ASPHALT BINDER GRADE SELECTION AND IGNITION OVEN CALIBRATION FACTORS FOR HMAC WITH RECYCLED ASPHALT PRODUCTS

Final Report

SPR 713

Oregon Department of Transportation

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by

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16. Abstract

This study investigated several characteristics of laboratory-fabricated and plant-produced hot-mix asphalt mixtures containing various proportions of RAP and RAS with the principal objectives of developing a procedure for selecting the virgin binder grade used in such mixtures as well as a procedure for determining ignition oven calibration factors for mixtures containing these materials. Other objectives included developing recommendations for procedures to effectively and efficiently recover asphalt binder from RAS, batch and mix reclaimed materials with virgin materials, and for quality control and quality assurance testing.

The blending chart analysis procedure described in AASHTO PP 53 for selecting a virgin binder grade was selected as a starting point for evaluation purposes, but the attempt to validate the procedure was unsuccessful. Consequently, an alternate approach was recommended for further investigation.

ODOT's current method for determining ignition oven calibration factors (TM 323) was evaluated using both laboratory-prepared and plant-produced mixtures. Findings from this evaluation provided strong evidence to suggest procedural changes to the current method are unnecessary. Further, modification of ODOT's current independent assurance parameter for asphalt binder content is not justified at this time. However, changes to the language in the test method to include RAS are needed and recommendations for these are provided.

Selection of procedures for extracting and recovering binder from RAS was accomplished through a literature search. Selection of procedures for QC and QA was accomplished in the same manner. However, detailed procedures for fabricating laboratory specimens containing RAS were not found. Consequently, taking into consideration existing procedures, new procedures were developed for batching and mixing specimens containing RAP, RAS, or combinations of RAP and RAS.

The applicability of using of nuclear density gauges to determine in-place density of mixtures containing RAS was also evaluated. Assessment was based on variability of density measurements obtained from nuclear gauges and from pavement cores. Findings indicated no difference in the quality of measurements made on mixtures containing RAP and RAS versus those containing only RAP.

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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

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DISCLAIMER

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1.0 INTRODUCTION

1.1 BACKGROUND

Recycled (or reclaimed) 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 percent), 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 percent) 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,and Carpenter 2007*). However, a Virginia study of 10 "high-RAP" paving projects (i.e., with 21 percent to 30 percent 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 percent or less) in laboratory tests for fatigue, rutting, and moisture damage (*Maupin, Diefenderfer, and Gillespie 2008*).

The first use of RAP by the Oregon Department of Transporation (ODOT) occurred in 1977 where nearly 45,000 tons of RAP was placed along the Hillsboro-Silverton (OR 219) Highway (*Dumler and Beecroft 1977; Whitcomb et al. 1979*). Interestingly, the specifications for the project called for 78 percent to 100 percent "recrushed asphalt concrete materials" (i.e., RAP), by weight of total mixture. Primarily due to emissions (smoke) from the hot mix plant during the first several days of production exceeding opacity criteria specified by the Oregon Department of Environmental Quality, the quantity of RAP was decreased to 70 percent and used for the remainder of the project (*Dumler and Beecroft 1977*). On average, the mixture placed along the project incorporated just over 75 percent (by weight of total mixture) of RAP (*Whitcomb et al. 1979*). Presently, RAP is used extensively on ODOT projects, but is limited to a maximum of 30 percent for mixtures exposed to low-to-moderate truck traffic and for base course mixtures on facilities exposed to heavy truck traffic, or 20 percent for wearing course mixtures exposed to heavy truck traffic (*ODOT 2008*).

Several state agencies also allow the use of recycled (or reclaimed) asphalt shingles (RAS) in HMAC mixtures, primarily with the intent to reduce the quantity of virgin asphalt cement required for HMAC mixtures as well as some of the fine aggregate. Asphalt shingle recycling dates back to the late 1970s and early 1980s when the first shingle recycling plants were developed and parallel work on HMAC mix designs incorporating RAS began (*Krivit and Associates 2007*). Since then, several HMAC producers have gained substantial in-house expertise in recycling asphalt shingles. Several state agencies have responded to the increased interest in using RAS in HMAC by allowing up to about 5 percent RAS, with several agencies allowing either manufacturer scrap or tear-off shingles obtained from re-roofing projects, but some allowing only manufacturer scrap. The low percentage of 5 percent RAS is principally due to RAS containing asphalt cement that is substantially stiffer (harder) than that used in typical

HMAC. Consequently, agencies remain cautious of its use since it may significantly affect the properties (e.g., stiffness and temperature susceptibility) of the blended binder if virgin binder grade adjustments are not made to account for the increased stiffness. 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.

Oregon's current standard specifications (*2008*) do not allow the use of RAS in HMAC mixtures. However, faced with legislative action under House Bill 2733, ODOT began investigating the use of RAS in HMAC in 2009. House Bill 2733, introduced before the 75th Oregon Legislature, contained language requiring that ODOT allow up to 5 percent RAS in HMAC on roadways under its jurisdiction and that ODOT establish (by administrative rule) specifications for HMAC mixtures containing RAS (*ODOT 2009*). With the use of RAP in HMAC already commonplace in Oregon, ODOT personnel were concerned that HMAC producers would include both RAP and RAS in HMAC mixtures if the bill was passed into law. The principal concern of ODOT personnel responsible for designing, constructing, and maintaining HMAC pavements was 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 personnel, the sponsor of House Bill 2733 agreed to postpone legislation on the bill until completion of a preliminary investigation of RAP and RAS in HMAC (*ODOT 2009*).

