations were made:

- The result trends were generally consistent with those from repeated load triaxial testing (discussed in section 9.6.2) and Hamburg Wheel-Track testing (discussed in section 9.8.2), with some exceptions.

- The PG 64-22 and PG 58-28 control mixes and the PG 64-22 mix with 25% NY RAP did not meet the FAA P-401 specification requirements [2]. All other mixes were well within the required limit.

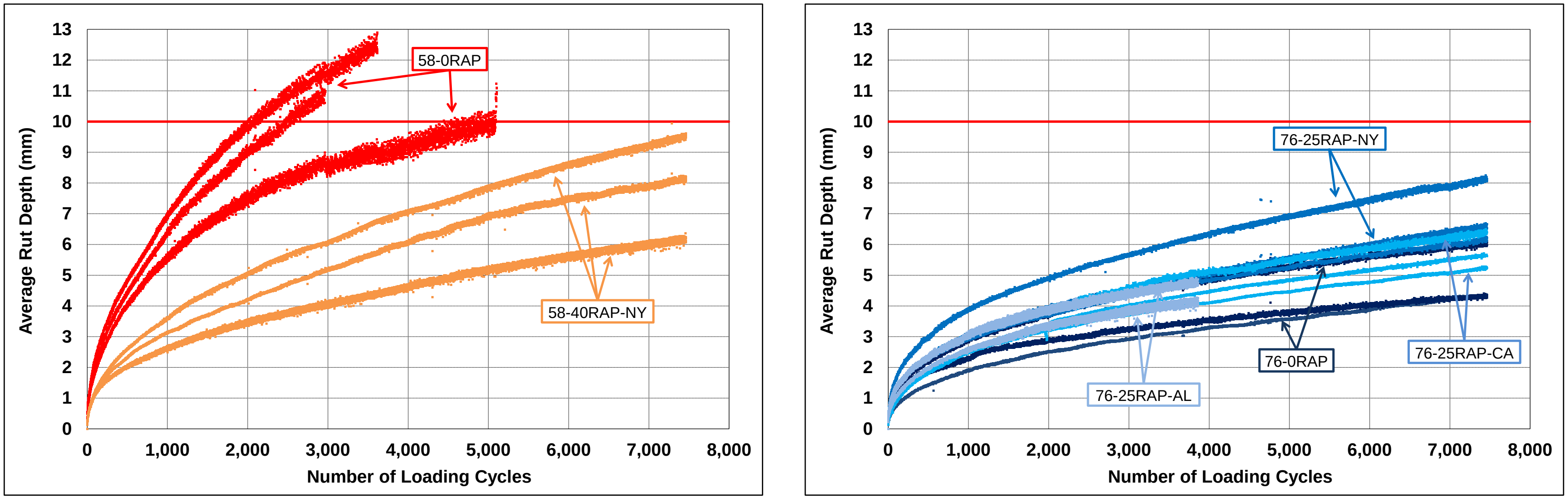
- Adding RAP to the PG 64-22 and PG 58-28 mixes improved rutting performance by a considerable margin. Adding RAP to the PG 76-22 PM mix appeared to have a negative effect on the rutting performance, which was inconsistent with the repeated load triaxial and Hamburg Wheel-Track Test results for these mixes. This was attributed in part to sensitivity of the test to possible dilution of the polymer modification by the 25% unmodified binder replacement.

- The mixes containing RAP sourced in CA and AL performed better than the mixes containing RAP sourced in NY, which is consistent with the results from the other tests.



All mixes

PG 64-22 mixes



PG 58-28 mixes

PG 76-22 PM mixes

Figure 73. Average APA Rut Progression for Full-Graded Mixes

9.7 EFFECT OF RAP ON RUTTING PERFORMANCE/MOISTURE SENSITIVITY USING HAMBURG WHEEL-TRACK TEST.

Hamburg Wheel-Track testing is not a specified requirement in the FAA P-401 specifications, but it was included in this study as an additional rutting test and to obtain an indication of the moisture sensitivity of the different mixes. Testing was carried out according to AASHTO T 324 [100] on gyratory-compacted specimens. Water temperature was maintained at 50°C (122°F). The Caltrans specification requirements [101] were used as a guide for interpreting the test results (table 35).

Table 35. Caltrans Specifications for Hamburg Wheel-Track Test

PG Grade	Minimum Number of Passes at12.5 mm Rut Depth	Minimum Number of Passes at Inflection Point
58	10,000	10,000
64	15,000	10,000
70	20,000	12,500
76	25,000	15,000

9.7.1 Specimen Air-Void Contents.

Specimen air-void contents ranged between 6.5% and 7.4%, with all specimens within the allowable range (figure 74). There was very little variability between the specimens in each mix.

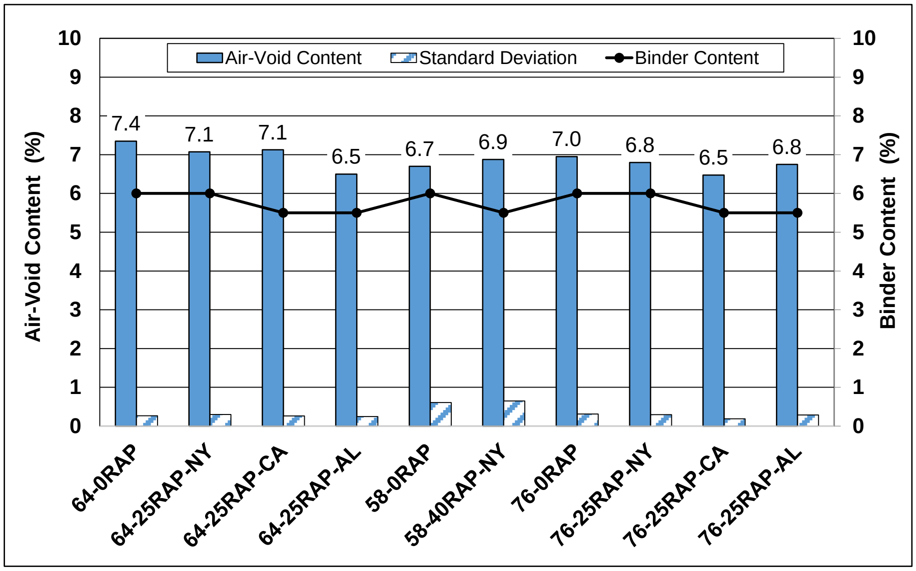


Figure 74. Average Air-Void Contents of Hamburg Wheel-Track Test Specimens

9.7.2 Test Results.

Figure 75 shows the average rut progression curves for the ten mixes evaluated. Figures 76 and 77 summarize the average and normalized maximum rut depth of each mix respectively after

10,000, 20,000, and 30,000 wheel passes. The approximate inflection points of each mix are summarized in figure 78. The following observations were made, taking into consideration that a liquid anti-strip additive was used during mix preparation to limit moisture damage (see section 7.2.4).

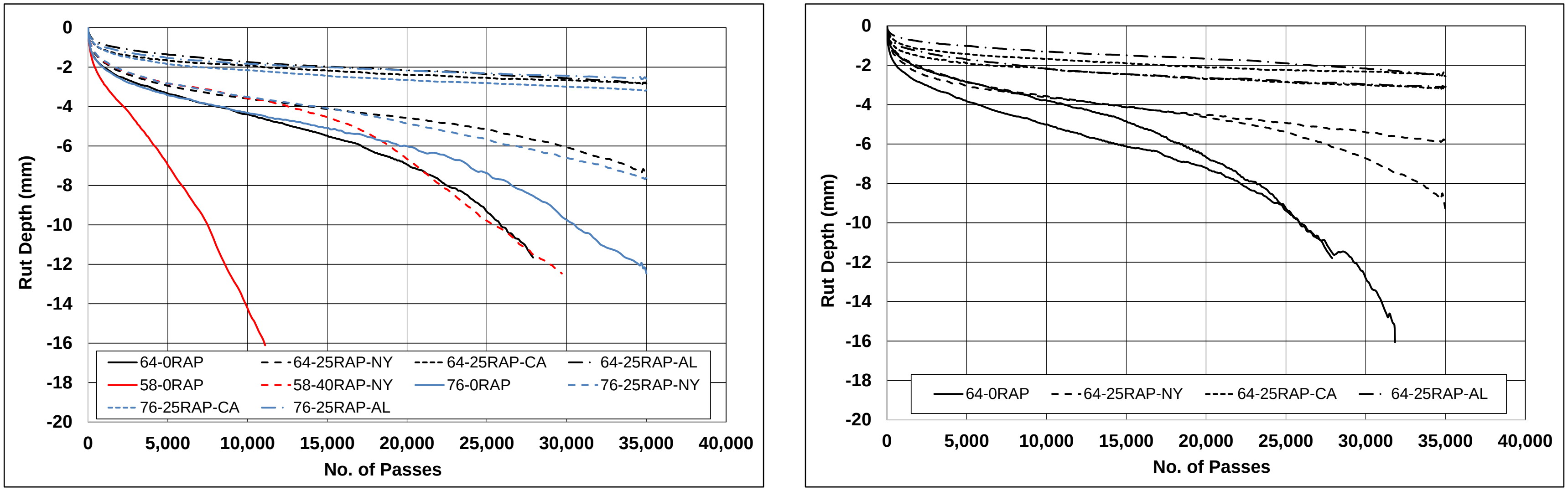
- There was a notable difference in rutting performance between the control mixes and the mixes containing RAP, with the control mixes having a considerably higher rate of rut depth increase than the mixes containing RAP. Adding RAP to the mix therefore appeared to improve both rutting performance and moisture resistance, which is consistent with the results from other tests.

