PRELIMINARY INVESTIGATION OF RAP AND RAS IN HMAC

Final Report

SR 500-291

Oregon Department of Transportation

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by

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Salem OR 97301-5192

February 2010

Technical Report Documentation Page

1. Report No. OR-RD-10-12	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Preliminary Investigation of RAP and RAS in HMAC		5. Report Date February 2010 6. Performing Organization Code
7. Author(s) Todd V. Scholz Kiewit Center for Infrastructure and Transportation, Oregon State University, Corvallis, Oregon 97331		8. Performing Organization Report No.
9. Performing Organization Name and Address Oregon Department of Transportation Research Section 200 Hawthorne SE, Suite B-240 Salem, Oregon 97301-5192		10. Work Unit No. (TRAIS) 11. Contract or Grant No. SR 500-291
12. Sponsoring Agency Name and Address Oregon Department of Transportation Research Section 200 Hawthorne SE, Suite B-240 Salem, Oregon 97301-5192		13. Type of Report and Period Covered Final Report 14. Sponsoring Agency Code
15. Supplementary Notes		

16. Abstract

A laboratory study was undertaken to investigate how various proportions of reclaimed asphalt pavement (RAP) and reclaimed asphalt shingles (RAS) added to hot mixed asphalt concrete (HMAC) mixtures affect the Superpave performance grade of the blended binder. Only tear-off shingles (those obtained from re-roofing projects of residential structures) were included in the study. Critical temperatures of the blended asphalt binders from mixtures with 5% RAS and 0% to 50% RAP were compared with the critical temperatures of the virgin binder. Results indicated that the mixture with 5% RAS but no RAP resulted in an increase of the performance grade of the blended binder. Binders recovered from the mixtures with both RAP and RAS indicated an increase in both the high temperature and low temperature performance grades of the blended binder with increasing RAP contents up to about 30%. RAP contents above 30% did not result in any further increases in the low temperature performance grade and only slightly impacted the high temperature performance grade of the blended binders (the high temperature performance grade of the blended binder asymptotically approached that of the high temperature performance grade of the RAP binder).

A secondary objective was to develop recommendations for changes to the mix design method and specifications for HMAC, incorporating RAS and RAP for use in special provisions for a pilot study. Specifications and special provisions of several agencies that allow tear-off RAS, and particularly those that allow tear-off RAS and RAP together, were reviewed to determine restrictions, criteria, test methods, mix design procedures, etc. applicable to inclusion of RAS and RAP in HMAC paving mixtures. Proposed modifications to ODOT specification SP745 were developed from this review.

17. Key Words HOT MIX ASPHALT PAVEMENTS, RECLAIMED ASPHALT PAVEMENT (RAP), RECLAIMED ASPHALT SHINGLES (RAS), SPECIFICATIONS		18. Distribution Statement Copies available from NTIS, and online at http://www.oregon.gov/ODOT/TD/TP_RES/	
19. Security Classification (of this report) Unclassified	20. Security Classification (of this page) Unclassified	21. No. of Pages	22. Price

SI* (MODERN METRIC) CONVERSION FACTORS

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	millimeters squared	mm^2
ft^2	square feet	0.093	meters squared	m^2
yd^2	square yards	0.836	meters squared	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	kilometers squared	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	ml
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	meters cubed	m^3
yd^3	cubic yards	0.765	meters cubed	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	Mg
		TEMPERATURE (exact)		
°F	Fahrenheit	(F-32)/1.8	Celsius	°C

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		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	millimeters squared	0.0016	square inches	in^2
m^2	meters squared	10.764	square feet	ft^2
m^2	meters squared	1.196	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	kilometers squared	0.386	square miles	mi^2
		VOLUME		
ml	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	meters cubed	35.315	cubic feet	ft^3
m^3	meters cubed	1.308	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.205	pounds	lb
Mg	megagrams	1.102	short tons (2000 lb)	T
		TEMPERATURE (exact)		
°C	Celsius	1.8C+32	Fahrenheit	°F

*SI is the symbol for the International System of Measurement

ACKNOWLEDGEMENTS

This project was funded by the Oregon Department of Transportation (ODOT). The Author gratefully acknowledges the assistance of the ODOT Technical Advisory Committee and other ODOT personnel in conducting this research effort and in developing this report. These individuals included:

Technical Advisory Committee Members:

- Cole Mullis, Oregon Department of Transportation
- Larry Ilg, Oregon Department of Transportation
- Norris Shippen, Oregon Department of Transportation
- Anthony Boesen, Federal Highway Administration
- Gary Thompson, Asphalt Pavement Association of Oregon
- Kevin Brophy, Oregon Department of Transportation
- Greg Bolt, ABC Roofing Co.

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- Elizabeth A. Hunt, Oregon Department of Transportation, Project Champion
- Wayne Brown, Oregon Department of Transportation, Bituminous Petroleum Chemistry Crew Leader

PRELIMINARY INVESTIGATION OF RAP AND RAS IN HMAC

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1.0 INTRODUCTION

1.1 BACKGROUND

Reclaimed (or recycled) asphalt pavement (RAP) is commonly used by several states to reduce the quantity of new (virgin) asphalt cement and aggregate used in the construction of hot mix asphalt concrete (HMAC) pavements. Its use has been shown to be economical and environmentally sound and, at low contents (i.e., below 20%), mixtures containing RAP generally have been found to perform as well as virgin mixtures (*NCHRP 2001*). Research has shown that HMAC mixtures containing higher percentages of RAP (i.e., 40%) can exhibit higher resistance to rutting, but decreased resistance to low temperature cracking and fatigue cracking (*NCHRP 2001*), this due to the stiffening effect imparted by the RAP binder to the blended binder (RAP binder plus virgin binder) in the mixture. Partly due to the adverse effects of reduced cracking resistance, higher percentages of RAP are not commonly used in practice (*Al-Qadi, Elseifi, Carpenter 2007*). However, a Virginia study of 10 "high-RAP" paving projects (i.e., with 21% to 30% RAP) found that, although the inclusion of RAP increased the stiffness of the blended binder, the high-RAP mixtures performed similarly to low-RAP mixtures (i.e., 20% or less) in laboratory tests for fatigue, rutting, and moisture damage (*Maupin, Diefenderfer, and Gillespie 2008*).

The history of asphalt shingle recycling dates back to the late 1970s and early 1980s, when the first shingle recycling plants were developed and experimenting began with HMAC mix designs that incorporated reclaimed (or recycled) asphalt shingles (RAS) (*Krivit and Associates 2007*). Since then, several HMAC producers have gained substantial in-house expertise in recycling asphalt shingles (*Krivit and Associates 2007*). Several state agencies have responded to the increased interest in using RAS in HMAC by allowing up to 5% RAS, but most only allow manufacturer scrap and not tear-off shingles obtained from re-roofing projects. This low percentage is principally due to RAS containing asphalt cement that is substantially stiffer (harder) than that used in typical HMAC, and agencies remain cautious of its use since it may significantly impact the properties (e.g., stiffness and temperature susceptibility) of the blended binder. Nevertheless, interest in the use of RAS derived from manufacturer scrap and tear-off shingles is gaining traction in states other than those that already allow its use.

1.2 PROBLEM STATEMENT

ODOT currently allows up to 30% RAP to be used in HMAC without changing (adjusting) the virgin asphalt grade. The use of blending charts for RAP proportions greater than 15% are used in other states to: a) establish the maximum RAP proportion so that the virgin binder properties are not adversely affected; or b) adjust the grade of the virgin binder so that the blended binder possesses the desired properties. It is currently not known by how much the properties of virgin binders used in Oregon are affected by current RAP percentages allowed by the specifications.

House Bill (HB) 2733, which was introduced before the 75th Oregon Legislative Assembly (2009 Regular Session), would require that ODOT allow up to 5% RAS in HMAC on roadways under its jurisdiction. HB 2733 does not indicate the source of RAS, which could be either tear-off shingles obtained from re-roofing projects (and, thus, may contain other materials such as asbestos, wood chips, nails, plastic, and other debris) or manufacturer scrap (which is largely devoid of other detritus). With the use of RAP in HMAC already being commonplace in Oregon, it is anticipated that HMAC producers will include both RAP and RAS in HMAC for ODOT projects if HB 2733 passes. The principal concern of ODOT personnel responsible for designing, constructing, and maintaining HMAC pavements is that too much RAP and/or too much RAS may significantly reduce the performance of the pavements resulting in early failures and significantly increased repair or rehabilitation costs. Due to these concerns and at the request of ODOT, the sponsor of HB 2733 agreed to postpone legislation on this bill until completion of this preliminary investigation of RAP and RAS in HMAC (*ODOT 2009*).

1.3 OBJECTIVES

The principal objective of this research effort was to investigate how various proportions of RAP and RAS added to HMAC mixtures affect the Superpave performance grade of the blended binder. A secondary objective was to develop recommendations for changes to the mix design method and specifications for HMAC incorporating RAP and RAS for use in special provisions for a pilot study (i.e., paving project with RAP and RAS in HMAC).

1.4 SCOPE

This research effort was limited in scope so that evidence could be obtained to answer the most pressing concerns of ODOT in as little time as possible and practical. Hence, the scope of work was limited to only a few proportions of RAP and RAS combined with one virgin binder grade and virgin aggregate in common usage in Oregon. In addition, only tear-off shingles were considered in this effort.

1.5 RESEARCH TASKS

Several research tasks were undertaken to satisfy the principal objective of this preliminary investigation. In summary, the tasks were as follows:

1. RAP, RAS, virgin aggregates, and virgin asphalt binder were obtained from an HMAC producer.
2. The virgin asphalt binder and the asphalt binders recovered from the RAP and RAS were tested at the ODOT Materials Laboratory to determine the high and low critical temperatures of the binders. The binder contents of the RAP and RAS were also determined.
3. Virgin aggregates, virgin asphalt binder, and various proportions of RAP and RAS were formulated and batched at the Oregon State University (OSU) laboratories and then mixed at the Asphalt Pavement Association of Oregon (APAO) laboratories and the OSU laboratories.

4. The blended binders from each of the mixtures were extracted (recovered) at the ODOT Materials Laboratory and tested to determine the high and low critical temperatures of the blended binders. The binder contents of each of the mixtures were also determined.
5. OSU personnel analyzed and summarized the results.
6. OSU personnel reviewed the literature and state specifications to develop recommendations for the pilot study.
7. OSU personnel developed this report to document the research effort.

2.0 MATERIALS

All materials utilized in this preliminary investigation, except for the RAS, were obtained from an HMAC producer in central Oregon. The materials were previously approved by ODOT for use in HMAC on state paving projects. Additionally, it was required that the HMAC producer provide materials that were used to obtain an approved mix design from ODOT. The RAS was obtained from an HMAC producer in western Oregon. This section provides a brief description of the materials.

2.1 VIRGIN AGGREGATES

Virgin aggregates were sampled from three stockpiles fractionated to sizes of 1/2"-1/4", #4-#8, and 1/4"-0. OSU received approximately 100 pounds each of the 1/2"-1/4"and 1/4"-0 aggregates and approximately 50 pounds of the #4-#8 aggregate. OSU also received approximately 5 pounds of lime. Properties of the aggregates provided by the HMAC producer and relevant to the mix design process for HMAC are shown in Table 2.1. The lime had a bulk specific gravity of 2.150.