The preliminary investigation, conducted by Oregon State University, had the principal objective of determining how various proportions of RAP and RAS added to HMAC mixtures affect the Superpave Performance Grade of the blended binder, where the blended binder was RAS binder plus virgin binder or RAP and RAS binders plus virgin binder (*Scholz 2010*). Findings from laboratory investigations clearly indicated that inclusion of RAS or RAP and RAS in HMAC mixtures resulted in significant increases in both the high and low critical temperatures of the blended binders relative to the virgin binder (except for one combination of materials that included 5 percent RAS and 10 percent RAP). The increases in the critical temperatures correspondingly resulted in substantial increases in the Superpave Performance Grades of the blended binders (again, with the exception of the mixture containing 5 percent RAS and 10 percent RAP). The findings also revealed unexpected results from the blended binders from mixtures containing both RAP and RAS in that the degree of increase in critical temperatures was lower than anticipated in all cases, and insignificant for the blended binder from the mixture containing 5 percent RAS and 10 percent RAP.

A secondary objective of the preliminary investigation was to develop recommendations for changes to Oregon's standard specifications to allow use of RAS in HMAC mixtures. This second objective was included to satisfy the requirements for postponement of House Bill 2733. Based on the review of specifications and special provisions from several states that allow RAS in HMAC mixtures, in combination with the findings from the laboratory investigations, the final report for the study contains several proposed modifications to Oregon's standard specifications for HMAC mixtures containing RAS or RAP and RAS (*Scholz 2010*). The report also includes several recommendations for further investigation of including RAS in HMAC mixtures. These recommendations formed the basis for the follow-on study to the preliminary investigation reported herein.

1.2 PROBLEM STATEMENT

Until recently, ODOT has not considered the use of recycled asphalt shingles in hot mix asphalt concrete mixtures. Consequently, Oregon's current standard specifications (2008) do not include provisions for its use, nor does ODOT presently have standard procedures specific to the design and testing of mixtures containing RAS. In order to effectively allow the use of RAS in HMAC, likely in combination with RAP, on highways under ODOT's jurisdiction, it is in the best interest of the agency to develop standard procedures for:

- Selecting the grade of virgin binder to be used in HMAC containing recycled asphalt materials (RAS or RAP and RAS);
- Effectively and efficiently recovering asphalt binder from RAS;
- Effectively batching virgin materials (binder and aggregate) with RAS or RAP and RAS;
- Determining ignition oven calibration factors for HMAC mixtures containing RAS or RAP and RAS; and
- Quality control and quality assurance (QC/QA) monitoring of mixtures containing RAS or RAP and RAS.

Such procedures are necessary for mix design purposes, using ignition ovens for the purposes of verifying HMAC binder content and determining price adjustments, and for verifying the quality of mixtures containing RAS or RAP and RAS. Without these procedures, it would be difficult if not impossible for ODOT to enforce specifications allowing the use of RAS in HMAC.

1.3 OBJECTIVES

The objectives of this research effort were to develop recommendations for:

1. 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;
2. A procedure for effectively and efficiently recovering asphalt binder from recycled asphalt shingles;
3. A procedure for batching virgin materials (binder and aggregate) with RAP or RAS, or combinations of RAP and RAS, for mix design purposes and ignition oven tests;
4. A procedure for determining ignition oven calibration factors for HMAC mixtures containing RAS or RAP and RAS;
5. 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); and

6. Conduct a pilot study of projects incorporating RAS with the intent of evaluating QC/QA procedures including mix design verification, and to evaluate mixture performance.

1.4 SCOPE

This report documents findings from a literature review, a laboratory study, and two pilots studies. Section 2 synthesizes findings from published literature concerning incorporation of RAS in HMAC. Since RAP and RAS share some basic attributes, the literature review also includes findings from studies on HMAC containing RAP. Based on findings from the literature review, Section 3 documents a set of procedures proposed for further evaluation in this research effort. Taking into consideration the findings from the literature review and the proposed procedures, Section 4 documents the experiment plans developed for the laboratory and pilot studies undertaken to satisfy the objectives of this research effort. Section 5 presents the results while Section 6 provides an analysis of the results, and Section 7 discusses these. Section 8 provides the recommended procedures for use by ODOT, and Section 9 provides conclusions and recommendations based on the work presented herein.

2.0 LITERATURE REVIEW

A literature review was conducted primarily to assist in satisfying the objectives of this study. In particular, it was conducted to summarize the findings from studies covering the following:

1. Virgin binder grade selection procedures for mixtures containing RAS and/or RAP;
2. Procedures for recovering binder from RAS and RAP and from HMAC mixtures containing RAS and/or RAP;
3. Mix design procedures for mixtures containing RAS and/or RAP;
4. Procedures for calibrating ignition ovens for mixtures containing RAS and/or RAP; and
5. Quality control/quality assurance procedures for HMAC containing RAS and/or RAP.

The following sections provide a synthesis of the findings from the literature review.

2.1 VIRGIN BINDER GRADE SELECTION PROCEDURES

Recognition of the potential need to adjust the virgin binder grade for HMAC mixtures containing RAP or RAS has existed for well over a decade, with the adjustment intended to offset the stiffening effect caused by the aged RAP binder or air-blown RAS binder. Published documents covering virgin binder selection procedures for HMAC mixtures containing reclaimed asphalt materials were reviewed. Most were concerned with mixtures containing RAP. The following summarizes the findings from the most relevant documents.

2.1.1 Procedures for Mixtures Containing RAP

The FHWA Superpave Mixtures Expert Task Group developed guidelines outlining the proper means of incorporating RAP in Superpave mixtures (*Bukowski 1997*). Recommendations for selecting a virgin binder grade for HMAC containing various proportions of RAP, by weight of total mixture, include:

- For HMAC containing 15 percent or less RAP (Tier I), no change in the virgin binder grade is required.
- For HMAC containing 16 to 25 percent (Tier II), one grade lower than the virgin binder grade for both the high and low temperatures is recommended.
- For HMAC containing greater than 25 percent RAP (Tier III), selection of the virgin binder grade (for both temperatures) through use of blending charts is recommended.

As part of NCHRP Project 9-12, McDaniel and Anderson (*2001*) developed a technician's manual for use of RAP in Superpave-designed HMAC. It includes guidelines for selecting a

virgin binder grade based on the percentage RAP added to the mixture and the recovered RAP binder grade as shown in Table 2.1. It should be noted that these recommendations were derived from investigation of mixtures containing 0, 10, 20, and 40 percent RAP; hence, some of the threshold percentages shown in Table 2.1 were interpolated from the results.