- The three control mixes showed some evidence of moisture sensitivity, with all three indicating a progression from creep slope to stripping slope. The number of wheel passes to reach the inflection point between the creep and stripping slopes differed between the mixes, with the PG 58-28 control mix being the most sensitive to moisture and the PG 76-22 PM control mix being the least sensitive. In terms of typical state department of transportation specifications, only the PG 58-28 control mix would be considered as moisture sensitive (i.e., rut depth >12.5 mm after 10,000 wheel passes; inflection point >10,000 wheel passes). The PG 64-22 and PG 76-22 PM control mixes exceeded minimum typical state department of transportation specification limits by a considerable margin (i.e., rut depth >12.5 mm after 15,000 and 25,000 wheel passes, respectively; inflection points >10,000 and 15,000 wheel passes, respectively).

- There was a distinct difference in rutting performance between the mixes containing NY RAP and the mixes containing CA and AL RAP. Initial embedment on the mixes containing NY RAP was notably higher than the other mixes regardless of binder grade. This performance was consistent with other rutting performance test results. The NY RAP mixes did not show a clear inflection point (i.e., the mix was not moisture sensitive and the binder did not strip from the aggregate), but rather showed continually increasing rut depth with increasing number of wheel passes. The NY RAP mix results were, however, still well within typical state department of transportation specifications for all binder grades.

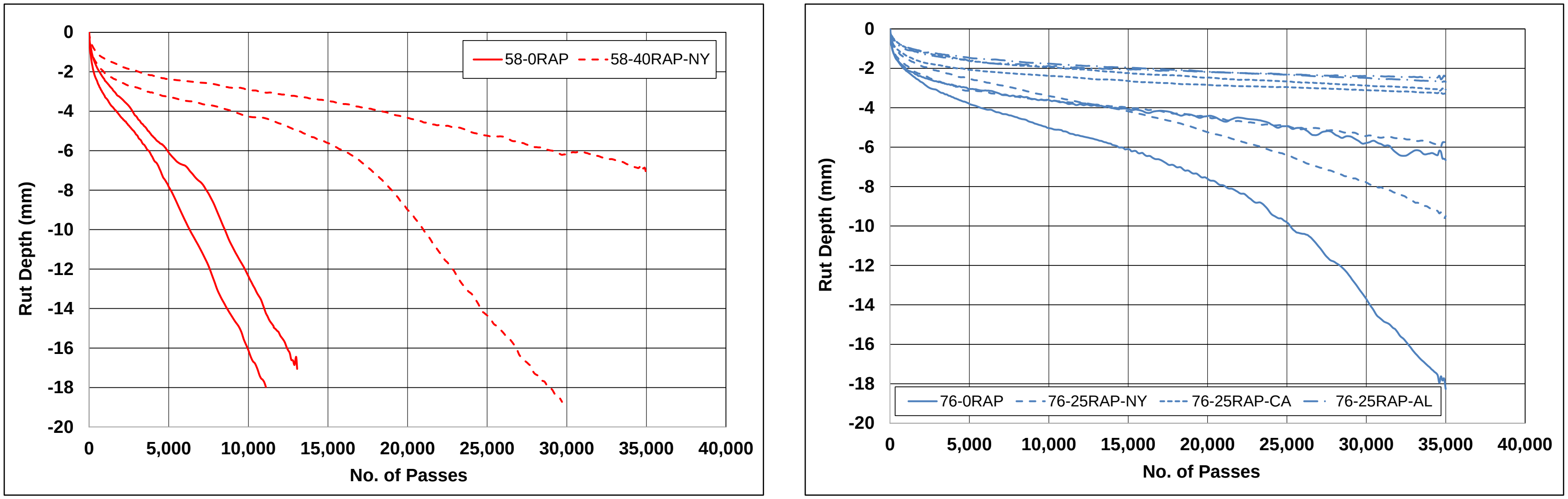
- The mixes with CA and AL RAP performed well in all mixes, and there was very little apparent difference between the mixes with the two binder grades. Limited early embedment occurred and thereafter the rate of rut depth increase was slow, with the average maximum rut depths of each mix not exceeding 3.5 mm after 35,000 wheel passes. Analysis in terms of normalized rut depth indicate that adding RAP to the PG 64-22 mixes had a marginally greater influence on performance than adding RAP to the PG 76-22 PM mixes, especially in terms of extended testing duration (i.e., after 20,000 and 30,000 wheel passes).

- The PG 58-28 mix with 40% NY RAP showed an initial embedment trend similar to those of PG 64-22 and PG 76-22 PM, but after approximately 15,000 wheel passes, the rate of rut depth of the PG 58-28 mix increased significantly, implying that stripping of the binder from the aggregate had started. The PG 58-28 mix with 40% NY RAP was the only RAP mix that indicated a clear inflection point.



All mixes

PG 64-22 mixes



PG 58-28 mixes

PG 76-22 PM mixes

Figure 75. Average Hamburg Wheel-Track Test Rut Progression for Full-Graded Mixes

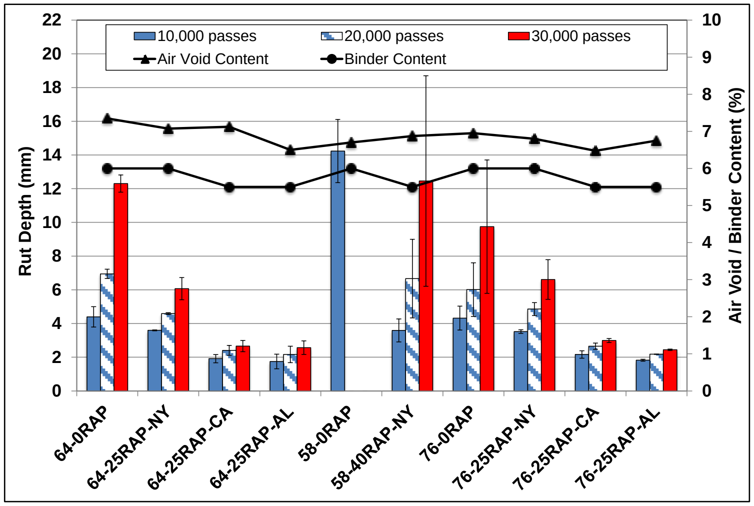


Figure 76. Average Hamburg Wheel-Track Test Rut Depth

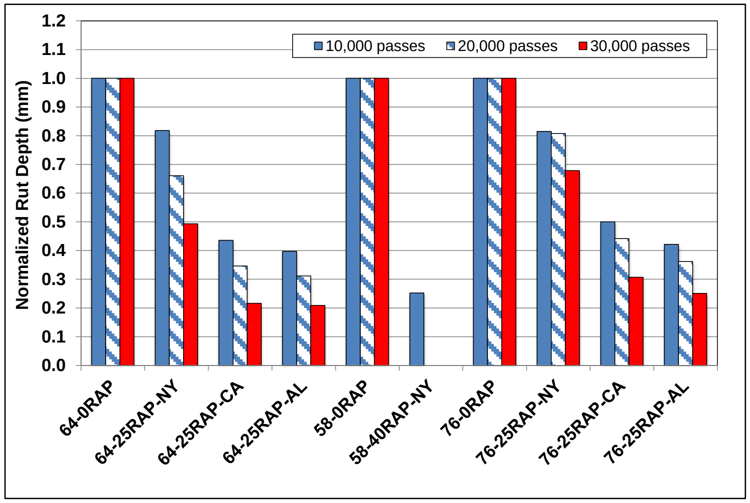


Figure 77. Normalized Hamburg Wheel-Track Test Rut Depth

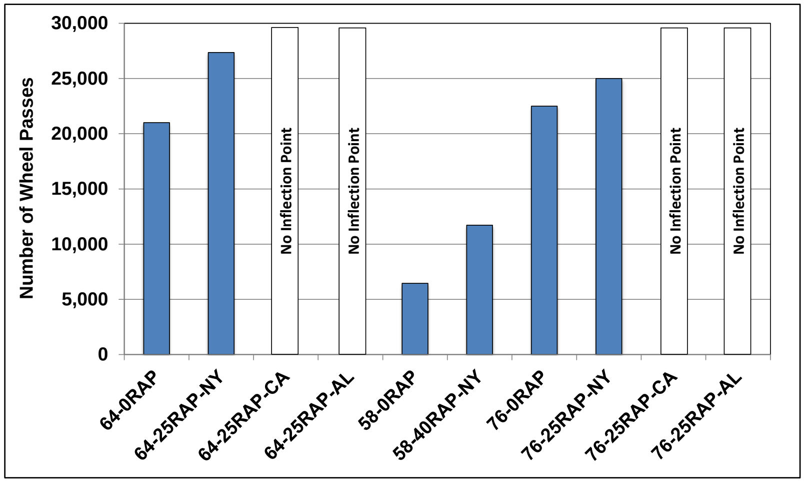


Figure 78. Approximate Hamburg Wheel-Track Test Inflection Points

9.8 EFFECT OF RAP ON FATIGUE/REFLECTIVE CRACKING PERFORMANCE USING FOUR-POINT BEAM TEST.

The four-point beam fatigue test provides an indication of the resistance of an asphalt mix to fatigue cracking. Beam specimens are subjected to four-point bending by applying sinusoidal loading at three different strain levels (high, intermediate, and low) at a frequency of 10 Hz and temperature of 20°C. The fatigue life at each strain level was selected as the cycle at which maximum values of stiffness multiplied by the number of cycles occurs.