Table 2.1: Virgin Aggregate Properties Provided by the HMAC Producer

Sieve Analysis, AASHTO T 27/T 11				
Sieve Size		Stockpile		
		1/2"-1/4"	#4-#8	1/4"-0
U.S.	Metric (mm)	Percent Passing		
3/4"	19.0	100	100	100
1/2"	12.5	96	100	100
3/8"	9.5	58	100	100
1/4"	6.35	8	85	88
#4	4.75	1	48	72
#8	2.36	1	8	45
#16	1.18	1	5	29
#30	0.600	1	4	21
#50	0.300	1	3	15
#100	0.150	1	3	12
#200	0.075	0.5	2.5	9.3
Specific Gravity & Absorption, AASHTO T 84 & T 85				
Bulk Spec. Grav. (G_{sb})		2.654	2.604	2.732
Apparent Spec. Grav. (G_{sa})		2.794	2.770	2.940
Percent Absorption		1.9	2.3	2.5

2.2 VIRGIN ASPHALT

The HMAC producer provided approximately one gallon each of virgin asphalt binders with labels indicating grades of PG64-28 and PG70-28. However, in testing these virgin binders at the ODOT Materials Laboratory, it was found that they were of the same grade (PG70-28) (see Section 3.3.1).

2.3 RECLAIMED ASPHALT PAVEMENT (RAP)

Approximately 100 pounds of RAP fractionated to a size of 1/4"-0 was provided by the HMAC producer. Properties provided by the HMAC producer and relevant to the mix design process for HMAC are shown in Table 2.2.

Table 2.2: RAP Properties Provided by the HMAC Producer

Sieve Analysis, AASHTO T 27/T 11		
Sieve Size		Average Percent Passing
U.S.	Metric (mm)	
3/4"	19.0	100
1/2"	12.5	100
3/8"	9.5	100
1/4"	6.35	95
#4	4.75	83
#8	2.36	57
#16	1.18	40
#30	0.60	30
#50	0.30	23
#100	0.15	18
#200	0.075	13.3

Specific Gravity of RAP Aggregates, AASHTO T 84 & T 85	
Bulk Specific Gravity (G_{sb})	2.603
Apparent Specific Gravity (G_{sa})	2.773

Asphalt Content Binder, AASHTO T 308	
Corrected Binder Content, %	4.25

2.4 RECLAIMED ASPHALT SHINGLES (RAS)

Three five-gallon buckets of 1/2" minus RAS was obtained from a stockpile at an HMA plant in western Oregon. Samples of the material were provided to the ODOT Materials Laboratory to determine the RAS binder content via ignition oven and gradation of the extracted aggregate for mixture batching purposes (see Section 3.3).

2.5 MIX DESIGN

The HMAC producer that supplied the virgin aggregates, lime, virgin binder, and RAP also provided an ODOT-approved HMAC mix design utilizing the materials provided. The mix design (see Appendix A) was used as the basis for batching mixtures. For mixtures containing RAS, adjustments were made to the fine aggregate (1/4"-0) material and to the virgin binder content to account for the aggregates and binder from the RAS.

3.0 LABORATORY STUDY

This section provides details regarding the laboratory study undertaken to satisfy the principal objective of this research effort. It begins with a brief explanation of the experiment plan and brief descriptions of the test methods employed. It then presents the results of the laboratory tests followed by analysis and discussion of the results.

3.1 EXPERIMENT PLAN

A simple experiment plan was developed for this research project to investigate how various proportions of RAP and RAS added to HMAC mixtures affect the Superpave performance grade of the blended binder. To accomplish this in as little time as was possible and practical, only seven combinations of materials (over a sufficiently broad range of reclaimed materials contents) were considered, and were as follows:

- 0% RAS and 0% RAP (control mixture with all virgin materials)
- 5% RAS and 0% RAP
- 5% RAS and 10% RAP
- 5% RAS and 20% RAP
- 5% RAS and 30% RAP
- 5% RAS and 40% RAP
- 5% RAS and 50% RAP

It should be noted that the percentages listed represent proportions by total weight of mixture. For example, the mixture with 5% RAS and 10% RAP had 15% reclaimed materials and 85% virgin materials by weight. It should be further noted that, to properly proportion the reclaimed materials with virgin materials and to determine the effect that the RAP and RAS binders had on the Superpave performance grade of the blended binders, tests to determine several properties of the as-received materials were also required.

Table 3.1 summarizes the experimental matrix for testing the as-received materials. As indicated, three samples of RAP and three samples of RAS were tested in an ignition oven to determine the binder contents of these materials. In addition, sieve analyses were conducted on the aggregates extracted from each of these tests to determine the gradation of the aggregates. Results from the binder content tests and sieve analyses were used for combining the constituent materials into accurate proportions for subsequent testing.

Table 3.1: Experimental Matrix for Tests on As-Received Materials and Extracted Binders

Laboratory Tests[a]	Material		
	Virgin Binder	RAP	RAS
Tests on Mixtures			
Binder Content, Ignition Oven (AASHTO T 308)		3[b]	3
Binder Extraction (AASHTO T 319)		2	2
Tests on Binders			
Flexural Stiffness (AASHTO T 313)	2	2	2
Fracture Properties (AASHTO T 314)	2	2	2
Rheological Properties (AASHTO T 315)	2	2	2
Test on Extracted Aggregates			
Sieve Analysis (AASHTO T 30)		3	3

[a]See Section 3.2 for test description.
[b]Numerals represent number of tests conducted.

Table 3.1 also indicates that two samples each of the virgin binder and the binders recovered from the RAP and RAS were tested for flexural stiffness, fracture properties, and rheological properties. These tests were conducted to determine the Superpave performance grade of the virgin binder and the recovered binders.

Table 3.2 summarizes the experimental matrix for testing the mixtures batched with various proportions of RAP and RAS as well as the binders extracted from these mixtures. The top four rows list the proportions of RAP and RAS as well as the proportions of total reclaimed materials and virgin materials contained in each mixture. The bottom four rows identify the tests conducted on the materials and the number of samples tested. That is, two samples each from the seven combinations of materials were tested in accordance with each test method listed.

Table 3.2: Experimental Matrix for Tests on Batched Mixtures and Extracted Binders

Composition of Mixtures[a]	RAS Content	0%	5%	5%	5%	5%	5%	5%
	RAP Content	0%	0%	10%	20%	30%	40%	50%
	Total Reclaimed Materials Content	0%	5%	15%	25%	35%	45%	55%
	Virgin Materials Content	100%	95%	85%	75%	65%	55%	45%
Test on Mixtures[b]	Binder Extraction (AASHTO T 319)	2[c]	2	2	2	2	2	2
Tests on Binder Extracted from Mixtures[b]	Flexural Stiffness (AASHTO T 313)	2	2	2	2	2	2	2
	Fracture Properties (AASHTO T 314)	2	2	2	2	2	2	2
	Rheological Properties (AASHTO T 315)	2	2	2	2	2	2	2

[a] Percentages represent the proportion by total weight of mixture.
[b] See Section 4.2 for test description.
[c] Numerals represent the number of tests conducted.

3.2 METHODS

As indicated in Section 3.1, tests were conducted on the as-received materials and binders extracted from the RAP and RAS. Section 3.1 also indicated that tests were conducted on batched mixtures and binders extracted from these mixtures. This section briefly describes each of the tests as well as the batching procedure.

3.2.1 Binder Content via Ignition Oven

AASHTO T 308, *Standard Method of Test for Determining the Asphalt Binder Content of Hot-Mix Asphalt (HMA) by the Ignition Method*, is used for quantitative determination of asphalt binder content in HMA mixtures and pavement samples for quality control, specification acceptance, and mixture evaluation studies (*AASHTO 2009*). The asphalt binder in the HMA mixture is heated to a temperature exceeding the flash point of asphalt binders in a furnace (ignition oven) to burn off the binder. The asphalt binder content, expressed as a mass percent of the moisture-free mixture, is determined by calculating the difference between the initial mass of the mixture and the mass of the remaining aggregate. A correction factor is applied to account for moisture content and loss of very fine aggregate. The residual aggregate may be used for gradation analysis in accordance with AASHTO T 30 (see Section 3.2.2).

3.2.2 Gradation of Extracted Aggregate

AASHTO T 30, *Standard Method of Test for Mechanical Analysis of Extracted Aggregate*, is used to determine the particle-size distribution of the coarse and fine fractions of aggregate extracted from HMA mixtures (*AASHTO 2009*). Samples of the dry aggregate of known mass are shaken over successively smaller sieve sizes (as specified) and the mass retained on each sieve is determined after a specified duration of shaking. The percent retained on each sieve (i.e., ratio of the mass retained on each sieve to the total sample mass, multiplied by 100) is converted to the percent passing each sieve to determine the particle-size distribution delineated by the sieve sizes specified.

3.2.3 Binder Extraction

AASHTO T 319, *Standard Method of Test for Quantitative Extraction and Recovery of Asphalt Binder from Asphalt Mixtures*, is used to extract/recover asphalt binder from hot mix asphalt (HMA) and reclaimed asphalt pavement (RAP) for further physical and chemical analyses and, optionally, to determine the asphalt binder content of the mixture (*AASHTO 2009*). In addition, aggregate recovered from the mixture can be used for sieve analysis. The procedure involves repeatedly washing and filtering an asphalt mixture using solvent in an extraction/filtration apparatus. The material (asphalt binder and solvent) passing the filtration medium is distilled under vacuum to remove the solvent, leaving residual asphalt binder for further testing and analysis.

In the laboratory testing for this project, significant difficulties with regard to recovering the binder from the RAS were encountered using this procedure.

3.2.4 Batching and Mixing Procedure

The mixtures were batched in accordance with the HMA Mixture Preparation procedure contained in AASHTO T 312, *Standard Method of Test for Preparing and Determining the Density of Hot-Mix Asphalt (HMA) Specimens by Means of the Superpave Gyratory Compactor* (*AASHTO 2009*). Prior to mixing, all materials except for the RAS were heated to the mixing temperature of the asphalt binder. For each combination of materials, a specified quantity of virgin binder was added to the other constituent materials and mixed thoroughly. Following mixing, the mixtures were placed in an oven set to the compaction temperature of the asphalt binder to simulate short-term aging.

Prior to batching the virgin aggregates were separated into size fractions of 3/4”-1/2”, 1/2"-3/8”, 3/8”-#4, #4-#8, #8-#16, #16-#30, #30-#50, #50-#100, #100-#200, and passing #200. Similarly, the RAP was divided into size fractions of 3/8”-#4, #4-#8, #8-#16, #16-#30, #30-#50, #50-#100, and passing #100. The RAS was separated into size fractions of 1/2"-#30 and passing #30. The individual size fractions of each material were then recombined to match the gradations of each material according to the mix design gradations shown in Appendix A. The virgin aggregate, RAP, RAS, and lime were bagged and labeled individually prior to mixing. All batching was conducted at the OSU laboratories.

Mixing of the materials with virgin asphalt occurred at the APAO and OSU laboratories. Mixing of the 40% and 50% RAP mixtures was accomplished at the OSU laboratories, while all other mixtures were mixed at the APAO laboratories. At both laboratories, it was noted during the mixing process that the mixtures with RAP and RAS appeared slightly dry at the lower RAP proportions and dry at the higher RAP proportions. These observations possibly indicate that a different mixing procedure is needed or that the binder from the RAS (which was at ambient temperature at the time it was introduced to the hot virgin aggregate and RAP) was not sufficiently mobilized during the short mixing period. This latter inference also supports the need for a different or modified mixing procedure.

3.2.5 Binder Tests

The virgin binder and residual asphalt binders recovered from the RAP, RAS, and batched mixtures were tested in accordance with AASTHO T 313, T 314, and T 315 to determine the critical temperatures required by AASHTO M 320, *Standard Specification for Performance-Graded Asphalt Binder* (*AASHTO 2009*), for determining the performance grade of the binders. This section briefly describes each of these tests.