Table 2.1: Binder Selection Guidelines for RAP Mixtures (adapted from McDaniel and Anderson 2001)

	RAP percentage, based on recovered RAP grade of:		
Recommended Virgin Asphalt Binder Grade	**PG xx-22 or lower**	**PG xx-16**	**PG xx-10 or higher**
No change in binder selection	<20%	<15%	<10%
Select virgin binder one grade softer than normal (e.g., select a PG 58-28 if a PG 64-22 would normally be used)	20-30%	15-25%	10-15%
Follow recommendations from blending charts	>30%	>25%	>15%

Three tiers of RAP usage are covered by the recommendations shown in Table 2.1. Note that the grades shown in the right portion of the table show the low-temperature components of the RAP binder grades and that higher percentages of RAP can be used with softer RAP binders. The top (first) tier indicates the maximum amount of RAP that can be used without changing the virgin binder grade. The middle (second) tier shows the maximum percentages of RAP that can be used when the virgin binder grade is decreased by one grade on both the high- and low-temperature components of the grade. The bottom (third) tier indicates that blending charts are necessary to determine the virgin binder grade for a given RAP binder grade and percentage of RAP.

If blending charts are used, the grade of the RAP binder must be determined. McDaniel and Anderson (*2001*) provide recommendations for accomplishing this, which predominately adhere to the procedures for determining a virgin binder grade as detailed in AASHTO R 29 (*AASHTO 2010*). That is, a portion of the recovered binder is tested as if it were unaged, and another portion is tested following accelerated aging in a rolling thin-film oven. However, the recovered binder is not aged in a pressure aging vessel prior to determining the intermediate or low critical temperatures. Also, critical temperatures are determined based on the slope of the binder stiffness (or m-value) versus temperature curves at the stiffness (or m-value) closely corresponding to the specification criterion for each test.

The technician's manual developed under NCHRP Project 9-12 also provides two procedures for developing blending charts as follows (*McDaniel and Anderson 2001*):

1. Method A: Blending at a known RAP percentage (virgin binder grade unknown)
2. Method B: Blending with a known virgin binder grade (RAP percentage unknown)

Method A would be used, for example, if a certain amount of RAP needed to be used on a project (say, to deplete a stockpile of millings), or the gradation and/or mix properties will limit

the amount of RAP that can be used. Method A might also be used when specifications limit the maximum amount of RAP that can be used in HMAC mixtures. In any case, the amount of RAP is chosen and, based on the RAP percentage and recovered RAP binder properties (critical temperatures), blending charts are used to determine the virgin binder grade needed to achieve a desired grade of blended binder.

Figure 2.1 provides an example blending chart using Method A to determine the high critical temperature of the virgin binder for a desired percentage of RAP and known recovered RAP binder properties (high critical temperature) to achieve a high critical temperature of 64°C (i.e., PG 64-xx). It is constructed by plotting the value for the high critical temperature of the RAP binder corresponding to 100 percent RAP (Point 1), plotting the value for the desired high critical temperature of the blended binder (i.e., 64°C) corresponding to the desired percentage of RAP (Point 2), and then extrapolating a line between these points to the vertical axis corresponding to 0 percent RAP (Point 3). The *minimum* high critical temperature of the virgin binder is represented by the point at which the line intersects the vertical axis (i.e., ordinate value of Point 3 in Figure 2.1). Hence, selection of a virgin binder grade of PG 58-xx is needed in order to achieve at least a PG 64-xx grade for the blended binder (selection of a virgin binder grade of PG 52-xx would result in a blended binder grade lower than a PG 64-xx). Determining the intermediate and low critical temperatures of the virgin binder is accomplished in similar fashion using the appropriate values for the intermediate and low critical temperatures of the recovered RAP binder and those desired for the blended binder.

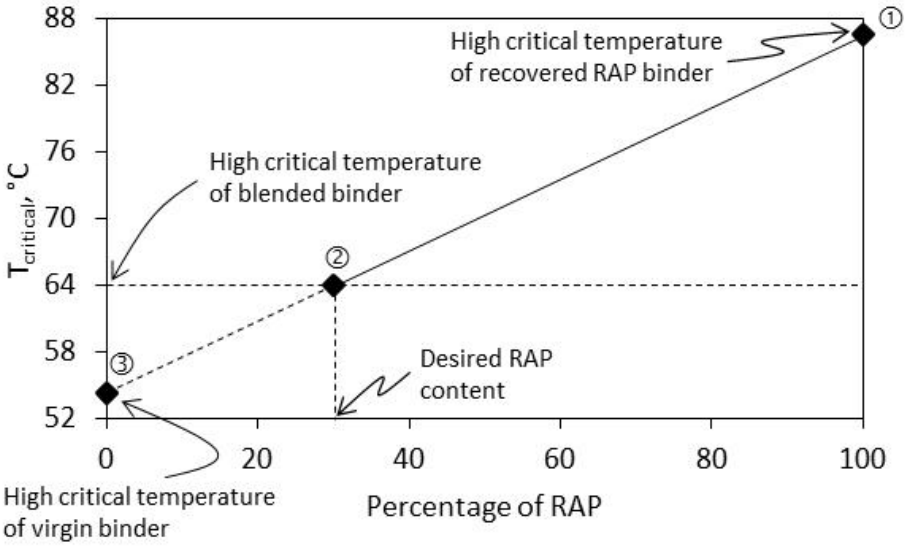


Figure 2.1: Example Blending Chart Using Method A (adapted from *McDaniel and Anderson 2001*)

As indicated in Figure 2.1, the high critical temperature of the blended binder is assumed to vary linearly between that of the virgin binder (0 percent RAP) and that of the recovered RAP binder (100 percent RAP). McDaniel and Anderson (*2001*) provide an equation for this relationship allowing direct calculation of the virgin binder critical temperature as shown in Equation 2.1. It can be applied to any of the three critical temperatures.

$$T_{Virgin} = \frac{T_{Blend} - (\%RAP \times T_{RAP})}{1 - \%RAP} \quad (2.1)$$

where:

T_{Virgin} = critical temperature of the virgin asphalt binder;
T_{Blend} = critical temperature of the blended asphalt binder;
%RAP = percentage of RAP expressed as a decimal; and
T_{RAP} = critical temperature of the recovered RAP binder.