In this study, the testing approach currently specified in AASHTO T 321 [98] 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 5), with strain levels selected, based on experience, to achieve fatigue lives between 10,000 and 100,000 load cycles and between 300,000 and 500,000 load cycles, respectively. Additional specimens were then tested at lower strain levels selected based on the initial linear relationship to achieve a fatigue life of about 1 million load repetitions. The regression relationship was then refined to accommodate the measured stiffness at the lower strain level.

$$LnN = A + B \times \varepsilon \tag{5}$$

where: N is fatigue life (number of cycles),
ε is the strain level (μstrain), and
A and B are model parameters.

9.8.1 Specimen Air-Void Contents.

The average air-void content and standard deviation of the beams produced for each mix are summarized in figure 79. Beam air-void contents in eight of the ten mixes were within the target range. Beam air-void contents in the remaining two mixes (i.e., 76-25RAP-NY and 76-25RAP-CA) were slightly below the target range, but as with the flexural modulus beam specimens, a decision was made to continue with testing due to the limited availability of materials and time constraints for compacting additional beams. Any potential influences of air-void content were considered during analysis of the results. Variation in air-void content between beams of the same mix was again larger than that achieved with the gyratory-compacted specimens, but was still acceptable, indicating that consistent compaction was achieved.

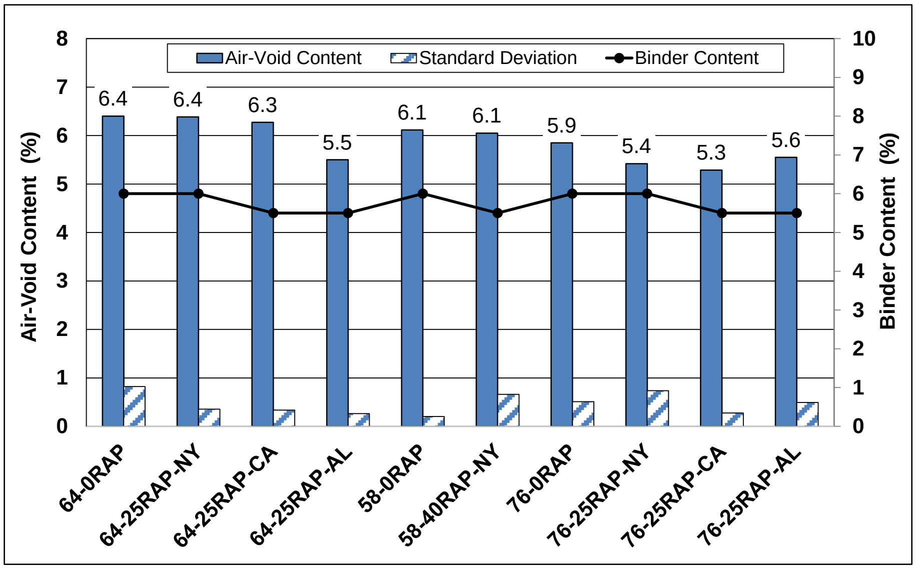


Figure 79. Average Air-Void Contents of Beam Fatigue Test Specimens

<u>9.8.2 Test Results</u>.

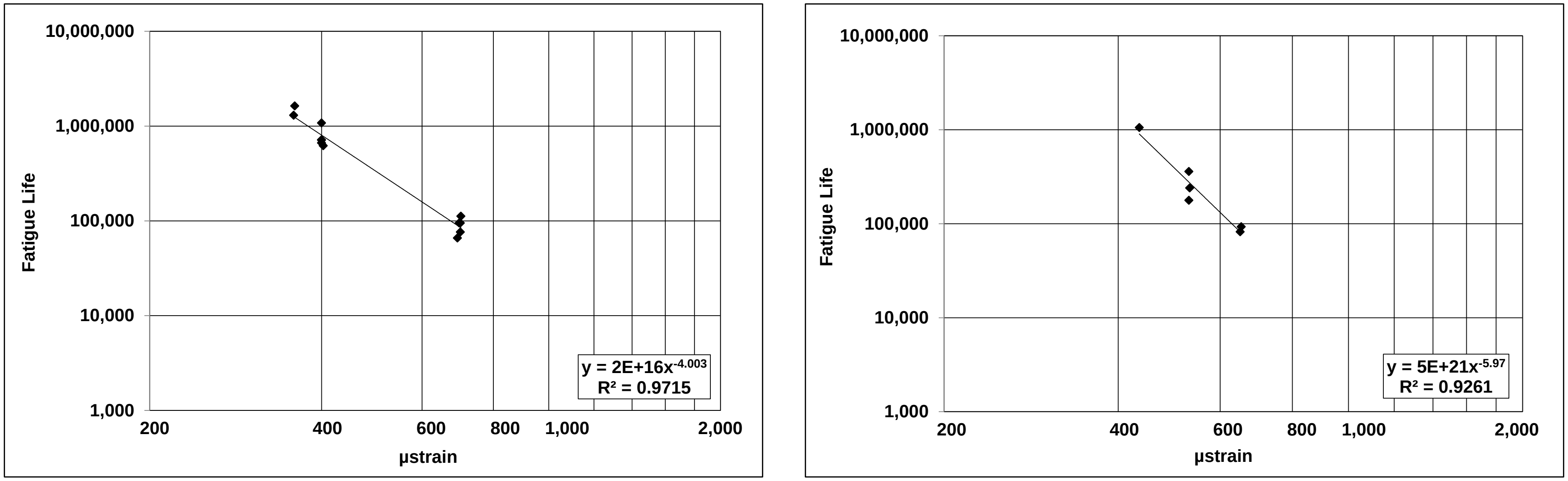
Plots of the fatigue models for each binder grade are shown in figures 80 through 82. The models were considered to be appropriate based on the high r^2 values of the model fitting and repeatability of the test results at each strain level. The variability of the results for the PG 76-22 PM mixes was higher than that of the other mixes (i.e., lower r^2 values), which was attributed to testing at higher initial strain levels compared to the unmodified PG 64-22 and PG 58-28 mixes. Calculated fatigue lives at 200 µstrain, 400 µstrain, and 600 µstrain of all the mixes are compared in figure 83. Note that no mixes were tested at 200 µstrain and that fatigue life at this strain level was extrapolated.

The following observations were made:

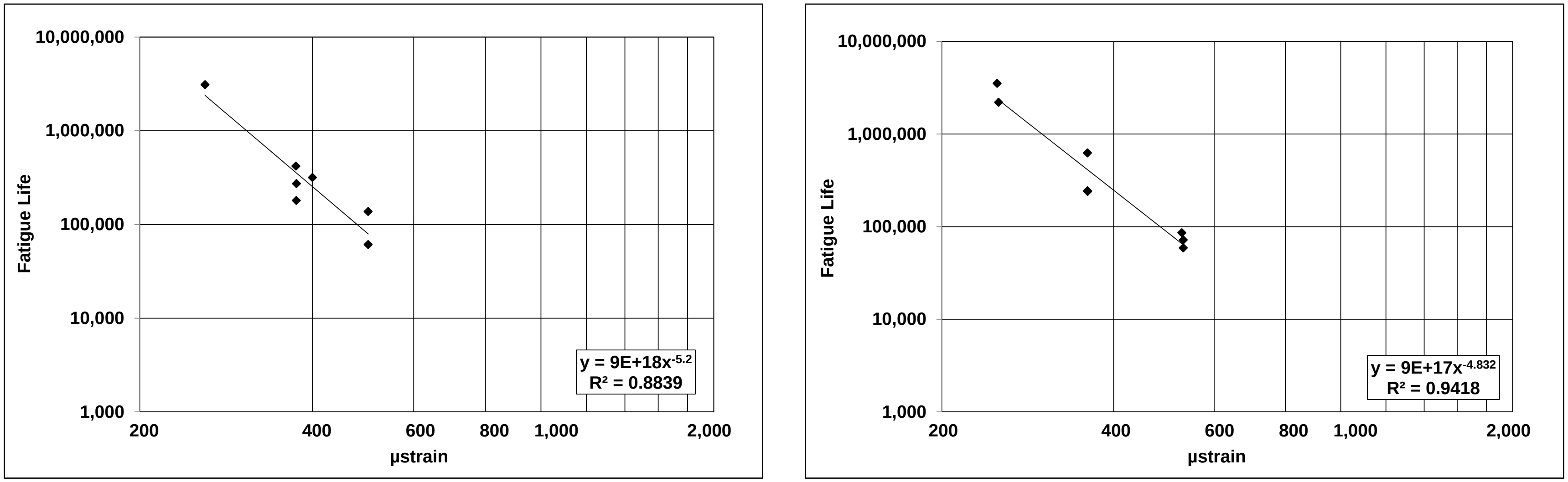
- The PG 76-22 PM control mix had the highest fatigue life and was therefore potentially considerably less susceptible to fatigue or reflective cracking than the other mixes. Adding 25% RAP to the mix reduced the fatigue life considerably, with the degree of reduction dependent on the RAP source. RAP from the NY source had the lowest impact, as expected, based on the results of the stiffness and rutting performance tests. RAP from the CA and AL sources had the highest impact on fatigue life, which is consistent with other test results. Mixes prepared with the CA and AL RAP had similar fatigue life performance.
- The PG 64-22 mixes had the lowest fatigue lives of the ten mixes. Mixes containing RAP from the CA and AL sources had the poorest performance, followed by the control mix and the mix prepared with RAP from the NY source. These results were again consistent with the results from the other tests (i.e., the PG 64-22 mixes with the best rutting performance had the lowest fatigue lives).