AASHTO T 313, *Standard Method of Test for Flexural Creep Stiffness of Asphalt Binder Using the Bending Beam Rheometer (BBR)*, is used to measure the low-temperature, stress-strain-time response of asphalt binders (*AASHTO 2009*). Under a constant load, midpoint deflections of small, prismatic, simply supported beams of asphalt binder are determined at specified loading times. Maximum stresses and strains are calculated to determine the stiffness of the asphalt beam at the prescribed loading times as well as the slope (*m* value) of the logarithm of the stiffness versus logarithm of time curve. The stiffness and *m* value at a loading time of 60 seconds are checked against criteria for determining the grade of the binder in accordance with AASHTO M 320.

AASHTO T 314, *Standard Method of Test for Determining the Fracture Properties of Asphalt Binder in Direct Tension (DT)*, is used to determine the failure stress and failure strain of asphalt binders loaded in direct tension at a specified constant rate of elongation (*AASHTO 2009*). Stress at failure is used to calculate the critical cracking temperature of the asphalt binder; which, in turn, is used in specifying the low temperature grade of the binder in accordance with AASHTO M 320. In addition, the strain at failure must be greater than a specified value.

AASHTO T 315, *Standard Method of Test for Determining the Rheological Properties of Asphalt Binder Using a Dynamic Shear Rheometer (DSR)*, is used to determine the complex shear modulus and phase angle of asphalt binders tested in oscillatory shear using a parallel plate test geometry (*AASHTO 2009*). In the test, a circular wafer of asphalt binder is sandwiched between two circular, parallel plates. At constant temperature, one plate is oscillated with respect to the other at a prescribed frequency under stress or strain control and the resulting strain or stress, respectively, is measured. In either case, the complex shear modulus is the ratio of maximum stress amplitude to maximum strain amplitude at the test temperature and testing frequency, and the phase angle is derived from the difference in time at which the maximum stress and maximum strain occur at the specified testing frequency. The complex shear modulus and phase angle are checked against criteria for determining the grade of the binder in accordance with AASHTO M 320.

3.3 RESULTS

This section provides a summary of the results obtained from the laboratory tests conducted on the materials investigated. Results from tests on both the as-received materials and the batched materials are presented.

3.3.1 As-Received Materials

The as-received virgin binders were tested by ODOT to determine the critical temperatures of the binders in accordance with AASHTO M 320. Table 3.3 indicates that, although the tins of asphalt were labeled with two different grades, the two binders were determined to have the same grade (i.e., both binders were determined to satisfy the requirements for a grade of PG70-28 according to AASHTO M 320).

Table 3.3: Critical Temperatures for the Virgin Binders

Grade Indicated by HMAC Producer	Critical High Temperature, $T_{c(high)}$, °C	Critical Low Temperature, $T_{c(low)}$, °C
PG64-28	72	-32
PG70-28	70	-30

The as-received RAP was tested by ODOT for asphalt binder content via ignition, gradation of the extracted aggregate, and for the critical temperatures of the recovered asphalt binder. Table 3.4 presents the results of these tests. As indicated, the RAP had an average asphalt binder content of 4.70%, and the recovered binder had high and low critical temperatures of 88°C and -9°C, respectively.

Table 3.4: RAP Properties Determined by ODOT

Asphalt Binder Content, AASHTO T 308		
Sample	Corrected Binder Content, %	Average Binder Content, %
1	4.77	4.70
2	4.70	
3	4.64	

Sieve Analysis, AASHTO T 30					
Sieve Size		Percent Passing			Average Percent Passing
		Sample			
U.S.	Metric (mm)	1	2	3	
3/4"	19.0	100	100	100	100
1/2"	12.5	100	100	100	100
3/8"	9.5	100	100	100	100
1/4"	6.35	100	99	100	100
#4	4.75	95	94	94	94
#8	2.36	68	69	69	69
#16	1.18	46	47	47	47
#30	0.60	33	33	33	33
#50	0.30	24	24	24	24
#100	0.15	18	18	18	18
#200	0.075	12.7	13.1	12.6	12.8

Asphalt Binder Critical Temperatures, AASHTO M 320	
Critical High Temperature, $T_{c(high)}$, °C	88
Critical Low Temperature, $T_{c(low)}$, °C	-9

The as-received RAS was also tested by ODOT for asphalt binder content via ignition, gradation of the extracted aggregate, and for the critical high temperature of the recovered asphalt binder. Despite a concerted effort to recover asphalt binder from the RAS, an insufficient quantity was recovered to conduct testing to determine the low critical temperature of the binder. Table 3.5 presents the results of the tests. As indicated, the RAS had an average asphalt binder content of 30.7%, and the recovered binder had a high critical temperature of 134°C.

Table 3.5: RAS Properties Determined by ODOT

Asphalt Binder Content, AASHTO T 308		
Sample	Corrected Binder Content, %	Average Binder Content, %
1	31.40	30.7
2	30.48	
3	30.17	

Sieve Analysis, AASHTO T 30					
Sieve Size		Percent Passing			Average Percent Passing
		Sample			
U.S.	Metric (mm)	1	2	3	
3/4"	19.0	100	100	100	100
1/2"	12.5	100	100	100	100
3/8"	9.5	99	100	99	99
1/4"	6.35	97	97	96	97
#4	4.75	95	96	94	95
#8	2.36	92	93	90	92
#16	1.18	71	71	68	70
#30	0.60	47	46	44	46
#50	0.30	40	39	37	39
#100	0.15	35	34	31	33
#200	0.075	28.8	27.5	24.9	27.1

Asphalt Binder Critical Temperatures, AASHTO M 320	
Critical High Temperature, $T_{c(high)}$, °C	134
Critical Low Temperature, $T_{c(low)}$, °C	---

3.3.2 Batched Mixtures

Seven mixtures were batched to the target gradation and the total binder content of the ODOT-approved mix design provided by the HMAC producer (see Appendix A). These included a control mixture without reclaimed materials, one mixture with only RAS, and five mixtures with RAP and RAS. For the mixture with only RAS and the mixtures with RAP and RAS, the quantity of virgin asphalt binder was reduced by the total amount of binder contained in the reclaimed materials so that the total asphalt binder content was as identified in the mix design (see Appendix A). The binder labeled as PG64-28 was used to batch the mixture without reclaimed materials as well as the mixtures with only RAS and those containing 10%, 20%, and 30% RAP. Due to an insufficient quantity of binder labeled PG64-28, the mixtures with 40% and 50% RAP were batched with the binder labeled PG70-28.

Following batching and simulated short-term aging (Section 3.2.4), the mixtures were split into two fractions. The binders were then recovered from each fraction (Section 3.2.3) and tested to determine the critical high and critical low temperatures of the binders (Section 3.2.5).

Table 3.6 presents the results from these tests. As indicated, the binders from the mixtures with reclaimed materials, in all cases, had critical high and critical low temperatures in excess of the binder from the mixture without reclaimed materials. The consistency in the individual results for a given mixture (for all mixtures except those with 40% and 50% RAP) was, in part, due to recovery of the binder from two fractions of the same batched mixture. Nevertheless, this consistency in results is indicative of a consistency in the extraction and recovery process utilized despite the difficulties encountered (see Section 3.5.4). For the mixtures with 40% and 50% RAP, the consistency in the individual critical high temperature results was principally due to conducting two tests on the same recovered binder. Comparisons of these results with those from other studies are provided in Section 3.5.

Table 3.6: Critical Temperatures for the Binders Recovered from the Batched Mixtures

Percentage of Reclaimed Material in Batched Mixture		Critical High Temperature, $T_{c(high)}$, °C		Critical Low Temperature, $T_{c(low)}$, °C	
RAP	RAS	Indiv. Result	Average	Indiv. Result	Average
0	0	67	67.5	-30.0	-29.5
		68		-29.0	
0	5	89	88.5	-21.0	-21.5
		88		-22.0	
10	5	71	70.5	-29.0	-29.0
		70		-29.0	
20	5	82	81.5	-23.0	-23.0
		81		-23.0	
30	5	89	89.5	-20.0	-20.0
		90		-20.0	
40	5	88[1]	88.0	-16.0[2]	-16.0
		88[1]			
50	5	85[1]	85.0	-17.0[2]	-17.0
		85[1]			

[1]Results from a split sample of the blended binder from a single extraction
[2]Results from only one test due to an insufficent quantity of material

3.4 ANALYSIS OF RESULTS

The results were analyzed to determine the effect of various proportions of RAP and RAS on the Superpave performance grade of the blended binder. This entailed simple calculations of the differences between the critical high and critical low temperatures of the blended binders and those of the as-received binders. Table 3.7 lists the critical high and critical low temperatures of the as-received binders, the critical high and critical low temperatures of the binders recovered from the batched mixtures, and the differences between the critical temperatures. Figure 3.1 displays these results graphically to illustrate trends in the results.

Table 3.7: Critical Temperatures of the Blended Binders Relative to the As-Received Binders

Percentage of Reclaimed Material in Batched Mixture		Critical High Temperature, $T_{c(high)}$, °C			Critical Low Temperature, $T_{c(low)}$, °C		
RAP	RAS	As-Received Binder	Blended Binder	Difference*	As-Received Binder	Blended Binder	Difference*
0	0	72.0	67.5	-4.5	-32.0	-29.5	+2.5
0	5	72.0	88.5	+16.5	-32.0	-21.5	+10.5
10	5	72.0	70.5	-1.5	-32.0	-29.0	+3.0
20	5	72.0	81.5	+9.5	-32.0	-23.0	+9.0
30	5	72.0	89.5	+17.5	-32.0	-20.0	+12.0
40	5	70.0	88.0	+18.0	-30.0	-16.0	+14.0
50	5	70.0	85.0	+15.0	-30.0	-17.0	+13.0

*Difference = Blended minus As-Recieved

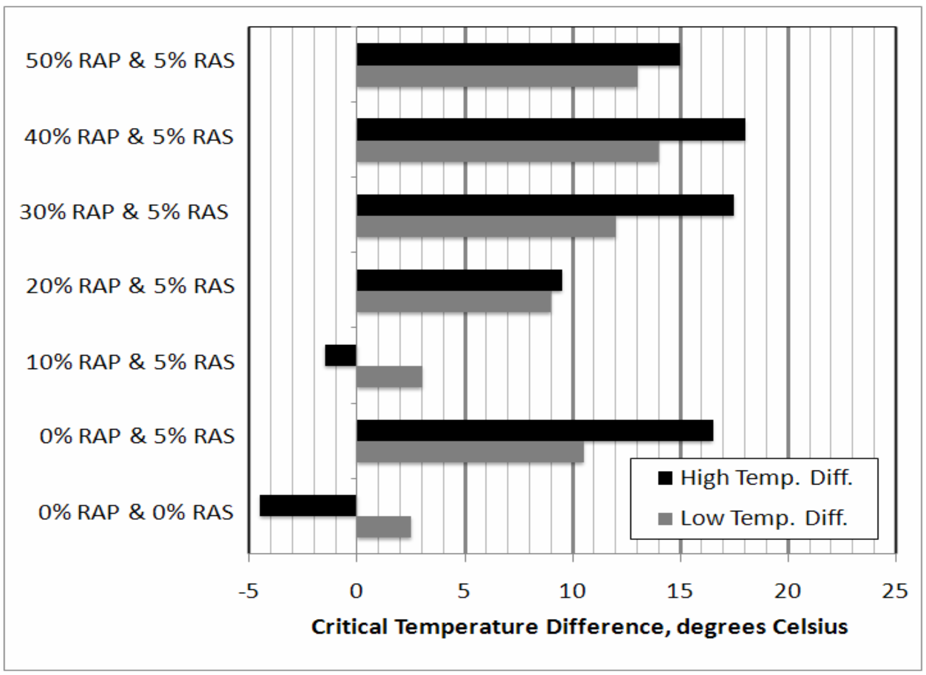

Figure 3.1: Critical Temperature Differences between Blended and As-Received Binders

As indicated in Table 3.7, the inclusion of RAP and RAS increased the critical high temperature of the blended binder by as much as 18.0°C (or three PG binder grades). Similarly, inclusion of RAP and RAS increased the critical low temperature of the blended binder by as much as 14.0°C (or two PG binder grades). It is further noted that the binder recovered from the mixture without reclaimed materials had a critical high temperature slightly below and a critical low temperature slightly above those determined for the as-received virgin binder.