Method B, on the other hand, would be used to determine the amount of RAP to be used in a mixture to achieve a target grade of the blended binder knowing the properties of the virgin and recovered RAP binders. Figure 2.2 provides an example of how to determine the RAP percentage to obtain a PG 64-xx grade for the blended binder. Note that the actual high critical temperature is plotted for the virgin binder, not the rounded temperature corresponding to the PG grade.

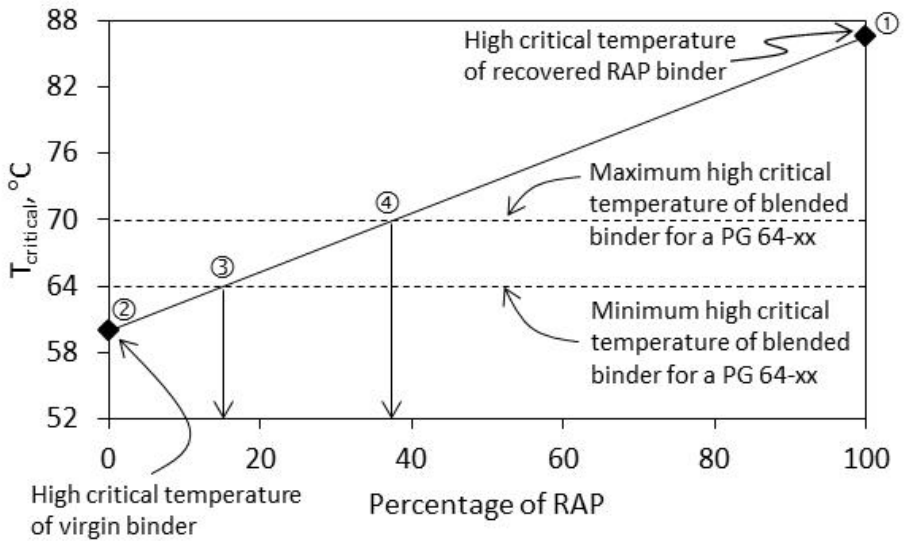


Figure 2.2: Example Blending Chart for Using Method B (adapted from *McDaniel and Anderson 2001*)

The chart is constructed by plotting the value for the high critical temperature of the RAP binder corresponding to 100 percent RAP (Point 1), plotting the value for the high critical temperature of the virgin binder corresponding to 0 percent RAP (Point 2), and drawing a line that connects these two points. Horizontal lines corresponding to the minimum and maximum critical temperatures for the desired blend binder grade are then drawn, and where these lines intersect with the sloped line connecting the two critical temperatures of the virgin and recovered RAP binders (Points 3 and 4), vertical lines are drawn downward to the horizontal axis to provide the percentages of RAP. The lower percentage represents the minimum amount needed to achieve the desired grade for the blended binder (i.e., a PG 64-xx in this example) and the higher percentage represents the maximum amount that can be added before the blended binder transitions to the next higher grade (i.e., a PG 70-xx in this example). Hence, from Figure 2.2, the range in the percentage of RAP to be added to the mixture so that the blended binder is

graded as a PG 64-xx is from approximately 17 percent to approximately 38 percent. Percentages based on the intermediate and low critical temperatures are determined in similar fashion and the final range in RAP percentage is determined by considering all three blending charts.

As is the case with Method A, in Method B the critical temperature of the blended binder is assumed to vary linearly between that of the virgin binder (0 percent RAP) and that of the recovered RAP binder (100 percent RAP). The percentage of RAP, therefore, can be determined directly through use of Equation 2.2 (*McDaniel and Anderson 2001*) as follows:

$$\%RAP = \frac{T_{Blend} - T_{Virgin}}{T_{RAP} - T_{Virgin}} \quad (2.2)$$

where:

%RAP = percentage of RAP expressed as a decimal;

T_{Blend} = critical temperature of the blended asphalt binder;

T_{Virgin} = critical temperature of the virgin asphalt binder; and

T_{RAP} = critical temperature of the recovered RAP binder.

Based on the work reported by McDaniel and Anderson *(2001),* the Superpave volumetric mix design specification detailed in AASHTO M 323 (*AASHTO 2010*) provides guidelines for virgin binder grade selection as shown in Table 2.2. The specification also contains detailed procedures for developing blending charts, based on the procedures documented by McDaniel and Anderson *(2001).*

Table 2.2: Binder Selection Guidelines for Reclaimed Asphalt Pavement (*AASHTO 2010*)

Recommended Virgin Asphalt Binder Grade	RAP Percentage
No change in binder selection	<15%
Select virgin binder one grade softer than normal (e.g., select a PG 58-28 if a PG 64-22 would normally be used)	15-25%
Follow recommendations from blending charts	>25%

Hajj et al. (*2007*) and Shrestha and Sebaaly (*2008*) document work funded by the Regional Transportation Commission (RTC) in Washoe County, Nevada to assessed the feasibility of using RAP in RTC projects and to develop guidelines for mix designs and quality control specifications. The researchers evaluated HMAC mixtures containing 15 and 30 percent RAP from three local sources (plant waste and RAP from two pavements following 15 and 20 years of service) blended with virgin aggregate and two virgin asphalt binders, a neat binder graded as PG 64-22 and a polymer-modified binder graded as PG 64-28NV, where the "NV" extension signifies that the binder was subjected to additional testing beyond that required by the AASHTO M 320 (Performance-Graded Asphalt Binder) specification (*AASHTO 2010*). As part of the research effort, the binders used in the study were evaluated to: 1) identify the grade of binder recovered from the RAP sources; 2) identify the required grades of the virgin binders to achieve the target binder grades; and 3) assess the effectiveness of using blending charts.