- The PG 58-28 control mix had slightly better fatigue life properties than the PG 64-22 control mix, as expected. Adding RAP from the NY source to the PG 58-28 mix appeared to improve performance at lower strain levels, but reduced the fatigue life at higher strain levels.

- The effect of increased strain level on the behavior of the PG 58-28 and PG 64-22 control mixes was notably different than that of the other mixes, with increasing strain level having less impact than on the mixes containing RAP. The effect of increasing strain level on the PG 76-22 PM mixes could not be distinguished, indicating that the polymer modification compensated for the potential stiffening effect of the RAP.

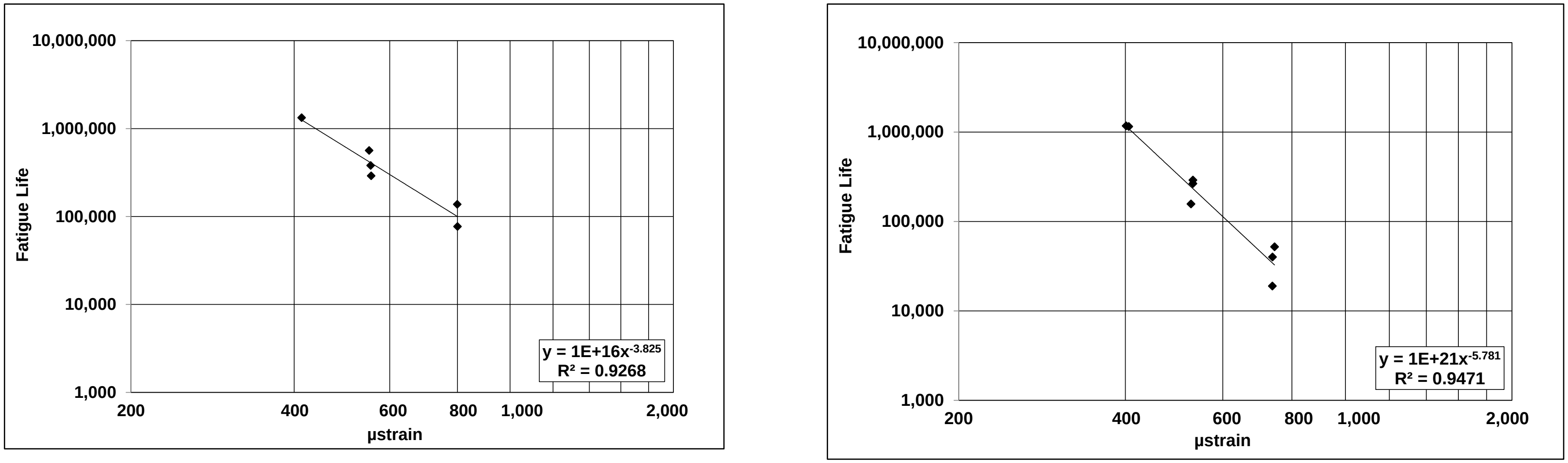


PG 64-0RAP PG 64-25RAP-NY



PG 64-25RAP-CA PG 64-25RAP-AL

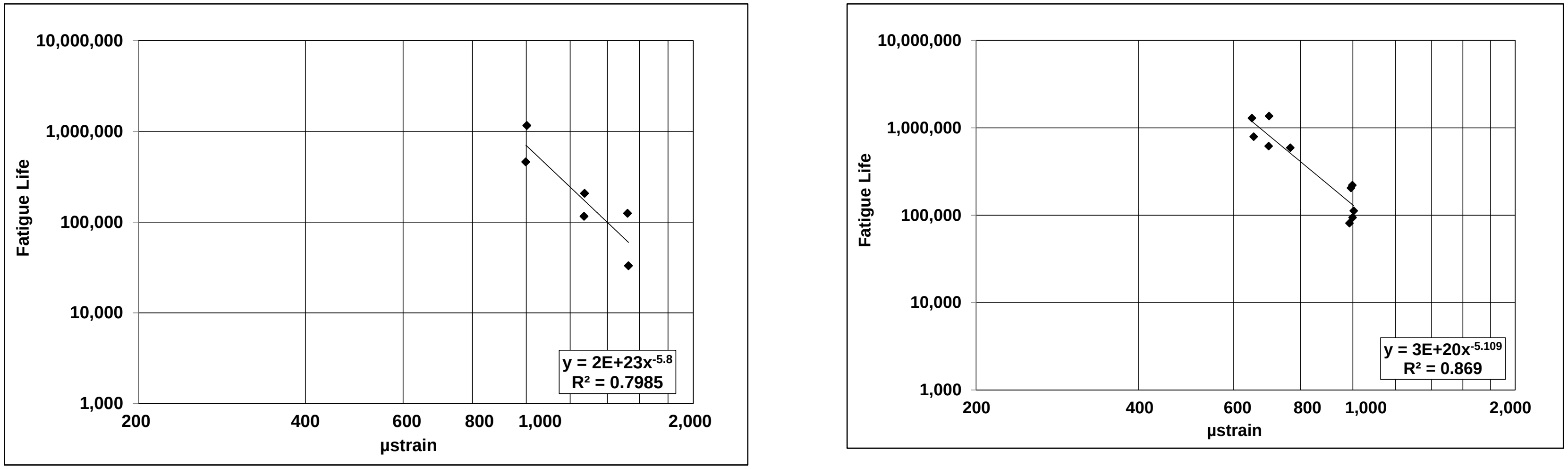
Figure 80. Fatigue Models for PG 64-22 Mixes