Figure 3.2 displays the results in the form of ranges from the low critical temperature to the high critical temperature. Included are the critical temperatures of the as-received virgin binders (shown as “PG64-28” and “PG70-28”) and those for the binders recovered from the batched mixtures (shown with the proportions of RAP and RAS in the mixture). The diamond symbols represent the individual test results, whereas the block arrows represent the ranges. The vertical, dashed lines represent the critical low and critical high temperatures of the as-received virgin binders.

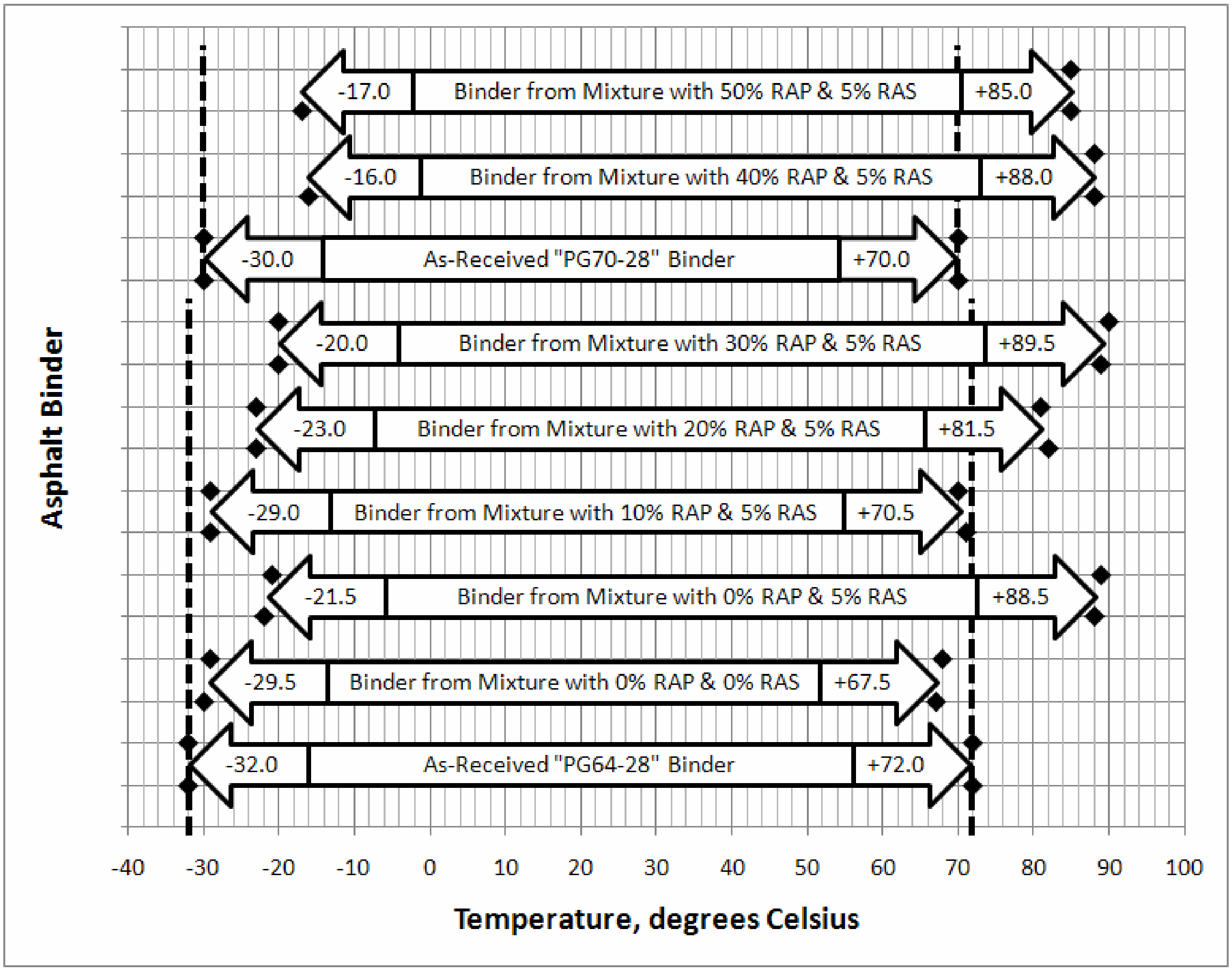

Figure 3.2: Critical Temperature Ranges of As-Received and Blended Binders

Table 3.8 summarizes the change in Superpave PG binder grade due to the addition of various proportions of RAP and RAS to the HMAC mixtures investigated. It is clear from these results, as well as those presented in Figure 3.2, that inclusion of only RAS (i.e., no RAP) in the HMAC mixture significantly affected the high temperature grade and had a moderate effect on the low temperature grade of the blended binder. However, in theory, reason would dictate an even greater impact by including RAP with the RAS (i.e., critical temperatures greater than those of the binder from the mixture with only RAS). The results clearly do not indicate a more pronounced impact due to inclusion of RAP. In fact, the results indicate that the binders from the mixtures with 30%, 40%, and 50% RAP (all in combination with 5% RAS) had essentially the same high critical temperatures as that of the binder from the mixture with 5% RAS and no RAP.

Table 3.8: Effect of Reclaimed Materials on the PG Grade of the Blended Binder

Percentage of Reclaimed Material in Batched Mixture		Superpave PG Grade (AASHTO M 320) of Recovered Binder	Change in High Temp. Grade[1]	Change in Low Temp. Grade[1]
RAP	RAS			
0	0	PG64-28	-1	+0
0	5	PG88[2]-22	+3	+1
10	5	PG70-28	+0	+0
20	5	PG82-22	+2	+1
30	5	PG88[2]-16	+3	+2
40	5	PG88[2]-16	+3	+2
50	5	PG82-16	+2	+2

[1]As-Received Virgin Binder Grade = PG70-28
[2]Extrapolated 1 PG grade above the highest temperature grade in AASHTO M 320

3.5 DISCUSSION OF RESULTS

This section provides a discussion of the results. Where possible, comparisons of the results to those found by other researchers are provided.

3.5.1 Binder from Mixture without RAP and RAS

The results from the binder recovered from the mixture without RAP and RAS indicated a slight increase in the critical low temperature relative to that of the as-received "PG64-28" binder. The results also indicated a moderate decrease in the critical high temperature. Although these results did not affect the low temperature grade of the binder, they do indicate a decrease of one PG grade for the high temperature grade. That is, the as-received virgin binder had a grade of PG70-28 (even though it was labeled as a PG64-28), whereas the binder recovered from the mixture without RAP and RAS had a grade of PG64-28. It is not known why the recovered binder had a lower high temperature grade, but one possibility is that polyphosphoric acid may have been used as a modifier in the binder, which may have resulted in a lower-than-expected test result. Another possibility is inherent random error in testing procedures.

3.5.2 Binder from Mixture with RAS

3.5.2.1 ODOT Results

The tests on the binder recovered from the mixture containing only RAS indicated that it would be graded as a PG88-22 (when the critical low temperature is rounded to the nearest whole number), but a PG88 does not exist in the AASHTO M 320 specification (i.e., the highest temperature grade in the specification is a PG82). Hence, for the high temperature grade, the binder from this mixture was three PG grades above the as-received virgin binder, and one PG grade above the highest temperature grade in the specification. For the low temperature grade, the binder was one PG grade above the as-received virgin binder.

3.5.2.2 MoDOT Results

Comparing these results to those from other studies is difficult in that published literature of studies that have investigated the change in binder grade due to replacement of a portion of virgin binder with RAS binder is very difficult to find. However, one document was found through a literature search that contains information allowing valid comparisons.

Schroer (*2009*) reported findings from research conducted by the Missouri Department of Transportation (MoDOT) where binders obtained from tear-off shingles and manufacturer waste shingles were blended with different grades of virgin binder. Blends with 20%, 40%, 60%, and 80% RAS binder were investigated. Critical temperatures of the virgin and blended binders are shown in Table 3.9. These data required further analyses so that valid comparisons could be made with the findings illustrated in Figure 3.2 and listed in Table 3.8. This was necessary because, in the ODOT study, the percentage of virgin binder replacement with RAS binder was 26% for the mixture with only RAS, which did not coincide with any of percentages used in the MoDOT study.

Table 3.9: Summary of Critical Temperatures for Virgin and Blended Binders from the MoDOT Study (adapted from *Schroer 2009*)

Virgin Binder Grade	Percent virgin binder replacement									
	0% (virgin binder)		20%		40%		60%		80%	
	$T_{c\ (high)}$	$T_{c\ (low)}$	$T_{c\ (high)}$	$T_{c\ (low)}$	$T_{c\ (high)}$	$T_{c\ (low)}$	$T_{c\ (high)}$	$T_{c\ (low)}$	$T_{c\ (high)}$	$T_{c\ (low)}$
PG58-22[1]	59	-28	73	-25	108	-17	105	-1	123	+8
PG52-28[1]	56	-31	64	-28	80	-19	99	-4	126	*
PG58-28[1]	60	-30	73	-24	78	-14	107	+2	123	+43
PG58-28[2]	60	-30	68	-22	79	-16	86	-10	98	-4

[1]Blended with binder from tear-off shingles
[2]Blended with flux (binder representing manufacturer waste)
*Temperature beyond testing limits

Using these data, the differences between the high and low critical temperatures of the blended binders and the high and low critical temperatures of the virgin binders were calculated. Table 3.10 lists the differences whereas Figures 3.3 and 3.4 show these results graphically. The charts include trend lines representing linear regressions with their respective coefficients of determination (R^2 values), which provide an objective measure of the proportion of the increase in critical temperatures that can be related linearly to an increase in RAS binder percentage. That is, if $R^2 = 1$, then the individual data points fall exactly on the linear regression line indicating perfect correlation. Conversely, if $R^2 = 0$, then there is no correlation between the data points and the regression line. For the linear regression lines shown in the charts, most of the coefficients of determination are close to unity, indicating that the increases in critical temperatures as a result of increases in RAS binder are well represented by linear relationships.