The recovered binders from the RAP sources were graded according to AASHTO M 320 (*AASHTO 2010*) by testing each RAP binder as original, after short-term aging through the rolling thin-film oven (RTFO), and after long-term aging through the pressure aging vessel (PAV). It should be noted that the two sources of RAP obtained from the pavements were aged in the same manner as the plant waste RAP in determining their grades. All three binders were graded as PG 82-16.

The required grades of the virgin binders to achieve the target binder grades were determined using the process described in the technician's manual developed under NCHRP Project 9-12 (*McDaniel and Anderson 2001*). Table 2.3 provides a summary of the outcomes of this process for the work reported by Hajj et al. (*2007*). As indicated, except for the target binder grade of PG 64-22 with RAP Source I (which was the plant waste RAP that had not experienced long-term, in-service aging like that of RAP Sources II and III), the required virgin binders for the mixtures with 15 percent RAP were determined (again, based on blending charts) to be one grade softer for the low-temperature component. Given that the recovered RAP binder was graded as a PG xx-16 for all three RAP sources, these results reinforce (in five of the six cases) the recommendations by McDaniel and Anderson (*2001*) shown in Table 2.1 for the low-temperature component, but not for the high-temperature component (i.e., the blending charts suggested use of a PG 64 whereas the recommendation from Table 2.1 suggests a PG 58).

Nevertheless, the researchers used the virgin asphalt binder grades shown in Table 2.3 to assess the effectiveness of using blending charts. To accomplish this, they compared the grades of binders obtained from: 1) blending virgin and recovered RAP binders; and 2) extracting and recovering binders from mixtures containing the RAP. Table 2.4, adapted from Hajj et al. (*2007*), summarizes the results of these efforts.

Table 2.3: Required Virgin Binder Grades for the Various RAP Sources and Contents (*Hajj et al. 2007*)

RAP	**Recovered RAP Binder Grade**	**Required Virgin Binder Grade (based on Blending Chart)**			
		Target Binder : PG664-22		T**arget Binder: PG64-28NV**	
		15% RAP	**30% RAP**	**15% RAP**	**30% RAP**
Source I	PG82-16	PG64-22	PG58-28	PG64-34	PG58-34
Source II	PG82-16	PG64-28	PG58-28	PG64-34	Pg58-34
Source III	PG82-16	PG64-28	PG58-28	PG64-34	PG58-34

Table 2.4: Summary of Results for Assessing the Effectiveness of Using Blending Charts (*Hajj et al. 2007*)

Target Binder Grade	RAP Source	Percent RAP in Mixture	Blending Chart Virgin Binder Grade[1]	Blended Binder Grade[2]	Extracted/ Recovered Binder Grade[3]
PG 64-22	I	15	PG 64-22	PG 64-22	PG 70-22
		30	PG 58-28	PG 64-22	PG 70-22
	II	15	PG 64-28	PG 64-22	PG 70-22
		30	PG 58-28	PG 64-22	PG 70-22
	III	15	PG 64-28	PG 70-22	PG 76-22
		30	PG 58-28	PG 64-22	PG 76-22
PG 64-28NV	I	15	PG 64-34	PG 64-34	PG 64-34
		30	PG 58-34	PG 64-34	PG 70-34
	II	15	PG 64-34	PG 64-34	PG 70-34
		30	PG 58-34	PG 64-28	PG 70-34
	III	15	PG 64-34	PG 64-34	PG 70-34
		30	PG 58-34	PG 64-28	PG 70-34

[1]Table 2.3

[2]Blended binders obtained by mixing virgin binders with those recovered from the RAP sources at their blending proportions; grades based on original (unaged) and RTFO-aged binder for high-temperature component, and RTFO-aged plus PAV-aged binders for intermediate- and low-temperature components.

[3]Blended binders obtained from extracting/recovering binders from mixtures containing the RAP; in determining the binder grades, the binders were not aged in the RTFO as they had been through the mixing process, but were aged in the PAV to simulate long-term aging.

Considering the targeted grade of PG 64-22, the results in Table 2.4 indicate that the low-temperature component of the blended binders was the same as the target grade in all cases. The high-temperature component of the blended binders was the same as the target grade in five of the six cases based on grades determined from the mixed binders, but one to two grades higher based on grades determined from the binders extracted/recovered from the mixtures. Based on these results alone (i.e., for the unmodified virgin binder), the effectiveness of the blending charts appeared to work well for the low-temperature component independent of the method for preparing blended binders. In most cases, the blending charts also suggested virgin binder grades to meet the target high-temperature component when the blended binders were prepared by mixing the virgin and RAP binders, but not when the blended binders were prepared by fabricating aggregate-binder mixtures and then extracting/recovering the blended binders.

Considering the polymer-modified binder with a target grade of PG64-28NV, the low-temperature component determined from tests on the mixed or extracted/recovered binders was one grade softer than the target in 10 of the 12 cases. The high-temperature component determined from tests on the mixed or extracted/recovered binders was on target in just over half of the cases and one grade harder for the remaining cases. Based on the test results obtained from the mixed binders, the blending charts correctly suggested virgin binder grades to meet the target high-temperature component in all six cases, but also suggested virgin binder grades that were one grade softer than necessary to meet the target low-temperature component in two-thirds of the cases. Considering the test results obtained from the extracted/recovered binders, the

blending charts suggested virgin binder grades that were one grade softer than necessary to meet the target low-temperature component in all six cases, and suggested a virgin binder grade one grade harder than necessary to meet the target high-temperature component in five of the six cases.