PG 58-0RAP

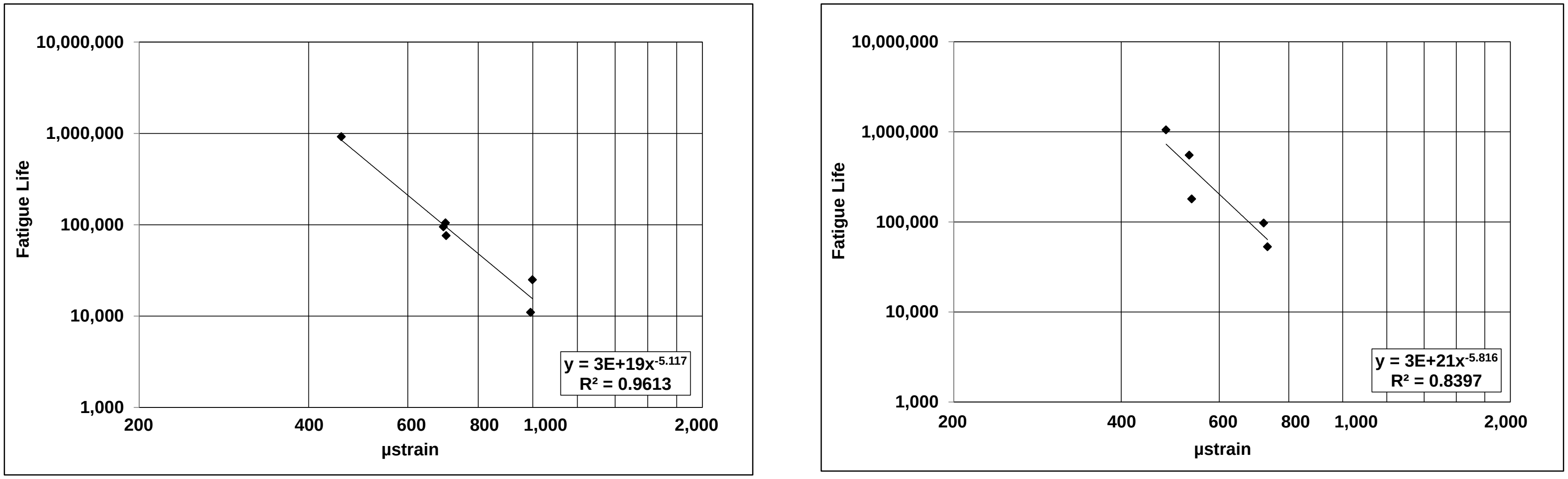
PG 58-40RAP-NY

Figure 81. Fatigue Models for PG 58-28 Mixes



PG 76-0RAP

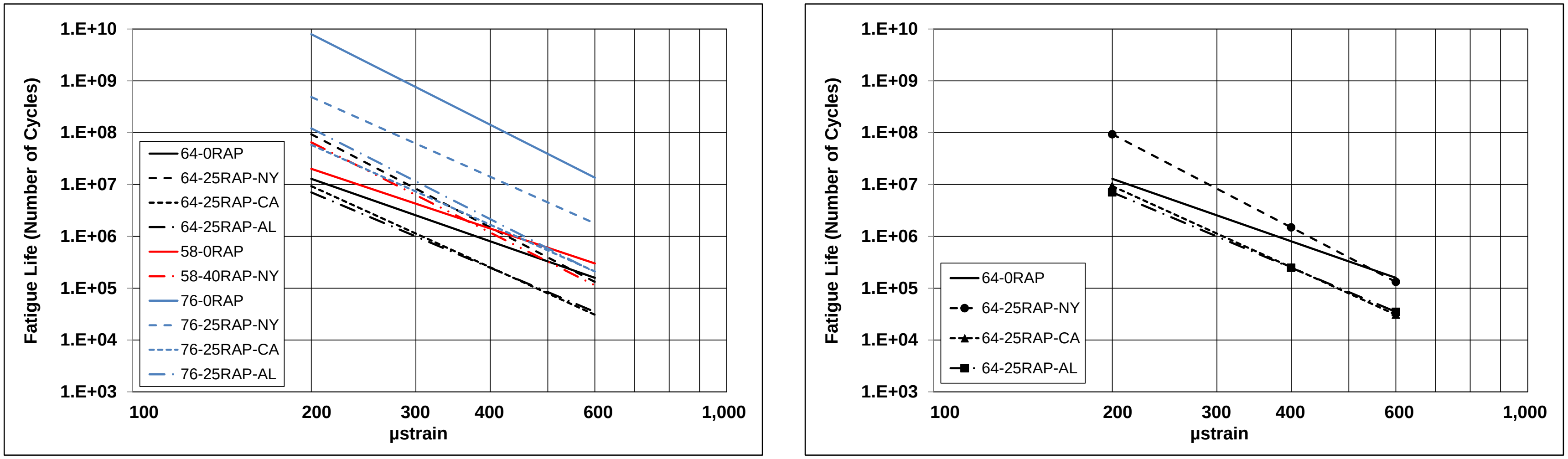
PG 76-25RAP-NY



PG 76-25RAP-CA

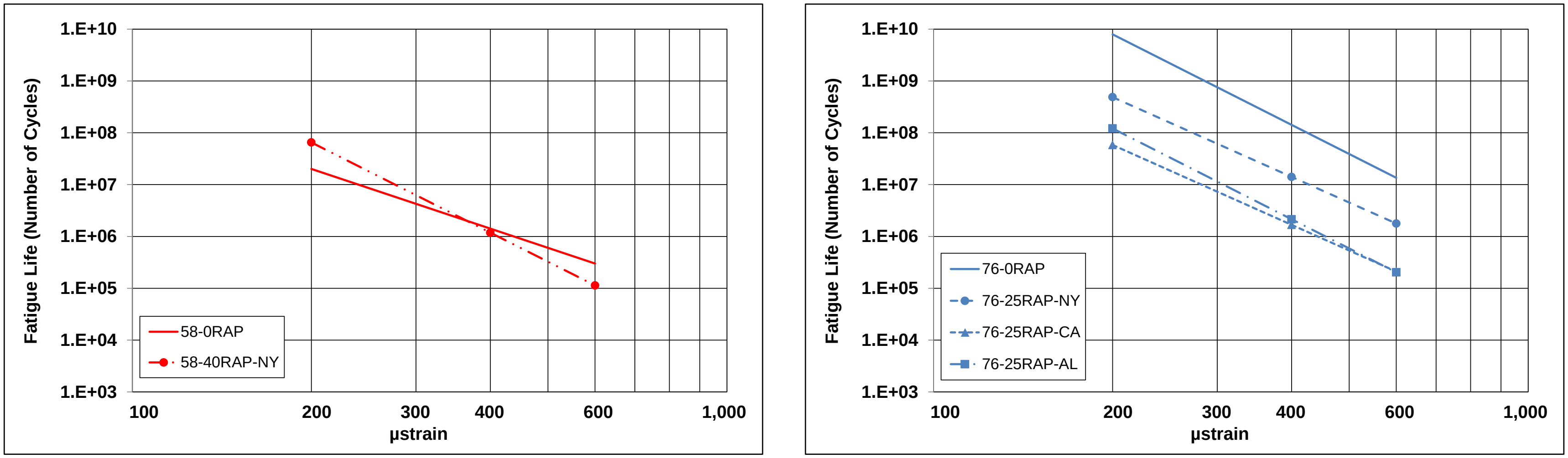
PG 76-25RAP-AL

Figure 82. Fatigue Models for PG 76-22 PM Mixes



All mixes

PG 64-22 mixes



PG 58-28 mixes

PG 76-22 mixes

Figure 83. Calculated Fatigue Life at 200, 400, and 600 µstrain

9.8.3 Mechanistic Analysis of Fatigue Performance.

The above observations were verified with a mechanistic analysis. The fatigue performance of an asphalt mix is a function of many factors including but not limited to the pavement structure, mix stiffness, mix strength, ambient temperature, wheel load, wheel configuration, and tire pressure. The maximum tensile strength at the bottom of the asphalt concrete layers (or at the bottom of individual asphalt concrete layers if debonding has occurred) is the critical pavement response for fatigue cracking. Therefore, to obtain a realistic evaluation of fatigue performance, the critical pavement responses must be calculated based on known asphalt stiffness and traffic load configurations.

Two pavement structures (table 36) were considered. Boeing (B)737-800 and B777F aircraft were used for the analysis; their wheel-gear footprints are shown in figures 84 and 85. The design loads per main gear strut were set at 37,250 kg (82,140 lb) and 159,900 kg (352,500 lb) for the B737-800 and B777F, respectively (information sourced from the Boeing website). The tire pressures of the main gear wheels were set at 1.4 MPa (204 psi) and 1.5 MPa (218 psi), respectively. One aircraft speed (50 km/h [31 mph]) was considered.

Table 36. Pavement Structures Used in the Fatigue Performance Analysis

	Thickness (mm)			Stiffness (MPa)			Poisson's Ratio		
Layer	AC	Base	SG	AC	Base	SG	AC	Base	SG
Structure 1 (Thin AC/thick base)	125	300	Infinite	Calc.	300	100	0.4	0.3	0.4
Structure 2 (Thick AC/thin base)	250	200	Infinite	Calc.	300	100	0.4	0.3	0.4
Structure 3 (Thick AC/thick base)	250	300	Infinite	Calc.	300	100	0.4	0.3	0.4

AC = Asphalt concrete
SG = Subgrade
Calc. = Calculated

Loading time was calculated using equation 6.

$$\text{Loading time} = 2 \times \text{radius of wheel loading area} \times \text{AC thickness} \qquad (6)$$

The inverse of the loading time was used as the loading frequency (in radian frequency, $\omega = 2\pi \times f\,(Hz)$). The loading frequency was determined to be 0.3 Hz for Structure 1, and 0.4 Hz for Structure 2 and Structure 3. Mix stiffnesses at a pavement temperature of 20°C were selected from the flexural stiffness master curves (figure 66).

The OpenPave software program was used to calculate maximum principal strains at the bottom of the asphalt concrete layers. The responses for the B737-800 were calculated under the center point of one tire and at the midpoint between one set of dual tires. The same responses plus the response at the midpoint between two of the main gear axles were calculated for the B777F. The maximum principal strain occurred under the center point of one tire for both aircraft. This calculated critical strain at the bottom of the asphalt concrete layer for each mix type was substituted into the respective fatigue models discussed in section 9.8.2 to estimate the fatigue life. Tables 37 and 38 summarize the critical maximum principal tensile strains and fatigue lives for the different mixes under B737-800 and B777F loading conditions. Table 39 ranks the different mixes in terms of fatigue life under B737-800 loading.

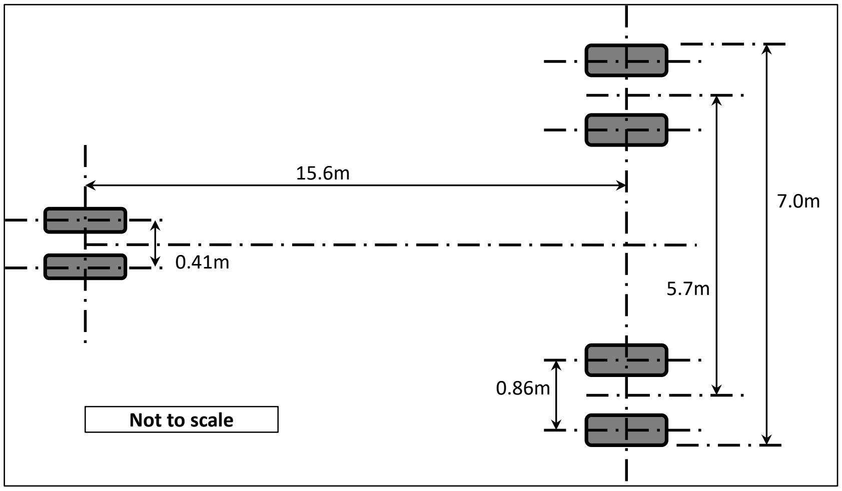


Figure 84. The B737-800 Gear Footprint

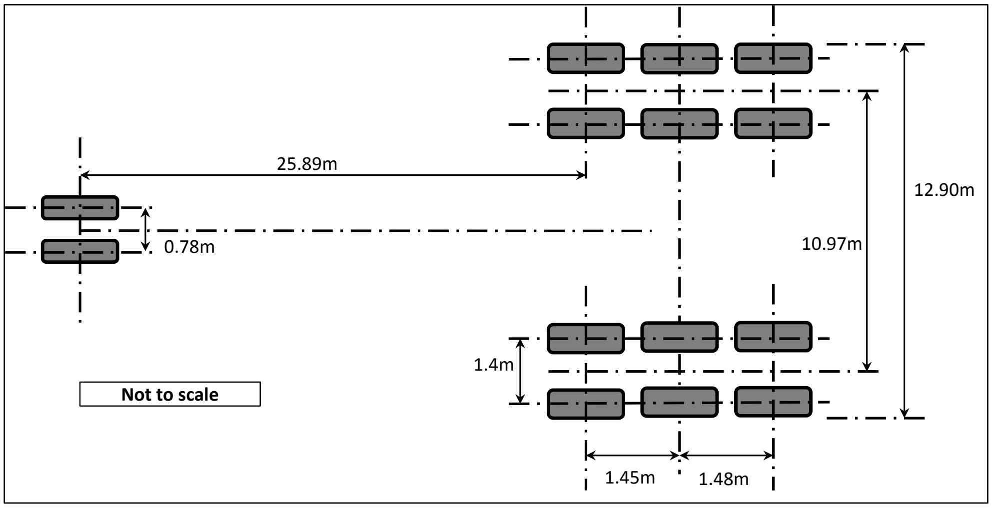


Figure 85. The B777 Gear Footprint

The following observations were made:

- The fatigue behavior of the mixes followed similar trends under both aircraft loading conditions, with the PG 76-22 PM mixes performing better than the PG 58-28 mix, which in turn performed better than the PG 64-22 mixes.