Table 3.10: Differences between Critical Temperatures of Blended and Virgin Binders (MoDOT Study)

Virgin Binder Grade	Change in high critical temperature (°C) at a percent virgin binder replacement of:				Change in low critical temperature (°C) at a percent virgin binder replacement of:			
	20%	40%	60%	80%	20%	40%	60%	80%
PG58-22[1]	+14	+49	+46	+64	+3	+11	+27	+36
PG52-28[1]	+8	+24	+43	+70	+3	+12	+27	+31
PG58-28[1]	+13	+18	+47	+63	+6	+16	+32	+73
PG58-28[2]	+8	+19	+26	+38	+8	+14	+20	+26

[1]Blended with binder from tear-off shingles
[2]Blended with flux (binder representing manufacturer waste)

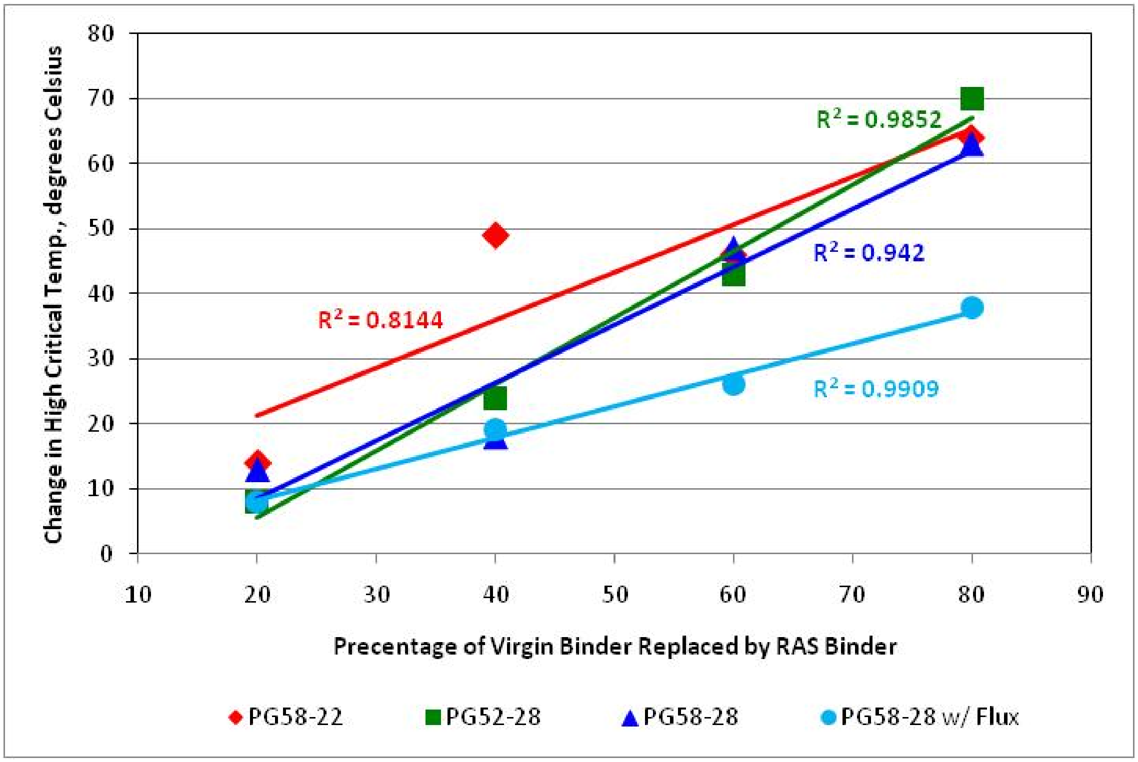

Figure 3.3: Change in High Critical Temperatures (MoDOT Study)

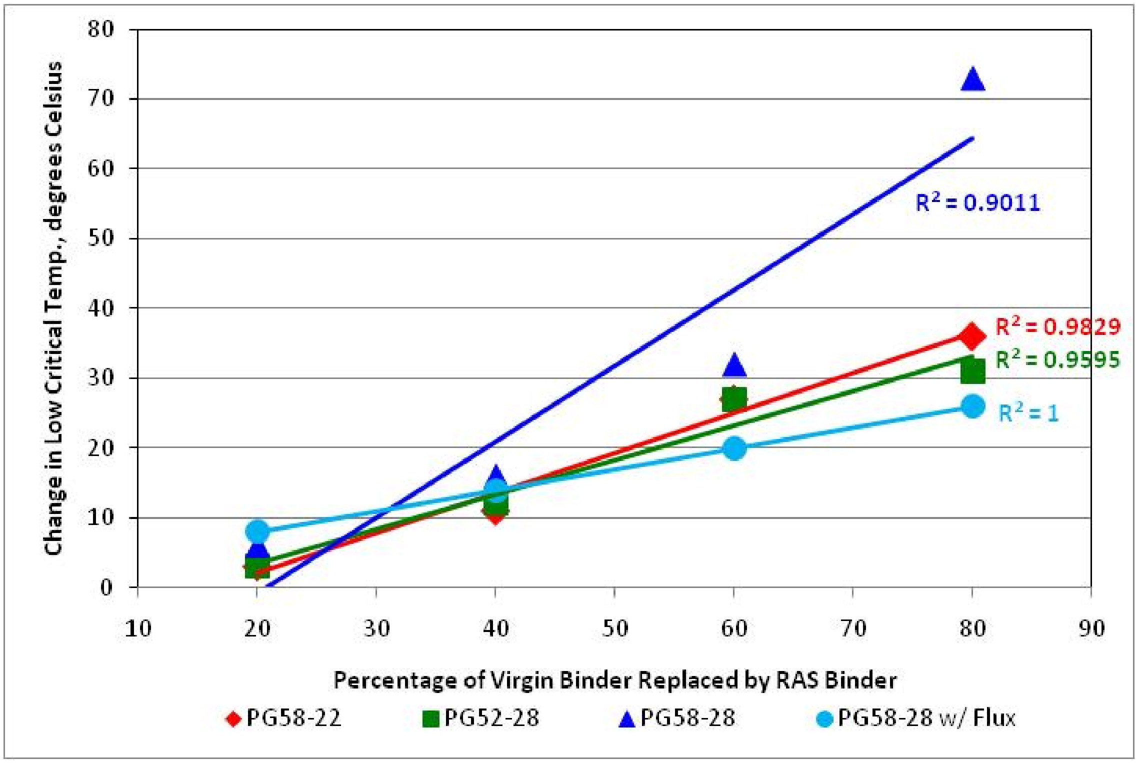

Figure 3.4: Change in Low Critical Temperatures (MoDOT Study)

3.5.2.3 Comparison between ODOT and MoDOT Results

Having established that the results from the MoDOT study closely follow linear relationships justifies the use of linear interpolation between RAS binder percentages of 20% and 40% to estimate the critical temperatures of a blended binder with 26% RAS binder (as used in the ODOT study). Estimation of the critical temperatures in this way allowed estimation of the changes in binder grade.

Table 3.11 provides the results of this analysis. As indicated, the estimated increase in the high critical temperature resulting from a RAS binder percentage of 26% (virgin binder percentage of 74%) ranged between 11 and 24°C, while that for the low critical temperature ranged between 5 and 10°C. Table 3.7 indicates that the increases in the high and low critical temperatures for the binder from the mixture with only RAS investigated in the ODOT study were 16.5 and 10.5°C, respectively, both of which were in close agreement with the estimated increases based on the MoDOT data.

Table 3.11 also indicates that the estimated high temperature grade of the blended binder, based on interpolation of the MoDOT study data, was between 2 and 4 PG grades higher than the virgin binder grade, and that the estimated low temperature grade was between 1 and 1½ PG grades higher than the virgin binder grade. Table 3.8 indicates that the high temperature grade of the binder from the mixture with only RAS investigated in the ODOT study was 3 PG grades higher than the virgin binder grade, and that the low temperature grade of the blended binder was 1 PG grade above that of the virgin binder, both of which were in close agreement with the estimated increases based on the MoDOT data.

Table 3.11: Interpolated Critical Temperatures and Binder Grade Increases of the ODOT Study Results using the Results from the MoDOT Study.

Virgin Binder Grade	Estimated increase in high critical temp. @26% binder replacement, °C	Estimated change in high temp. PG grade @26% binder replacement	Estimated increase in low critical temp. @26% binder replacement, °C	Estimated change in low temp. PG grade @26% binder replacement
PG58-22[1]	24.5	+4	5.4	Nearly +1
PG52-28[1]	12.8	+2	5.7	Nearly +1
PG58-28[1]	14.5	+2	9.0	+1.5
PG58-28[2]	11.3	Nearly +2	9.8	+1.5

[1]Blended with binder from tear-off shingles
[2]Blended with flux (binder representing manufacturer waste)

3.5.3 Binders from Mixtures with RAP and RAS

3.5.3.1 ODOT Results

Considering only the mixtures with RAP, it can be seen from Figure 3.2 and Table 3.8 that the high critical temperatures initially increased with added RAP content, but reached a plateau at a critical high temperature that was essentially the same as that for the RAP binder (i.e., 88°C). Similarly, it can be seen that the critical low temperatures also initially increased with increasing RAP content, but reached a plateau of approximately -16°C (approximately 7°C below the critical low temperature of the RAP binder).

3.5.3.2 Mn/DOT Results

Published literature of studies that have investigated the change in binder grade due to replacement of a portion of virgin binder with RAP binder in combination with RAS binder has been difficult to find. Nevertheless, one document was found through a literature search that contains information allowing two comparisons.

McGraw et al. (*McGraw et al. 2007*) reported findings from a study sponsored by the Minnesota Office of Environmental Assistance (now an office of the Minnesota Pollution Control Agency) and conducted by the Minnesota Department of Transportation (Mn/DOT) and the University of Minnesota, herein referred to as the Mn/DOT Study. The researchers investigated hot mix asphalt concrete with 20% RAP as a control mixture and two experimental mixtures with 15% RAP and 5% RAS, where the RAS was derived from both tear-off shingles and manufacturer waste shingles. The intent of the study was to determine the feasibility of including tear-off shingles in the Mn/DOT specifications (use of manufacturer waste shingles were already allowed by the Mn/DOT specifications). Table 3.12 displays the results of binder grade testing conducted as part of this study. Critical temperature differences (i.e., differences between high and low critical temperatures of the blended binders and the high and low critical temperatures of the virgin binder) could not be determined because the critical temperatures for the virgin binder were not included in the document.

Table 3.12: Critical Temperatures and Grade Increases of Binders Tested in the Mn/DOT Study (adapted from *McGraw et al. 2007*)

Mixture	Critical Temperatures, °C		Change in PG Grade[1]	
	$T_{c\,(high)}$	$T_{c\,(low)}$	High Temp.	Low Temp.
20% RAP (control)	64.2	-29.2	+1	+0
15% RAP & 5% RAS from tear-off shingles	73.2	-28.8	+2	+0
15% RAP & 5% RAS from manufacturer waste shingles	70.9	-26.2	+2	+1

[1]Relative to virgin binder grade of PG58-28

3.5.3.3 Comparison between DOT and Mn/DOT Results

A direct comparison of results cannot be made because the mixtures in the ODOT study contained different RAP percentages, and different RAP, RAS, and virgin binder grades than those of the mixtures investigated in the Mn/DOT study. However, the RAP percentages of the mixtures in the ODOT study bracket those of the mixtures in the Mn/DOT study allowing for an indirect comparison of results. It should also be mentioned that interpolation using the ODOT study results cannot be performed due to the lack of data on the critical temperatures of the virgin binder used in the Mn/DOT study. Hence, the only valid comparisons that can be made are those of change in binder grade.

Table 3.13 summarizes the appropriate results from both studies that can be compared. As indicated, the change in high temperature grade of the mixture with 15% RAP and 5% tear-off RAS from the Mn/DOT study matches that of the mixture with 20% RAP and 5% tear-off RAS from the ODOT study. In addition, the change in the low temperature grade of the same mixture from the Mn/DOT study matches that of the mixture with 10% RAP and 5% tear-off RAS from the ODOT study. It can also be seen that the change in both the high and low temperature grades of the mixture with 15% RAP and 5% manufacturer waste RAS from the Mn/DOT study matches those of the mixture with 20% RAP and 5% tear-off RAS for the ODOT study. These comparisons indicate that the changes in binder grade determined in the ODOT study were of similar magnitude to the changes in binder grade determined in the Mn/DOT study for mixtures with similar RAP contents.