2.1.2 Procedures for Mixtures Containing RAS

Published literature specifically covering procedures for selecting the virgin binder grade for mixtures containing RAS was difficult to find. Most of the information found during the literature search regarding this topic came from specifications of states that allow RAS in HMAC. This revealed that limitations are typically placed on the quantity of RAS allowed so as to minimize the effects imparted by the stiffer RAS binder rather than specifying a specific procedure for determining a virgin binder grade to be used with RAS.

Nevertheless, the literature search uncovered AASHTO Provisional Practice PP 53 (*AASHTO 2010*) which does specifically contain a virgin binder grade selection procedure for mixtures containing RAS. The procedure in AASHTO PP 53 makes use of the blending chart approach documented in AASHTO M 323 (*AASHTO 2010*) for blending at a known RAP percentage; basically, Method A as proposed by McDaniel and Anderson (*2001*). Two important differences in the methodology are incorporated in AASHTO PP 53 as follows:

1. Blending charts are based on percentage of binder replacement; and

2. The practice includes a procedure for estimating the contribution of the shingle asphalt binder to the final blended binder.

With regard to the first difference listed, the percentage of RAP in the procedure documented in AASHTO M 323 appears to be the percentage of RAP *by weight of aggregate* or *by total weight of mixture*. The same can be said of the procedure documented by McDaniel and Anderson (*2001*), on which the procedure in AASHTO M 323 is based. In either case, the basis for the percentage of RAP is not explicitly stated but, based on the language used, this appears to be the case. In AASHTO PP 53, which utilizes the methodology proposed by McDaniel and Anderson (*2001*) but adapted for RAS, the selection of a virgin binder grade is based on the desired grade of blended binder, the critical temperatures of the binder extracted and recovered from the RAS, and the percentage of RAS binder in the final blended binder (or, stated another way, the percentage of virgin binder replaced by RAS binder).

With regard to the second difference listed above, the procedure documented in AASHTO PP 53 includes a factor referred to as the *shingle asphalt binder availability factor* that can be used to adjust the percentage of shingle asphalt binder present in the final blended binder. A similar factor does not exist in the procedure documented in AASHTO M 323. The shingle asphalt binder availability factor can be used, for example, to account for differences in the percentage contribution of binder from coarse-ground or fine-ground (or fractionated) RAS, where a higher percentage contribution would be expected from finer RAS grindings (or RAS with a smaller maximum size). AASHTO PP 53 provides a procedure for estimating the shingle asphalt binder availability factor.

2.2 EXTRACTION/RECOVERY OF ASPHALT BINDER FROM RAS

Button et al. (*1995*) investigated the performance of HMAC mixtures containing RAS. During this investigation, RAS binder was recovered using the Abson recovery method. McDaniel et al. (*2000*) recommended two methods to recover RAP binder: 1) modified AASHTO TP 2, and 2) the combination of centrifuge extraction (AASHTO T 164 Method A) and rotavapor recovery (ASTM D 5404). McDaniel et al. (*2000*) preferred the modified AASHTO TP 2 method because of good repeatability and efficient filtration. Huang et al. (*2005*) used a combination of AASHTO T 164 and AASHTO T 170 to extract/recover RAP binder, whereas McGraw et al. (*2007*) used a combination of AASHTO T 164 Method A and ASTM D-5404 to extract /recover RAS binder.

Al-Qadi et al. (*2009*) recommended the recovery of the RAP binder using AASHTO TP 2. They proposed a few modifications to improve recovery of binder from the recovery flask by inverting it over a tin and placing it in oven at 302°F for 15 minutes, followed by 347°F for another 10 minutes.

Mehta (*2009*) conducted a detailed literature review of methods to efficiently extract and recover binder from RAP. From this Mehta provided advantages and disadvantages as shown in Tables 2.5 and 2.6, and recommended a combination of AASHTO T 164 and ASTM D 5404.

In separate studies, the University of Nevada, Reno investigated the impact of RAP in HMAC mixtures for the purposes of developing mix design guidelines and quality control specifications (*Hajj et al. 2007*), and the addition of RAP in HMAC mixtures for airport pavements (*Hajj et al. 2008*). In both studies, extractions and recoveries were accomplished using AASHTO T 164 Method A and ASTM D 5404.

Maupin et al. (*2008*) studied the impact of increasing the RAP percentage in HMAC. The detailed investigation showed no significant impact on the performance of the mixture due to increased RAP content. Binder recoveries were conducted in accordance with the Abson recovery method (AASHTO T 170).

Table 2.5: Summary of Extraction Methods (reproduced from *Mehta 2009*)

Extraction	Method	Solvent	Advantage	Disadvantage
Centrifuge	A	Cold	• Simple test • Widely practiced • Can be used for binder properties	• Leaves 4% binder
Reflux	B C D	Hot	• Widely practiced	• Aging effects from high temp • Causes hardening of binder • Leave too much binder • Should not be used for binder properties
Vacuum	E	Cold	• No aging from high temp	• Not much is known
SHRP	-	Cold	• Leaves 1% binder • No aging from high temp • Can be used for binder properties	• Labor intensive test • Costly (vessel machining/ owner supply)

Table 2.6: Summary of Method Used to Recover Binder (reproduced from *Mehta 2009*)

Recovery	Advantage	Disadvantage
Abson	Widely practiced (1930s) Less costly procedure	Leaves residual solvent (lowers stiffness) Skewed binder properties High energy (ages binder) Labor intensive
Rotary Evaporator	Widely practiced (1970s) Less heat (less aging of binder) Mixes for a uniform binder consistency Less labor intensive	Aging effects from high temp

2.3 BATCHING/MIXING PROCEDURES

The literature search uncovered minimal information regarding detailed procedures for batching and mixing laboratory-prepared mixtures incorporating RAS. Tighe, et al. (*2008*) document a laboratory investigation of mixtures with and without RAP and RAS, but they do not include detailed procedures of how the mixtures were fabricated in the laboratory. However, they do indicate that agglomeration of processed shingles is the largest construction concern created by using RAS, and offer the following as ways to minimize this problem:

> "*Agglomerated shingles result in poor shingle dispersion in the mix and can be avoided by either shredding shingles immediately prior to mixing; or combining RAS with fine aggregate; or blending with RAP (where permissible) if the RAS will not be used immediately*".