- The ranking of the mixes based on fatigue performance was generally independent of the pavement structure.

- The PG 76-22 PM control mix had the best performance and the PG 64-22 mix with 25% RAP from the CA source had the poorest performance, which is consistent with the laboratory test results.

- Adding RAP to the mixes significantly reduced the fatigue life of the mix in all but one of the mixes tested. The effect was more severe on pavements with thicker asphalt concrete surfacings. In most cases, the RAP from the NY source had the least effect on fatigue life, while the RAP from the CA source had the largest impact on fatigue life.

- Adding RAP to the mixes had a larger negative impact on the fatigue performance of the PG 76-22 PM mixes (i.e., percent change in fatigue performance compared to the control mix) than on the performance of the PG 64-22 binder mixes. This implies that adding RAP to mixes with PM binders could significantly reduce the benefits of the polymer in terms of cracking resistance.

- Adding 40% RAP to the PG 58-28 mix improved the fatigue performance of the mix on the pavements with thicker asphalt concrete surfacings; this was attributed to increases in the initial stiffness of the mix. This result supports other work in the literature suggesting that selecting a binder one performance grade lower than the design grade for high RAP-content mixes can compensate for the stiffening effect of the RAP. It should be noted that the RAP from the NY source did appear to be relatively unaged and that the extracted binder tested softer than those of the other RAP sources.

- Fatigue performance increased with increasing pavement thickness, as expected.

Table 37. Tensile Strains and Corresponding Fatigue Lives for B737-800 Loading

Mix Identification	Structure 1 (Thin AC/Thick Base)			Structure 2 (Thick AC/Thin Base)			Structure 3 (Thick AC/Thick Base)		
	Maximum Tensile Strain	Fatigue Life (N_f)	% Change From Control	Maximum Tensile Strain	Fatigue Life (N_f)	% Change From Control	Maximum Tensile Strain	Fatigue Life (N_f)	% Change From Control
64-0RAP	713	8.0.E+04	0	570	1.9.E+05	0	528	2.6.E+05	0
64-25RAP-NY	680	6.3.E+04	21	629	1.0.E+05	49	581	1.6.E+05	39
64-25RAP-CA	554	4.6.E+04	42	655	2.0.E+04	90	604	3.0.E+04	89
64-25RAP-AL	506	8.0.E+04	0	516	7.3.E+04	67	479	1.0.E+05	61
58-0RAP	742	1.3.E+05	0	366	2.0.E+06	0	345	2.5.E+06	0
58-40RAP-NY	603	1.1.E+05	17	318	4.4.E+06	-124	301	6.1.E+06	-145
76-0RAP	751	3.7.E+06	0	530	2.8.E+07	0	492	4.3.E+07	0
76-25RAP-NY	691	8.7.E+05	76	421	1.1.E+07	61	394	1.5.E+07	64
76-25RAP-CA	606	2.0.E+05	95	409	1.5.E+06	95	384	2.1.E+06	95
76-25RAP-AL	596	2.1.E+05	94	415	1.7.E+06	94	389	2.5.E+06	94

Table 38. Tensile Strains and Corresponding Fatigue Lives for B777F Loading

Mix Identification	Structure 1 (Thin AC/Thick Base)			Structure 2 (Thick AC/Thin Base)			Structure 3 (Thick AC/Thick Base)		
	Maximum Tensile Strain	Fatigue Life (N_f)	% Change From Control	Maximum Tensile Strain	Fatigue Life (N_f)	% Change From Control	Maximum Tensile Strain	Fatigue Life (N_f)	% Change From Control
64-0RAP	741	6.8.E+04	0	594	1.7.E+05	0	556	2.1.E+05	0
64-25RAP-NY	712	4.7.E+04	21	657	7.7.E+04	49	613	1.2.E+05	46
64-25RAP-CA	587	3.4.E+04	42	684	1.6.E+04	90	637	2.3.E+04	89
64-25RAP-AL	534	6.1.E+04	0	534	6.1.E+04	63	503	8.2.E+04	62
58-0RAP	763	1.2.E+05	0	379	1.7.E+06	0	360	2.1.E+06	0
58-40RAP-NY	636	8.1.E+04	17	330	3.6.E+06	-124	315	4.7.E+06	-121
76-0RAP	771	3.2.E+06	0	549	2.3.E+07	0	516	3.3.E+07	0
76-25RAP-NY	721	6.9.E+05	76	434	9.3.E+06	61	411	1.2.E+07	62
76-25RAP-CA	640	1.5.E+05	95	422	1.3.E+06	95	400	1.7.E+06	95
76-25RAP-AL	630	1.5.E+05	94	428	1.4.E+06	94	406	2.0.E+06	94

Table 39. Ranked Fatigue Life for B737-800 Loading

	Structure 1		Structure 2		Structure 3	
Rank	Mix Identification	Fatigue Life (N_f)	Mix Identification	Fatigue Life (N_f)	Mix Identification	Fatigue Life (N_f)
1	76-0RAP	3.7.E+06	76-0RAP	2.8.E+07	76-0RAP	4.3.E+07
2	76-25RAP-NY	8.7.E+05	76-25RAP-NY	1.1.E+07	76-25RAP-NY	1.5.E+07
3	76-25RAP-AL	2.1.E+05	58-40RAP-NY	4.4.E+06	58-40RAP-NY	6.1.E+06
4	76-25RAP-CA	2.0.E+05	58-0RAP	2.0.E+06	58-0RAP	2.5.E+06
5	58-0RAP	1.3.E+05	76-25RAP-AL	1.7.E+06	76-25RAP-AL	2.5.E+06
6	58-40RAP-NY	1.1.E+05	76-25RAP-CA	1.5.E+06	76-25RAP-CA	2.1.E+06
7	64-0RAP	8.0.E+04	64-0RAP	1.9.E+05	64-0RAP	2.6.E+05
8	64-25RAP-AL	8.0.E+04	64-25RAP-NY	1.0.E+05	64-25RAP-NY	1.6.E+05
9	64-25RAP-NY	6.3.E+04	64-25RAP-AL	7.3.E+04	64-25RAP-AL	1.0.E+05
10	64-25RAP-CA	4.6.E+04	64-25RAP-CA	2.0.E+04	64-25RAP-CA	3.0.E+04

9.9 PHASE 2c TESTING SUMMARY.

Key observations from Phase 2c testing on full-graded mixes include the following:

- The test methods used in this phase of the study were sufficiently sensitive to distinguish the behavior of the different mixes and to consistently distinguish the differences in performance of mixes containing no RAP (i.e., control mixes) and mixes containing RAP. However, all testing was undertaken on newly prepared laboratory specimens, and consequently do not necessarily reflect long-term performance of the mixes or the longer-term effects of the RAP binder on the rate of aging of the virgin binder.

- Adding RAP increased the stiffness of the mixes, which in most instances improved the rutting resistance properties of the mix but diminished the cracking resistance properties.

- The degree of change in rutting and cracking resistance was dependent on the RAP source, with test results for each source ranking consistently across the different tests (i.e., the RAP from the NY source consistently had the least effect on mix performance, while the RAP from the CA and AL sources consistently had the largest effect). This implies that RAP cannot be considered as a generic material with consistent properties.

- Adding RAP to mixes with PM binders appears to have a limited effect in terms of improving rutting performance but a significant effect in terms of reducing fatigue life. This implies that the known benefits of adding polymer to asphalt binders may be compromised by replacing some of the virgin binder with binder from RAP.

- The use of a softer binder to compensate for the stiffening effect of high RAP binder replacement rates (i.e., above 25%) appears to be justified.

10. SUMMARY.

Although road agencies and some airport authorities are increasingly allowing the use of RAP and RAS in new mixes placed on highways, current FAA specifications do not permit their use in asphalt surfacings placed on aprons, taxiways, or runways at federally funded airports. This report describes a study that investigated the potential implications of using reclaimed asphalt in new asphalt concrete used in airfield pavements. The study included a literature review, preliminary testing to develop alternative methods for assessing the properties of virgin binders blended with RAP, the development of mix designs for mixes containing varying reclaimed asphalt contents, and the testing of the properties of the blended binders, FAM mixes, and full-graded mixes.