Table 3.13: Comparison of Changes in Binder Grade between Mixtures with Similar RAP and RAS Contents

Mixture	Change in <u>High</u> Temp. PG Grade	Change in <u>Low</u> Temp. PG Grade
ODOT Study		
10% RAP & 5% tear-off RAS	+0	+0
20% RAP & 5% tear-off RAS	+2	+1
Mn/DOT Study		
15% RAP & 5% tear-off RAS	+2	+0
15% RAP & 5% manufacturer waste RAS	+2	+1

3.5.4 Potential Sources of Error

Although the previous sections provided evidence indicating that the results from the mixture with only RAS and from the mixtures with RAP and RAS are comparable to results from other studies, there still remains the question as to why the results suggest a lesser impact of RAP and RAS as compared with only RAS. A number of possibilities could account for these apparently anomalous results. Random or systematic errors during any part of the entire process were likely causes; that is, during batching and mixing, extraction and recovery, and testing. However, having reviewed the efforts undertaken during these components of the entire process, it was reasoned that the most likely cause was rooted in the process utilized to extract the asphalt binders from the mixtures.

Discussions with the personnel that performed the extractions and recoveries of the binders from the mixtures revealed that they encountered significant difficulties during the extraction process (i.e., removal of the asphalt binder from the mineral aggregate particles). The process utilized involved tumbling the mixture in a vessel containing a solvent to dissolve the binder, and then removing the solution from the vessel. The vessel contained screens (sieves) to prevent removal of the mineral aggregate particles of size greater than or equal to 75 microns. Removal of the solution from the vessel was accomplished by use of a reduced pressure (vacuum). During this part of the process, the effluent was passed through a replaceable 20 micron filter to remove mineral aggregate particles of size greater than or equal to 20 microns, and the solution passing the filter was collected in a flask. Additional solvent was added to the vessel containing the aggregate particles and the process was repeated as many times as required to obtain a straw-colored effluent, which was a subjective assessment for determining that the vast majority of binder had been removed from the aggregate particles. Following this, the solution of asphalt binder dissolved in the solvent was transferred to another flask and placed in a recovery (distillation) device to remove the solvent, leaving only asphalt binder in the flask. The flask was then inverted over a beaker (i.e., flask opening facing downward) and heated in an oven to remove the binder from the flask.

The laboratory personnel that performed the extractions reported that the mixtures containing RAS significantly clogged the screens and the outlet of the extraction vessel during the first and second washings. They indicated that the material was very thick and viscous, a "black, sticky goo." It is believed that this was most likely due to the cellulose and/or glass fibers and the relatively large proportion of very fine mineral aggregate in the RAS. They reported that the effluent also significantly clogged the 20 micron filter. Although a reduction of the quantity of material initially placed in the vessel partially mitigated these problems, it did not completely prevent them, especially with regard to the clogging of the 20 micron filter.

These issues point to inefficient and incomplete extraction of the binders from the mixtures. If this were indeed the case, it is suspected that the binder from the RAP and RAS was not completely removed from the aggregate particles. It is further suspected that the hardest (most viscous) components of the binders remained adhered to the aggregate particles. These components have the greatest molecular weight and polarity and, therefore, form the strongest bonds with the aggregate surface, which may have needed a stronger solvent to break the bonds. Given these suspicions, the components of the binders that were removed from the aggregate particles would have been the softer, less viscous, components resulting in lower-than-expected critical temperatures of the blended binders.

Another consideration regarding the extraction process is that the equipment and procedure was new to the laboratory personnel. In addition, the binder from the mixture with only RAS was extracted before any of binders were extracted from the mixtures with both RAP and RAS. Hence, it is plausible that the technique used to extract the binders evolved as the laboratory personnel became familiar with the equipment and procedure, possibly affecting the physical properties of the extracted binders.

Of course, testing error cannot be ignored as a possible explanation for the unexpected results between the mixture with only RAS and those with both RAP and RAS. Given the results listed in Table 3.7, two possibilities immediately come to mind: 1) random error during the testing of the binder extracted from the mixture with only RAS, and 2) systematic error during the testing of the mixtures with both RAP and RAS. Still another possibility is the combined effects of extraction technique and testing, with the former having an impact on the latter.

3.5.5 Need for Mixture Testing

It should be emphasized that the increased high temperature grade of the blended binders from the mixture with only RAS and from those with 20% or more RAP and 5% RAS means that the blended binders were stiffer than the virgin binder at high temperature. This increased stiffness potentially translates to improved resistance to permanent deformation and rutting. However, it also potentially translates to a greater vulnerability to fatigue cracking at intermediate (moderate) temperatures. The increased low temperature grades of the binders from mixtures with reclaimed materials suggest a greater propensity to low temperature cracking due to the increased stiffness and brittleness of the binders at low temperatures. It should be further emphasized that verification of these statements requires conducting performance tests on mixtures with reclaimed materials and/or evaluation of the performance of such mixtures in the field. The following paragraphs provide evidence from other studies indicating that the inclusion of reclaimed binders did not have a significant impact on the low temperature strength and high temperature stiffness characteristics of HMAC mixtures containing the reclaimed binders.

One recent study investigated plant-mixed HMAC mixtures with two virgin binder grades and RAP contents of 15%, 25%, and 40% in comparison with a control mixture containing one of the virgin binder grades and no RAP (*Shah et al. 2007*). Mixtures obtained from the plant and compacted in a laboratory were tested for creep compliance and indirect tensile strength at low temperatures and dynamic modulus at high temperatures. Results from the low temperature testing on the mixtures indicated an overall trend of increasing indirect tensile strength with increasing percentages of RAP as indicated in Figure 3.5. However, statistical analyses comparing the strengths of the various mixtures indicated no significant difference between any of the mixtures at a significance level of 0.05. Similarly, results from the high temperature tests on the mixtures indicated an overall trend of increasing modulus with increasing percentages of RAP as indicated in Figure 3.6. Statistical analyses comparing the moduli of the various mixtures indicated significant differences (again, at a significance level of 0.05) in 12 of the 18 comparisons made. Together, these results indicated that the various proportions of RAP did affect the intermediate to high temperature stiffness of the mixtures, but did not affect the low temperature strengths. The authors concluded that adding reclaimed asphalt binder from RAP did not change the mixture properties substantially and that, for the materials used in the study, it appeared that the design binder grade could be used for RAP contents up to 40%.

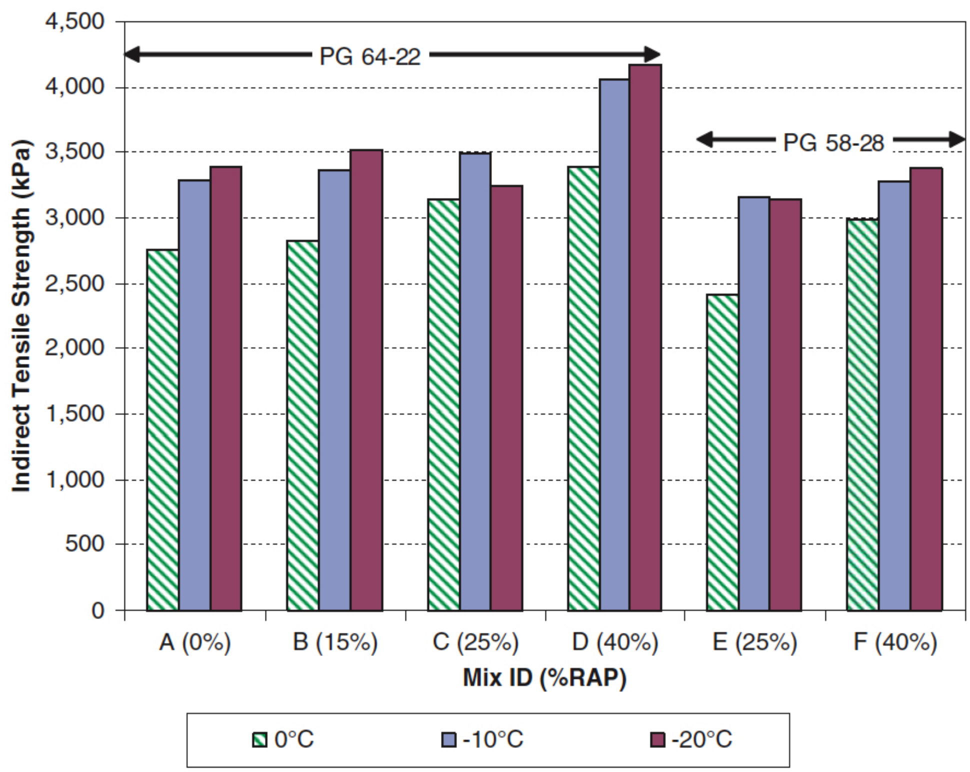

Figure 3.5: Indirect Tensile Strength of Plant-Mixed, Lab-Compacted HMAC Mixtures (*Shah et al. 2007*)

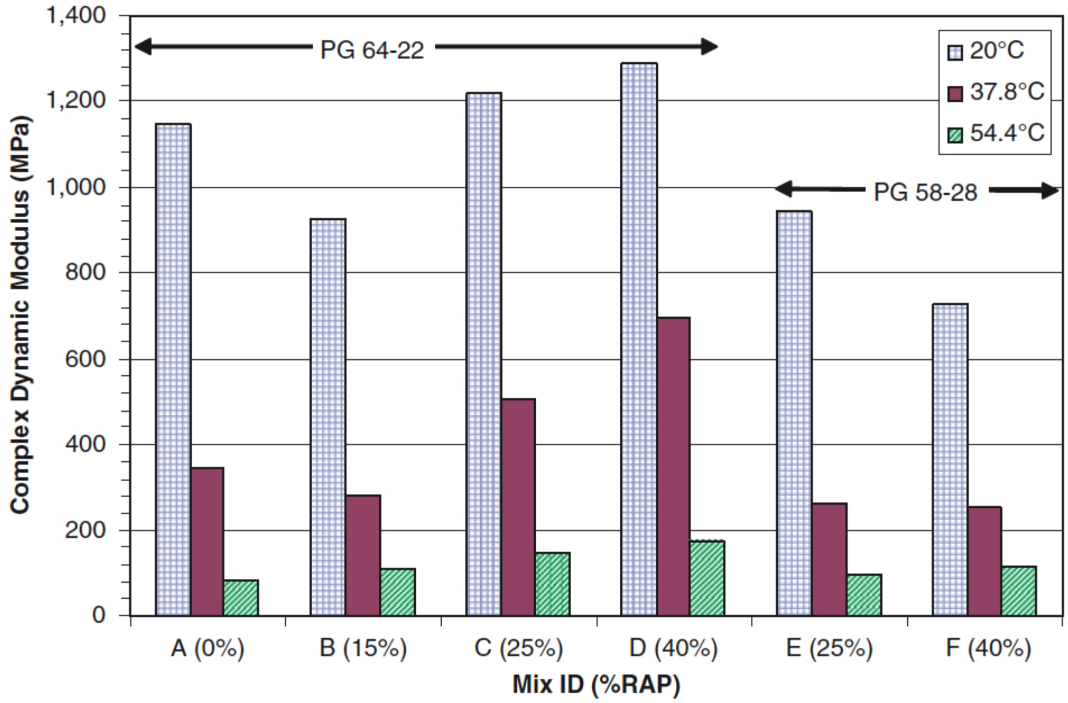

Figure 3.6: Dynamic Modulus of Plant-Mixed, Lab-Compacted HMAC Mixtures (*Shah et al. 2007*)

In the Mn/DOT study (*McGraw et al. 2007*), described previously in Section 4.5.3, the researchers also conducted direct tension tests on the mixtures at three low temperatures (-12, -18, and -24°C) and overlaid the results on thermal stress curves to determine the temperature at which the two intersect, representing the low critical temperature of the mixtures. The researchers found that the low critical temperature of the mixture with 15% RAP and 5% manufacturer waste RAS was almost identical to that of the mixture with 20% RAP and no RAS. They also found that the low critical temperature of the mixture with 15% RAP and 5% tear-off RAS was only about 4°C above that of the mixture with 20% RAP. These results are incongruent with those indicated by the binder test results as shown in Table 3.12. That is, the binder tests indicated that the mixture with tear-off RAS had essentially the same low critical temperature as that of the mixture with 20% RAP, whereas the mixture tests suggested a 4°C increase. Similarly, the binder tests indicated that the mixture with manufacturer waste RAS had a low critical temperature 3°C higher than that of the mixture with 20% RAP, but the mixture tests suggested essentially no difference.