Given that agglomeration of RAS has been identified as a serious concern during the construction process, it will almost certainly be a concern in fabricating laboratory-prepared specimens containing RAS. Hence, a laboratory procedure for batching and mixing specimens containing RAS should take this into consideration.

Johnson et al. (*2010*) document research sponsored by the Minnesota Department of Transportation consisting of extensive laboratory testing and evaluations of in-service pavements containing RAP and RAS. The report contains details of how mixtures containing RAS were prepared in the laboratory, which are summarized as follows:

1) Virgin aggregate and RAP were fractionated as follows:
    - Virgin aggregate was split on the No. 8 sieve and the portion with size greater than the No. 8 sieve (i.e., coarse fraction) was further separated into individual sizes.
    - RAP was split on the No. 4 sieve and the portion with size greater than the No. 4 sieve (i.e., coarse fraction) was further separated into individual sizes.

      NOTE: Both manufacturer waste and tear-off shingles were investigated, but neither were split or fractionated. However, both were of a relatively fine grading with 100 percent of the manufacturer waste shingles passing the 3/8-in. sieve and 100 percent of the tear-off shingles passing the No. 4 sieve.

2) Batching appears to have been accomplished as follows:

   - The separated fractions were recombined into the proper proportions for each blend investigated. Batch weights of the RAP were adjusted to account for the weight of binder on the RAP particles. Although not explicitly stated, it appears that the RAP fractions were combined with the virgin aggregate fractions.

   - The RAS was blended with the sand (i.e., fine aggregate fraction). Although not explicitly stated, it is assumed that the weight of binder on the RAS particles was taken into account when weighing the amount of RAS added.

3) The report provides a more detailed account of the mixing procedure, summarized as follows:

   - The virgin aggregate and RAP were preheated to 315°F (157°C) for 4 to 5 hours. Unfortunately, the report does not provide details of how this temperature was determined; for example, corresponding to a kinematic viscosity of 170 ± 20 mm^2/s for the unaged virgin binder as specified in AASHTO T 312 (*AASHTO 2010*).

   - Although not explicitly stated, it is assumed that the blend of RAS and fine aggregate was also preheated to the same temperature since the report indicates these materials had been blended "prior to preheating."

   - Using a Lancaster Batch Mixer, the aggregate blend was mixed for one to two minutes before introduction of virgin binder.

   - With mixer still rotating, virgin binder was then added and the blend was mixed for an additional two minutes.

4) Following mixing, the mixtures were conditioned (short-term aged) for two hours in an oven at a temperature of 275°F (135°C).

5) Following short-term aging, the mixtures were compacted in a gyratory compactor to produce specimens used for further evaluation.

Having difficulty in locating published literature providing explicit details regarding batching and mixing procedures for mixtures containing RAS, literature providing details of procedures for mixtures containing RAP was sought and only a few were found. Two of particular note are discussed in the following paragraphs.

NCHRP Report 452 (*McDaniel and Anderson, 2001*) includes details for developing batch quantities for mixtures containing RAP and provides recommendations for handling RAP in the laboratory. In the former regard, they stress the importance of adjusting RAP batch weights to account for the amount of binder on the RAP particles as well as fractionating the various materials and then recombining them to the proper proportions. They also provide an illustrative example for accomplishing a batch plan for mixtures containing RAP as well as a step-by-step mix design procedure.

With regard to handling RAP in the laboratory, McDaniel and Anderson (*2001*) indicate that RAP must be heated to make it workable enough to mix with virgin materials and recommend a heating temperature of 110°C (230°F) for no more than two hours for sample sizes from 1 to 2 kilograms. They further recommend that virgin aggregate should be heated to 10°C (18°F) above the mixing temperature prior to mixing with virgin binder. Aside from this, there are few details regarding a recommended mixing procedure except that they state, "…the mix components should be mixed, aged, and compacted as usual."

Al-Qadi et al. (*2009*) document the results of a laboratory study sponsored by the Illinois Department of Transportation that investigated the usable residual asphalt binder in RAP. To address the inherent variability in RAP stockpiles due to issues such as the stockpile being comprised of RAP from more than one pavement layer and/or from different pavements, contaminated with joint sealants, fabrics, or other materials, agglomeration of RAP particles, etc., the researchers fractionated the RAP prior to batching and mixing. The procedure described is much like an ordinary sieve analysis on virgin aggregate except that the analysis was conducted on the RAP (i.e., coated particles) to determine an "apparent gradation," which was subsequently used for batching purposes. The authors emphasize that the apparent gradation of a RAP sample is very different from the gradation of aggregate recovered from the same sample and therefore should not be used for job mix formula calculations but, nevertheless, can be used for batching purposes. Unfortunately, the report does not provide details regarding the mixing process utilized except to indicate that the mixtures were compacted with 50 gyrations to produce test specimens with an air void content of 4.0 percent. Nevertheless, the researchers concluded that, "Fractionation of the RAP stockpiles into four fractions for mix designs of laboratory prepared specimens produced excellent quality control."

Aside from the literature synthesized above, no other published literature was found that provided detailed procedures for batching and mixing HMAC with RAP and/or RAS. There are, of course, established standard procedures for preparation of HMAC specimens—for example, AASHTO T 245, T 247 and T 312 (*AASHTO 2010*)—but these do not include provision for incorporating reclaimed materials such RAP and/or RAS. Irrespective, the basic procedures described in these standards can form the basis for developing a detailed procedure for batching and mixing HMAC mixture specimens that contain RAP and/or RAS.

Provisional test method ODOT PTM 1 (*ODOT 2011*), on the other hand, does specifically address incorporation of RAP when preparing HMAC mixtures in the laboratory. It describes techniques to combine virgin aggregate with RAP so as to closely emulate a blend of these materials that would be produced by a full-scale plant. It covers batching procedures for mix design purposes as outlined in the ODOT Contractor Mix Design Guidelines. The procedures may also be used for fabricating proficiency samples as required by the ODOT Quality Assurance Program and for preparing samples for determining ignition oven calibration factors as per ODOT TM 323 (*ODOT 2011*).