10.1 KEY POINTS FROM THE LITERATURE REVIEW.

- The asphalt binder in RAP and RAS can blend appreciably with virgin binder in new mixes. The level of blending between the aged and new binders depends on numerous factors including the chemical composition of the individual binders. To ensure the optimal performance of asphalt mixes containing high proportions of reclaimed asphalt, the compatibility of reclaimed and virgin asphalt binders from different sources and with different performance grades needs to be well understood.

- Appropriate methods for extracting aged binder from reclaimed asphalt materials are still being developed, with a focus on reducing the effects of extraction solvents on the properties of recovered binders. The solvents in current use are considered to be aggressive enough to fully blend the binders extracted from new mixes containing aged and virgin binders, and thereby provide potentially misleading binder replacement values and nonrepresentative PGs of the blended binders. Alternative methods to the use of extraction and recovery are being explored to better characterize the performance properties of blended virgin and RAP and/or RAS binders. Tests on mortar and FAM mixes warrant further investigation.

- Adding RAP to a new asphalt mix can alter the volumetrics and performance of the mix. However, volumetric requirements can still be met with relatively high RAP contents (i.e., up to 25%). Compared to equivalent mixes without RAP, rutting performance was generally improved by the addition of RAP, but cracking performance was generally worse. Conflicting results with regard to laboratory test performance were reported.

- Given that the use of RAP as binder replacement and not just as aggregate replacement is a relatively new practice, there is limited knowledge on the long-term field performance of mixes containing high RAP contents (i.e., above 25% binder replacement), specifically with regard to the rate of binder aging and its effect on stiffness and susceptibility to cracking. Conventional laboratory aging procedures have not been verified for high RAP mixes.

- Only limited published research on the use of RAP and/or RAS in airfield pavement mixes was located.

10.2 KEY POINTS FROM PRELIMINARY LABORATORY TESTING ON THE PROPERTIES OF RAP AND RAS BINDERS.

- Asphalt binder extracted and recovered from RAS could not be tested due to its very high stiffness. The RAS binder was not sufficiently workable to mold samples for testing in a DSR or BBR.
- The guidelines recommended in NCHRP 9-12 [7] for determining the PG of binders recovered from RAP samples were considered to be appropriate for this study. Recovered binders from three different RAP sources were tested according to these guidelines.
- Initial attempts to produce a simulated RAP binder in the laboratory with performance properties comparable to recovered binders provided mixed results. Various PAV test scenarios were considered, but only the high critical temperature of the simulated binder was similar to the recovered binders. The low critical temperatures were significantly different. It is not clear whether this was attributable to the aging procedure or to the effect of the extraction chemicals.

10.3 KEY POINTS FROM PRELIMINARY LABORATORY TESTING OF ASPHALT MORTARS.

- Mortar samples with RAP binder replacement rates of up to 25% were sufficiently workable to fabricate specimens that could be tested in a DSR. Samples with RAP binder replacement rates greater than 25% were generally unworkable and specimens could not be fabricated satisfactorily.
- Although the mortar test deserves further investigation, it may not be appropriate for testing samples with high binder replacement rates (i.e., >25%). Given that this UCPRC study was focused on investigating the influence of binder replacement rates of up to 40% on the performance properties of the blended binders, the use of mortar testing was not considered for the remainder of the study.

10.4 KEY POINTS FROM PRELIMINARY TESTING ON FAM MIXES.

- Asphalt binder extracted and recovered from RAS could not be tested due to its very high stiffness. The RAS binder was not sufficiently workable to mold specimens for testing in a DSR or in a BBR.
- Preliminary testing of FAM mixes (prepared with materials passing the 2.36 mm [#8] sieve) indicated that this approach appears to be repeatable (consistent results on multiple specimens by the same operator) and reproducible (consistent results by different operators), and produces representative results for characterizing the performance-related properties of composite binder at binder replacement rates up to 40% and possibly higher.
- The effect of RAP in increasing the stiffness of blended binders was dependent primarily on the asphalt binder grade and, to a lesser extent, on the source of the asphalt binder.

- The FAM mixes containing RAS showed similar stiffnesses to the corresponding control mixes (i.e., containing no reclaimed materials), suggesting that the RAS binder did not effectively blend with the virgin binder at the temperatures and mixing durations used in this study. Based on these results, RAS was not included in further phases of this study.

- The influence of RA on reducing the blended binder and FAM mix stiffnesses was evident. Additional testing (beyond the scope of this study) is required to evaluate the long-term behavior of mixes produced with RAs to determine whether the benefits are limited to production and early life, or whether they extend through the design life of the layer.

- Reasonable correlations were observed between the stiffness of asphalt binder and the stiffness of FAM mixes. Discrepancies between the two measured stiffnesses may indicate that complete blending of the virgin and RAP binders was not achieved in the FAM mix, but was forced during the chemical extraction and recovery. The specific chemical solvent used in the extraction process also may have influenced the RAP binder properties. These factors warrant further investigation.

10.4.1 Mix Design Phase.

- The FAA P-401 grading and volumetric property specification requirements were difficult to meet when RAP binder replacement rates exceeded 25%.

- RAP source had a notable influence on the volumetric properties, which implies that RAP cannot be considered as a generic material with consistent properties, even when only using the fine fractions (i.e., material passing the 4.75 mm [#4] sieve).

10.4.2 Binder and FAM Mix Testing.

- The degree of change in PG grade after addition of RAP binder varied depending on the virgin binder grade and the RAP source. This was attributed to various factors including but not limited to the degree of aging of the RAP binder, the original PG of the RAP binder, and the extent of the dilution of the polymer in virgin PM binders.

- Using RAP binder to replace a portion of the virgin binder always increased the stiffness of the binder, but the degree of increase was dependent on the RAP source.

- Results from FAM mix testing were consistent with the results from binder testing. Differences were attributed to the differences in the degree of blending during preparation of the binders (stirred with a glass rod in a glass beaker) and preparation of the FAM mixes (standard laboratory mixing process), and to possible effects of the chemical solvent on the properties of the extracted and recovered binder.

- The FAM mix test results further supported the use of this test approach as an appropriate procedure for evaluating the properties of blended asphalt binder in mixes containing relatively high quantities of RAP.

10.4.3 Full-Graded Mix Testing.

- The test methods used in this phase of the study were sufficiently sensitive to distinguish the behavior of the different mixes and to consistently distinguish the differences in performance of mixes containing no RAP (i.e., control mixes) and mixes containing RAP. However, all testing was undertaken on newly prepared laboratory specimens, and consequently do not necessarily reflect long-term performance of the mixes or the longer-term effects of the RAP binder on the rate of aging of the virgin binder.

- Adding RAP increased the stiffness of the mixes, which in most instances improved the rutting resistance properties of the mix but diminished the cracking resistance properties. The degree of change in rutting and cracking resistance was dependent on the RAP source, with test results for each source ranking consistently across the different tests (i.e., the RAP from the NY source consistently had the least effect on mix performance, while the RAP from the CA and AL sources consistently had the largest effect). Given that the mixes had the same gradation and binder content and similar volumetric properties, the results support an earlier observation that RAP cannot be considered as a generic material with consistent properties.

- Adding RAP to mixes with PM binders appears to have limited effect in terms of improving rutting performance but a potentially significant effect in terms of reducing fatigue life. This implies that the known benefits of adding polymer to asphalt binders may be compromised by replacing some of the virgin binder with binder from RAP.

- The use of a softer binder to compensate for the stiffening effect of high RAP binder replacement rates (i.e., above 25%) appears to be justified.

11. CONCLUSIONS AND RECOMMENDATIONS.

11.1 CONCLUSIONS.

Based on the test results summarized in section 10, the following conclusions are made.

- There is considerable interest in the use of reclaimed asphalt in new asphalt concrete mixes, primarily due to the cost savings and environmental benefits associated with substituting some of the virgin binder with the binder from the reclaimed asphalt. However, the laboratory testing in this study has clearly shown that although adding reclaimed asphalt (from reclaimed asphalt pavement (RAP)) to new mixes is likely to increase the stiffness of the mix, which in most instances will potentially improve the rutting resistance properties of the mix, the cracking resistance properties are likely to be worse. Therefore, before use of reclaimed asphalt in new mixes placed on airfield pavements is implemented, further testing is proposed to better understand the implications of using this process.

- Preliminary findings from this study indicate that the asphalt binder in recycled asphalt shingles may not effectively mobilize and blend with virgin asphalt. Using this reclaimed asphalt as a binder replacement could reduce the actual effective binder content in the mix, which could in turn lead to early cracking and raveling.

- Testing the properties of blended virgin and reclaimed asphalt binders can be influenced by the chemistry of the solvents used to extract and recover the binders. Fine aggregate matrix (FAM) mix testing is considered to be a potentially appropriate alternative procedure for evaluating the properties of blended asphalt binder in mixes containing relatively high quantities of reclaimed asphalt.

- Although considerable laboratory testing has been undertaken to evaluate the performance of mixes in which reclaimed asphalt binders are a partial replacement for virgin binders, only limited longer-term full-scale field testing has been undertaken. Consequently, any potential effects of accelerated aging of these mixes caused by the presence of the aged recycled asphalt binder are not fully understood.

- RAP cannot be considered as a generic material with consistent properties, and some form of mix performance testing (FAM or full-grading) will need to be undertaken as part of the project mix design process to assess the influence of the RAP binder replacement on longer-term performance.

- The known benefits of adding polymer to asphalt binders may be compromised by replacing some of the virgin binder with recycled asphalt binder. This is of particular importance in airfield pavements where polymer-modified binders are commonly used.