One observation that can be made from these studies is that results from binder tests alone are not necessarily good predictors of the performance of the binders in HMAC mixtures. Hence, although the results of the binder tests reported herein (i.e., in Table 3.7) suggest significant impacts to both the high and low properties of the blended binders, mixture tests and/or evaluation of mixtures in field trials should be conducted to determine the real impacts on mixture performance.

4.0 PILOT STUDY RECOMMENDATIONS

Specifications and special provisions of several agencies that allow tear-off RAS, and particularly those that allow tear-off RAS and RAP together, were reviewed to determine restrictions, criteria, test methods, mix design procedures, etc. applicable to inclusion of RAP and/or RAS in HMAC paving mixtures. Documents from Alabama DOT, Missouri DOT, South Carolina DOT, Texas DOT, Virginia DOT, Wisconsin DOT, and the King County Solid Waste Division in Washington were reviewed for these purposes. Appendix B provides a summary of the relevant findings from the review. Based on the review of these documents as well as the findings from the laboratory study, the following modifications to ODOT Standard Specification, Section 00745 - Hot Mixed Asphalt Concrete (HMAC) (SP745) are recommended:

1. Modify 00745.03 to indicate that the quantities of RAP do not apply when RAP is used in combination with RAS. This could be accomplished by adding a sentence to the bottom of the first paragraph. The following sentence is suggested:

   The above quantities of RAP shall be reduced as indicated in 00745.04 when reclaimed asphalt shingles (RAS) are also included in the HMAC pavement material.

2. Add a subsection immediately below 00745.03 to describe RAS and specify limits of its use. The following is suggested for this purpose:

   00745.04 Reclaimed Asphalt Shingles (RAS) – Reclaimed asphalt shingles (RAS) used in the production of new HMAC is optional. Either manufacturer waste (post-manufacturer) RAS or tear-off (post-consumer) RAS may be used. Manufacturer waste RAS refers to processed asphalt shingle material derived from manufacturer's shingle scrap. Tear-off RAS refers to processed asphalt shingle material derived from shingle scrap removed from residential structures.

   Process the RAS by grinding at ambient temperature so that 100% of the shredded pieces are less than 1/2 inch in any dimension and that 90% are less than 3/8 inch in any dimension. The Contractor shall certify that the RAS does not contain asbestos fibers in any amount. For the purposes of testing for asbestos, a minimum of 1 sample per 100 tons of RAS shall be obtained and tested. The RAS shall also be substantially free of other deleterious materials such as nails, glass, rubber, soil, brick, tars, paper, plastic, wood chips, metal flashing, etc. The percentage of deleterious materials shall be limited to 3.0%, by weight, of the stockpiled RAS as determined on material retained on the 4.75 mm (No. 4) sieve. Lighter material such as paper, plastic, and wood shall not exceed 1.5%, by weight, of the stockpiled as determined on material retained on the 4.75 mm (No. 4) sieve[1].

Fine aggregate meeting the requirements of 00745.10(c) may be added to the RAS in a quantity not to exceed 4% by weight of RAS to keep the material workable and to prevent conglomeration of the shingle particles in the stockpile. Any added fine aggregate for these purposes must be taken into account in the mix design. Stockpiled RAS shall not be contaminated by dirt or other foreign materials. The Contractor shall take necessary steps to ensure that excessive moisture is not retained in the RAS stockpiles, and the moisture content of the material fed into the batch plant or drum plant shall not exceed 5% when tested in accordance with AASHTO T 329[2].

No more than 5% RAS by total weight of mixture will be allowed in HMAC mixtures. In addition, the maximum allowable percentage of asphalt binder replacement shall be restricted to 20% for base courses and 15% for wearing courses in HMAC containing only RAS[3].

When RAS is used in conjunction with RAP, no more than 20% reclaimed materials by total weight of mixture will be allowed in Level 1, Level 2, and Level 3 HMAC, and no more than 15% will be allowed in Level 4 HMAC. In addition, the maximum allowable percentage of binder replacement shall be restricted to 30% for base courses and 25% for wearing courses[3].

For HMAC mixtures containing only RAS, the amount of asphalt cement in the RAS shall be established in the mixture design phase in accordance with ODOT TM 319 having established a calibration factor for the RAS in accordance with ODOT TM 323. For HMAC mixtures containing RAP and RAS, the RAS shall be added to the RAP and tested in accordance with ODOT TM 319 to establish the asphalt content of the combined reclaimed materials. Develop mixture designs as per the ODOT Contractor Mix Design Guidelines for Asphalt Concrete[4].

3. In the paragraph beginning with “A request for…” in subsection 00745.16(b-1-a) add a sentence immediately following the sentence beginning with “Adjustments for RAP…” to indicate the allowable adjustments for RAS. The following sentence is suggested:

   Adjustments for RAS content shall be within 1% of the original JMF, but shall not exceed the requirements of 00745.04.

---

[1]*Author’s Note*: It is realized that this will have a significant impact on the amount of both QC and QA testing. However, better blending and utilization of the RAS binder can be achieved with a finer RAS gradation, thus obtaining more recovered binder per dollar spent. In addition, it is recommended that ODOT take measures to prevent too much deleterious materials from being included in mixtures incorporating tear-off RAS. Finally, it is suspected that asbestos may be present in older roofing materials which may find its way into the shredder, and should definitely be avoided.
[2] *Author’s Note*: The oven temperature specified in AASHTO T 329 may need to be reduced when testing RAS.
[3] *Author’s Note*: The values listed are within the boundaries established by other agencies as identified in Appendix B.
[4] *Author’s Note*: Modifications to ODOT TM 319, TM 323, TM 330, and the Guidelines will be required to accommodate RAS

5.0 CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

Based on the findings from the laboratory study undertaken to investigate how various proportions of RAP and RAS added to HMAC mixtures affect the Superpave performance grade of the blended binder, the following conclusions appear warranted:

1. Inclusion of 5% RAS (by total weight of mixture), but no RAP, in the dense-graded HMAC mixture resulted in an increase in both the high temperature and low temperature performance grades of the blended binder relative to the virgin binder. Comparison of these findings with those derived from another study indicated increases of similar magnitude.

2. Binders recovered from the mixtures with both RAP and RAS indicated an increase in both the high temperature and low temperature performance grades of the blended binder with increasing RAP contents up to about 30%. RAP contents above 30% did not result in any further increases in the low temperature performance grade and only slightly impacted the high temperature performance grade of the blended binders. The high temperature performance grade of the blended binder asymptotically approached that of the high temperature grade of the RAP binder. At RAP contents of 20% and higher (in combination with 5% RAS), the high temperature and low temperature performance grades of the blended binders were higher than those of the virgin binder. Comparison of these findings with those derived from another study indicated increases of similar magnitude.

3. At sufficiently high RAP contents (i.e., 30% or more), in combination with 5% RAS, the low temperature performance grades of the blended binders exceeded (were higher than) that of the blended binder from the mixture with only RAS. Similarly, at RAP contents of 30% and 40%, the high temperature performance grade of the blended binders equaled that of the blended binder from the mixture with only RAS.

4. Although inclusion of RAS and sufficient quantities of RAP in the HMAC mixtures significantly affected the performance grades of the blended binders, there exists evidence to suggest that high RAP contents (but not RAS) do not have a significant impact on the low temperature strength characteristics of HMAC with RAP.

5.2 RECOMMENDATIONS

Based on the findings and information presented above, the following recommendations appear warranted:

1. An improved laboratory batching/mixing procedure should be established for mixtures containing RAS, or combinations of RAP and RAS, for use in ODOT's mix design process and ignition oven tests.

2. A procedure for effectively and efficiently recovering asphalt binder from RAS should be identified for use in Oregon.

3. A procedure for determining ignition oven calibration factors for HMAC mixtures containing RAP and/or RAS should be established for use in Oregon.

4. Quality control and quality assurance (QC/QA) test procedures for mixtures incorporating RAP or RAS, or combinations of RAP and RAS, as well as independent assurance parameters associated with determining asphalt binder content based on incineration (ignition oven tests), are needed.

5. A design process for selecting the grade of virgin asphalt binder for HMAC mixtures containing RAP or RAS, or combinations of RAP and RAS, such that the blended binder meets the design grade for the mixture should be established for use in Oregon.

6. The low temperature performance characteristics (i.e., tensile strength) of mixtures containing RAP or RAS, or combinations of RAP and RAS, should be investigated. The findings from such an investigation could either support or refute the need for a design process for selecting the grade of virgin binder as recommended previously.

7. The intermediate temperature performance characteristics (i.e., fatigue cracking resistance) of mixtures containing RAP or RAS, or combinations of RAP and RAS, should be investigated.

8. The recommended modifications to SP745 should be adopted for use in a pilot study that involves the production, placement, and performance monitoring of an HMAC pavement containing RAP and RAS. The effects of RAP and RAS binder on the properties of the blended binder should be validated during this effort. It is further recommended that ODOT's current QC and QA requirements be applied during the pilot study, with the applicable additional requirements identified in Section 4 of this document. However, it may be in the contractor's best interest to sample and test the RAP and RAS more frequently than required by ODOT to verify consistency of the RAP and RAS as well as the consistency of the final mixture.

6.0 REFERENCES

AASHTO. *Standard Specifications for Transportation Materials and Methods of Sampling and Testing*, American Association of State and Highway Transportation Officials, Washington, D.C., 2009.

Al-Qadi, Imad L., M. A. Elseifi, and S. H. Carpenter, *Reclaimed Asphalt Pavement – A Literature Review*, Research Report FHWA-ICT-07-001, Illinois Center for Transportation, University of Illinois at Urbana-Champaign, Urbana, IL, 2007.

Krivit, Dan and Associates. *Recycling Tear-Off Asphalt Shingles: Best Practices Guide*, prepared for the Construction Materials Recycling Association, St. Paul, MN, October 11, 2007.

McGraw, J., A. Zofka, D. Krivit, J. Schroer, R. Olson, and M. Marasteanu. "Recycled Asphalt Shingles in Hot Mix Asphalt," *Journal of the Association of Asphalt Paving Technologists*, St. Paul, MN, Vol. 76, pp 235-274, 2007.

Maupin, G.W., Jr., S. D. Diefenderfer, and J. S. Gillespie, *Evaluation of Using Higher Percentages of Recycled Asphalt Pavement in Asphalt Mixes in Virginia*, Report No. VTRC 08-R22, Virginia Transportation Research Council, Charlottesville, VA, June 2008.

NCHRP. "Recommended Use of Reclaimed Asphalt Pavement in the Superpave Mix Design Methods: Guidelines," *National Cooperative Highway Research Program Research Results Digest*, No. 253, Transportation Research Board of the National Academies, Washington, D.C., March, 2001.

ODOT. *Legislative Summary 2009*, Oregon Department of Transportation, Salem, Oregon, September 2009.

Schroer, Joe, "Missouri's Use of Recycled Asphalt Shingles (RAS) in Hot Mix Asphalt," *Proceedings of the 2009 Mid-Continent Transportation Research Symposium*, Iowa State University, Ames, Iowa, 2009.

Shah, Ayesha, R. S. McDaniel, G. A. Huber, and V. L. Gallivan. "Investigation of Properties of Plant-Produced Reclaimed Asphalt Pavement Mixtures," *Journal of the Transportation Research Board, Transportation Research Record No. 1998*, pp 103-111, Transportation Research Board of the National Academies, Washington, D.C., 2007.

APPENDIX A:
MIX DESIGN FROM HMAC PRODUCER

Stage 3 Blend Sheets

PROJECT	0	MIX CLASS	1/2" Dense	
CONTRACT NO.	N/A	LEVEL (2,3,4)	LEVEL 3 (80 gyr)	
MIX PRODUCER	XXXXXXXXXXXXXX	PROJECT MANAGER	N/A	
CMDT (print)		SUPPLIER MIX ID NO.	XXXXXX	Date: 2/5/2009

QL Levels

XXXXXXXXXXXXXXXXXX

XXXXXXXXXXX

Stockpile:	1/2"-1/4"	#4-#8	1/4"-0			0	Lime	1/4"-0 RAP-2	1/2"-0 RAP-1		Fine Blend			Source History Target Blend	Golden Gradation		ODOT Specification (745-13)
Final Blend	32.0	8.0	29.0	0.0	0.0	0.0	1.0	30.0	0.0	100.0							
1"	100	100	100	0	0	100	100	100	100	1"	100.0			100	100	1"	
3/4"	100	100	100	0	0	100	100	100	100	3/4"	100.0			100	100	3/4"	100
1/2"	96	100	100	0	0	100	100	100	92	1/2"	98.7			98	95	1/2"	90-100
3/8"	58	100	100	0	0	100	100	100	82	3/8"	86.5			89	82	3/8"	-90
1//4"	8	85	88	0	0	100	100	95	66	1//4"	64.4			65	65	1//4"	
#4	1	48	72	0	0	100	100	83	57	#4	51.0			53	55	#4	
#8	1	8	45	0	0	100	100	57	41	#8	32.0			33	34	#8	28-58
#16	1	5	29	0	0	83	100	41	30	#16	22.3			21	21	#16	
#30	1	4	21	0	0	62	100	30	23	#30	16.6			15	15	#30	
#50	1	3	15	0	0	54	100	23	18	#50	12.5			11	10	#50	
#100	1	3	12	0	0	46	100	17	14	#100	10.1			8	7	#100	
#200	0.5	2.5	9.3	0.0	0.0	35.3	100.0	13.3	10.3	#200	8.0			6.8	5.0	#200	2.0-10.0

Dust to be wasted at plant: 1.75

Bulk Sp.Gr., Gsb	2.654	2.604	2.732	1.000	1.000	1.000	2.150	2.603	2.631
Bulk SSD Gsb SSD	2.704	2.664	2.803	1.000	1.000	1.000			
Apparent Sp.Gr., Gsa	2.794	2.770	2.940	1.000	1.000	1.000	2.150	2.773	2.763
% Absorption	1.890	2.278	2.502	1.000	1.000	1.000			

Dust correction

1"	100.0			100	100	1"	
3/4"	100.0			100	100	3/4"	100
1/2"	98.7			98	95	1/2"	90-100
3/8"	86.3			89	82	3/8"	-90
1//4"	63.7			65	65	1//4"	
#4	50.1			53	55	#4	
#8	30.8			33	34	#8	28-58
#16	20.9			21	21	#16	
#30	15.2			15	15	#30	
#50	11.0			11	10	#50	
#100	8.5			8	7	#100	
#200	6.4			6.8	5	#200	2.0-10.0

Gsb	2.650		
Estimated Gse	2.784		
Gsa	2.818		

[redacted] Mix Design Summary

PROJECT			MIX CLASS	1/2" Dense
CONTRACT NO.	N/A		LEVEL (2,3,4)	LEVEL 3 (80 gyr)
MIX PRODUCER	[redacted]		PROJECT MANAGER	N/A
CMDT (print)			SUPPLIER MIX ID NO.	[redacted]

AGGREGATE & OTHER CONSTITUENTS (RAP,BL,SAND,LIME, ECT.)

Stockpile Designation	1/2"-1/4"	#4-#8	1/4"-0				Lime	1/4"-0	1/2"-0
Source	[redacted]					0	[redacted]		
ODOT Source Id.No.	07-047-4	07-047-4	16-024-4						
Percent Combined (Psp)	32%	8%	29%	0%	0%	0%	1%	30%	0%
Passing .075mm (No. 200) Sieve %	0.5	2.5	9.3				100.0	13.3	
Bulk specific Gravity (Gsb)	2.654	2.604	2.732				2.150	2.603	
Bulk specific Gravity (Gsa)	2.794	2.770	2.940					2.752	
Absorption, %	1.89	2.28	2.50						

Design developed with "Dryback" Gmm (Y/N)? **Y**

MIXTURE AT DESIGN ASPHALT CONTENT

Maximum Specific Gravity (Gmm)	2.504
Gyratory Bulk Gravity (Gmb)	2.402
Air Voids, % (Va)	4.0
VMA, %	14.7
VFA, %	72
Effective Asphalt Content, % (Pbe)	4.6
P200/Pbe Ratio	1.4
Combined Aggregate (Gsb)	2.650
Effective Specific Gravity (Gse)	2.784
Combined Apparent Gravity (Gsa)	2.818
Tensile Strength Ratio (TSR)	**98.2**
TSR Compaction Average Gyrations	47
VIR	12.47%
Absorbed Asphalt, % (Pba)	1.38
APA Rut depth-mm	
(Gmb) Sample Weight @ JMF	4778.6
Number of Gyrations (Ndesign)	80
Draindown % (open grade)	NA
Plant Dust Correction (dust removal)	**1.75%**
Film Thickness (Tf) optional	11.7
Date	**02/20/08**
Signature	[redacted]
Blend Chosen?	**2**

JOB MIX FORMULA

Aggregate Gradation	
Sieve	
1"	**100**
3/4"	**100**
1/2"	**99**
3/8"	**86**
1/4"	**64**
#4	**50**
#8	**31**
#16	**21**
#30	**15**
#50	**11**
#100	**8**
#200	**6.4**
Total asphalt Content, % (Pb)	5.91%
Virgin asphalt content, %	4.64%
Asphalt percent in RAP (Pbr)	4.25%
Asphalt percent in RAP (Pbr)	
Asphalt percent in Shingles (Sbr)	
Anti Strip, %	1%
Asphalt Brand	Albina
Asphalt Grade	70-28
Mix Temperature range	319-327
Placement Temperature range	295-304
Asphalt Sp. Gr. (Gb) 77/77 F	1.0388
Asphalt Sp. Gr. (Gb) 60/60 F	1.0430

Comments Oil content chosen from history

APPENDIX B:
SPECIFICATIONS FROM AGENCIES ALLOWING TEAR-OFF RAS AND RAP

Agency	Relevant Specifications
Alabama DOT	• 100% smaller than 1/2 inch in any dimension. • Tear-off RAS content: 3% max., by weight of aggregate. • Manufacturer waste RAS content: 5% max., by weight of aggregate. • 15% max. RAP+RAS content for surface layers (Superpave or SMA). • 20% max. RAP+RAS content for all other layers (Superpave or SMA). • 20% max. RAP+RAS content for plant mix bituminous base. • RAS shall be free from foreign materials such as paper, nails, wood, and metal flashing.
Missouri DOT	• Shingles shall be ground to 1/2 inch minus. • RAS content (tear-off or manufacturer waste): 7% max. with PG 64-22. • If the ratio of virgin binder to total binder is less than 70%, the grade of the binder shall be PG 58-28 or PG 52-28 (instead of PG 64-22). • Tear-off RAS shall contain no more than 1.5% wood by weight or no more than 3.0% total deleterious materials by weight. It shall be certified to contain less than the maximum allowable amount of asbestos as defined by local and national standards.
South Carolina DOT	• Particle size less than 1/2 inch. • RAS content (tear-off or manufacturer waste): 3-8%, by total weight of aggregate. • Material shall be 99.7% (by weight) free of any debris. Must be certified to be free of all chemicals, oils, or any other hazardous materials (e.g., asbestos).
Texas DOT	• 100% smaller than 1/2 inch. • RAS content (tear-off or manufacturer waste): 5% max., by total weight of mixture. • Ratio of virgin binder to total binder must exceed 65% for surface mixtures and 60% for non-surface mixtures. • For mixtures with RAS and fractionated RAP: ▪ 20% max. RAP+RAS content for surface mixtures. ▪ 30% max. RAP+RAS content for non-surface mixtures. • For mixtures with RAS and un-fractionated RAP: ▪ 10% max. RAP+RAS content for surface mixtures. ▪ 20% max. RAP+RAS content for non-surface mixtures. • Must be certified to pass non-hazardous recyclable materials guidelines. • Stockpiled RAS must not have more than 1.5% by weight of deleterious materials.

<table>
<tr><th>Agency</th><th>Relevant Specifications</th></tr>
<tr><td>Virginia DOT</td><td>

100% smaller than 1/2 inch in any dimension.
RAS content (tear-off or manufacturer waste): 5% max., by total weight of mixture.
Combined percentage of RAP and RAS shall not contribute more than 25% of the total asphalt content of the mixture according to:

$$\frac{\left[\left(\%RAS\right)_{mix} \times {}^{\%AC_{RAS}}/_{100}\right) + \left(\%RAP_{mix} \times {}^{\%AC_{RAP}}/_{100}\right)}{\%AC_{JMF}}$$

Where:
$\%RAS_{mix}$ = Percent RAS in the Job Mix Formula
$\%AC_{RAS}$ = Average percent AC in the RAS
$\%RAP_{mix}$ = Percent RAP in the Job Mix Formula
$\%AC_{RAP}$ = Average percent AC in the RAP
$\%AC_{JMF}$ = Design AC content of the Job Mix Formula

Contractor must certify that RAS does not contain asbestos fibers at a testing frequency of 1 per 100 tons prior to or during stockpile approval process.

</td></tr>
<tr><td>Wisconsin DOT</td><td>

100% smaller than 1/2 inch.
Max. allowable percent binder replacement, ratio of binder recovered from FRAP (fractionated RAP), RAP, and RAS, expressed as a percentage:

<table>
<tr><th>Recycled Asphalt Material</th><th>Lower Layers</th><th>Upper Layer</th></tr>
<tr><td>RAS only</td><td>20</td><td>15</td></tr>
<tr><td>RAP only</td><td>35</td><td>20</td></tr>
<tr><td>FRAP only</td><td>35</td><td>25</td></tr>
<tr><td>RAS and RAP</td><td>30</td><td>20</td></tr>
<tr><td>RAS and FRAP</td><td>30</td><td>25</td></tr>
<tr><td>RAS, RAP, and FRAP</td><td>30</td><td>25</td></tr>
</table>
</td></tr>
<tr><td>King County Solid Waste Division</td><td>

100% smaller than 1/2 inch and min. of 95% smaller than 3/8 inch.
RAS must be free of whole, intact nails. Extraneous materials such as metals, glass, rubber, nails, soil, brick, tars, paper, wood, and plastic shall not exceed 3.0% by mass as determined by material retained on the No. 4 sieve. Lighter materials such as paper, wood, and plastic shall not exceed 1.5% by mass as determined by material retained on the No. 4 sieve.
The final RAS product shall not contain more than 5.0% moisture. The contractor shall take necessary steps to ensure excessive moisture is not retained in the RAS stockpiles.

</td></tr>
</table>