- The use of a softer virgin binder to compensate for the stiffening effect of high RAP binder replacement rates (i.e., above 25%) appear to be justified. For example, in an area where performance grading (PG) 64-22 binders are typically used, a PG 58-28 mix with 40% RAP would probably have generally similar performance to a PG 64-22 mix with 25% RAP. Performance properties will always need to be confirmed, however.

11.2 RECOMMENDATIONS.

The following recommendations are made based on the findings from this study.

- Given the interest in using reclaimed asphalt from recycled asphalt pavement for partial binder replacement in new mixes placed on airfield pavements, the benefits and risks of the process should be further quantified in controlled full-scale field studies and associated laboratory testing. Accelerated loading tests with the FAA's Heavy Vehicle Simulator are proposed as part of this research. A proposed test plan is provided in section 12.

- Any future research phases should also include assessments of the following:

  - The effects of reclaimed asphalt on the low-temperature properties of the mix

  - The influence of different rejuvenating agents on mix properties and on short-, medium-, and long-term performance

  - The influence of warm mix additives and the implications of producing mixes containing RAP at warm mix temperatures

  - Comparisons of test results on chemically extracted RAP binders with those from tests on FAM mixes

12. PROPOSED TEST PLAN FOR ACCELERATED WHEEL LOAD TESTING.

The preliminary laboratory testing discussed in the previous chapters indicates that adding RAP to new asphalt mixes to partially replace virgin aggregate and asphalt binder can affect the properties of the blended binder and the properties and performance of the mix. The test results show that adding RAP appears to improve rutting performance but worsen cracking performance. Although this study only evaluated fatigue cracking, it is believed that low-temperature cracking performance will likely also be affected. Given the increasing interest in the use of reclaimed asphalt to replace some virgin binder in new mixes, an accelerated load test, monitoring of full-scale field performance on pilot projects, and additional laboratory testing are warranted to better understand the benefits and consequences of this practice. It is recommended that subsequent testing be conducted in a phased study, given that numerous variables will need to be considered to address all possible concerns. Research in later phases should be planned based on the results of completed phases.

12.1 PHASE 1: EFFECT OF RAP CONTENT ON MIX PERFORMANCE.

12.1.1 Project Objective.

This project would assess the effect of RAP content on the rutting performance, and potentially on the fatigue-cracking performance, of asphalt surface mixes on airfield pavements.

12.1.2 Proposed Experiment Plan.

The study should include the following:

- A mix design following the procedure described in this report to accommodate 15% and 25% RAP binder replacement. A single binder (suggested PG 64-22) and a single RAP source will be used.

- Construction of three test lanes at the NAPMRC. The lanes should include a control with no RAP, one with 15% RAP binder replacement, and one with 25% RAP binder replacement.

- Testing with the FAA HVS. Both high- and low-temperature tests should be conducted to assess and rutting and cracking performance, respectively. All tests should be conducted with a tire pressure of 254 psi.

- Laboratory testing on binder sampled during mix production, on specimens prepared in the laboratory from loose mix sampled during construction, and on specimens cored and sawn from the test track. Tests should be conducted on binder, FAM mixes, and full-graded mixes following a testing plan similar to that described in this report. The testing plan should be prepared once the project has been finalized, but tests should include, but not be limited to, those for determining binder grades and binder properties, mix stiffness (dynamic modulus and flexural modulus), rutting performance (repeated load triaxial, APA, Hamburg Wheel-Track), cracking performance (fatigue and low-temperature cracking), and moisture sensitivity (indirect tensile strength and Hamburg Wheel-Track).

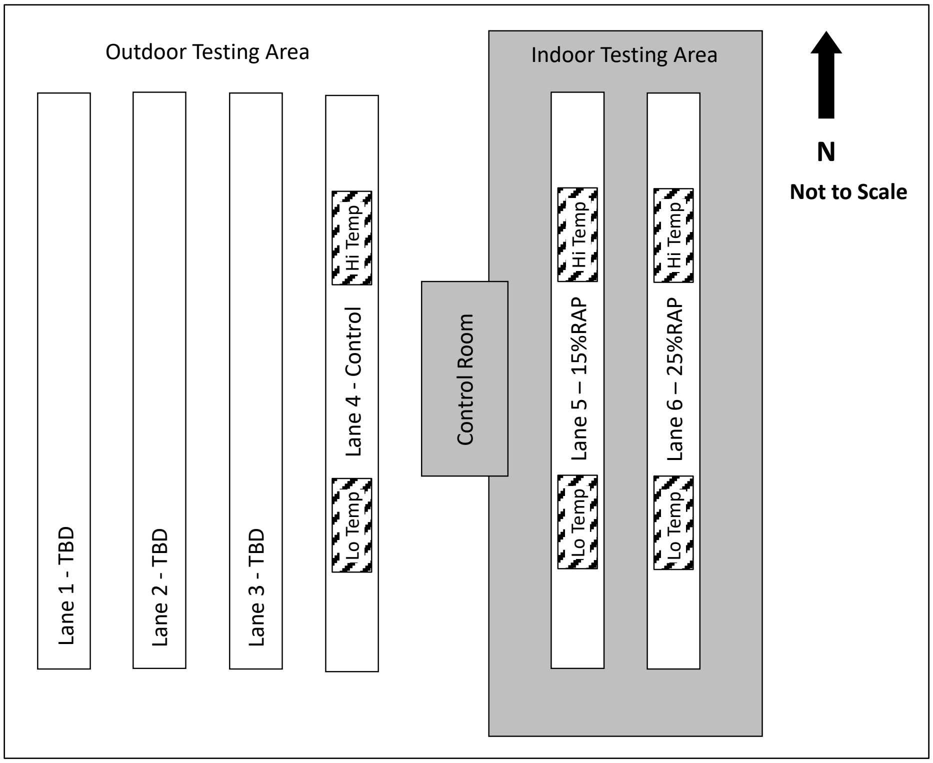
- If time and budget permit, additional laboratory tests should be conducted on specimens prepared in the laboratory with aggregate and RAP sampled during mix production to assess the effects of using different binder grades, higher RAP contents (if feasible in terms of meeting current FAA P-401 volumetric specifications), RAs, warm mix additives, and mix production at warm mix temperatures. The results from this additional testing should be used to decide whether further phases of accelerated testing are justified.

- Analysis using appropriate mechanistic-empirical procedures.

- A report and recommendations for further phases of accelerated wheel load testing and associated laboratory testing, if warranted. The report should include preliminary recommendations on the use of RAP in airfield pavement mixes and suggested changes to mix design procedures and specifications to accommodate RAP, if justified.

12.1.3 Proposed Test Track Layout.

Preliminary test track planning for the second construction cycle at NAPMRC has allocated two lanes for testing mixes containing RAP. A third lane constructed as a control for another study will be used as the control for the RAP study. The provisional proposed test track layout is shown in figure 86.

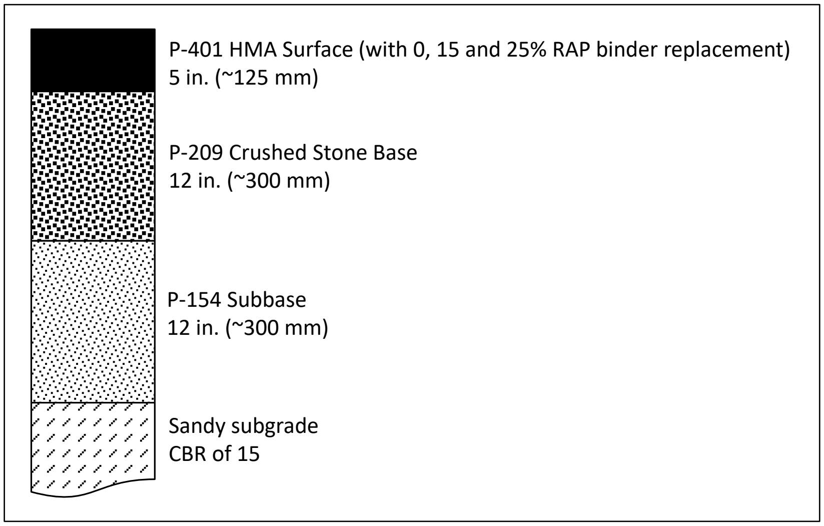


TBD – To be determined

Figure 86. Provisional NAPMRC TC-2 Test Track Layout

12.1.4 Proposed Pavement Structure.

The proposed pavement structure will likely correspond with the current test cycle (TC-1) pavement structure, as shown in figure 87.



CBR – California Bearing Ratio

Figure 87. Proposed Pavement Structure for RAP Mix Testing

12.1.5 Test Track Instrumentation.

Each test section should be instrumented in accordance with standard FAA procedures for accelerated wheel load testing on asphalt concrete surfacings.

12.1.6 Testing Configuration and Measurements.

Test plans, test parameters, tire pressures, loading rates, wander patterns, measurements, and visual assessments, etc., should be in accordance with standard FAA procedures for accelerated wheel load testing on testing asphalt concrete surfacings. This will facilitate comparison of results with previous tests on other asphalt mixes. Visual assessments should include location and identification of any cracks.

12.2 PHASE 2: ACCELERATED WHEEL LOAD TESTING.

Recommendations for further phases of accelerated wheel load testing with the FAA's HVS, monitoring of full-scale pilot projects at selected airfields, and associated laboratory testing will be made, if warranted, based on the results of the Phase 1 testing.

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