It is prudent to also point out that provisional practice AASHTO PP 53-09 (*AASHTO 2010*) provides guidance for designing new HMAC mixtures that incorporate RAS. It does not contain detailed batching and mixing procedures, but offers relevant design considerations that can be summarized as follows:

- The designer must take into account the percentage and gradation of aggregate contained in the RAS and adjust the gradation of the virgin aggregate, if necessary, to meet the overall gradation requirements of the HMAC mixture.

- The size of the RAS (i.e., maximum particle size) can be expected to affect the amount of binder released from the RAS and, therefore, the proportion of reclaimed binder comprising the final blended binder. The provisional practice indicates that RAS ground to a size passing the No. 4 (4.75-mm) sieve can be expected to release more binder than RAS ground to a size passing the 1/2-in. (12.5-mm) sieve; up to 95 percent as opposed to 20 to 40 percent, respectively. The amount of binder released by the RAS can, therefore, affect the quantity of virgin binder required.

- During production of HMAC containing RAS, the asphalt binder released by the RAS will mix with the virgin binder resulting in a blended binder with properties that can be considerably different from those of the virgin binder. The provisional practice offers a threshold of 30 percent (by mass) of reclaimed binder, above which the properties of the blended binder (virgin plus reclaimed binder) may be measurably different from the desired (design) properties (i.e., performance grade) of the binder specified for the HMAC mixture.

Hence, the provisional practice emphasizes the importance of accounting for aggregate gradation of the RAS, the maximum size of the ground RAS particles, and the influence of the RAS binder on the properties of the blended binder. Accounting for the aggregate gradation of the RAS has obvious implications when developing a batching plan, whereas all three considerations will have some effect on mixing RAP and virgin materials.

2.4 IGNITION OVEN CALIBRATION

The measured binder contents obtained from ignition oven tests are usually higher than the true binder contents due to loss of aggregates (*Zhang 1996*). Hence, an adjustment is made to the binder content obtained from ignition oven testing through use of an ignition oven calibration factor. This section summarizes findings from other researchers regarding calibration factors as well as information regarding their accuracy.

Early work by Antrim and Busching (*1969*) showed the need for calibrating ignition ovens. They burned 1000-gram HMAC samples at 843°C (1550°F) for 30 minutes and determined binder content based on sample weight before and after ignition. They found that a much higher loss resulted when the mixtures contained limestone as opposed to granite gneiss. They found errors up to approximately 1 percent, but concluded that typical ranges were ±0.25 to ±0.50 percent, depending on aggregate type.

Yu (*1992*) developed a procedure using lower temperatures in a small muffle furnace that significantly reduced aggregate loss and increased the accuracy of determining binder content, but required 4.5 hours to complete. This work utilized a 600-gram sample and Equation 2.3 for determining binder content of HMAC samples. Using this approach, aggregate weight loss was shown to increase the measured binder content by up to 0.4 percent above the actual binder content.

$$P_m = \left(\frac{W_m - W_t}{W_m} \right) \times 100 \quad (2.3)$$

Where:

P_m = measured binder content, percent, by weight of mixture
W_m = weight of the HMAC mixture before burning, and
W_t = aggregate weight after burning

Brown and Murphy (*1994*) extended Yu's work by doubling the sample sizes to 1,200 grams and burning these in a programmable ignition oven set to 593°C. The larger sample size resulted in increased accuracy of the residual aggregate gradation and reduced testing time to 2 hours. They also modified Yu's equation to include masses rather than weights as shown in Equation 2.4. They determined ignition oven calibration factors by burning three samples of known binder content and calculating the differences between the known binder content and the average of the three measured binder contents. Using this approach, they found deviations from the true binder contents of ±0.3 percent.

$$P_m = \left(\frac{M_m - M_t}{M_m} \right) \times 100 \quad (2.4)$$

Where:

P_m = measured binder content, percent, by mas of mixture
M_m = mass of the HMAC mixture before burning, and
M_t = aggregate mass after burning

In a publication discussing the historical developments of determining asphalt binder contents by the ignition oven method, Brown et al. (*1995*) concluded that the method can be used successfully to accurately determine binder contents, and laboratory work showed these to be as good as binder contents determined from extraction methods. They also concluded that calibrations are needed for some aggregates to accurately determine binder contents, but not necessary for aggregate gradation.

McKeen (*1997*) investigated the precision of the ignition oven method to determine the binder content of HMAC and found it to be significantly comparable to the reflux extraction and nuclear gauge methods. Based upon these findings, ignition oven was recommended to determine the binder content of HMAC mixtures.

Prowell (*1996*) investigated various methods for determining the binder content of HMAC mixtures with four types of aggregates (Shadwell Greenstone, Grottoes River Gravel, Boscobel Granite/Gneiss, and Bluefield Limestone) and at different binder contents. Tests on surface mixtures indicated that the error associated with ignition oven tests was less than all other methods investigated except for that associated with an ashing furnance (Table 2.7). Statistical comparisons (Table 2.8) showed that the differences between binder contents obtained from

ignition ovens and the reflux extraction method were not significant. Table 2.9, however, indicates that aggregate type influences the magnitude of the ignition oven calibration factor.

Table 2.7: Summary of Results by Test Method for Surface Mixture Specimens (*Prowell 1996*)

Test Method	Number of Observations (n)	Standard Deviation, AC, %	Bias AC, %	Absolute % Error	MSE
Reflux Extraction	23	0.290	-0.113	5.16	0.0969
Nuclear Gauge	108	0.140	0.070	2.51	0.0245
Muffle Furnace	12	0.203	-0.439	9.09	0.2339
AshingFurance (HOT)	10	0.152	-0.007	2.51	0.0232
Ashing Furnace (COLD)	5	0.057	0.006	1.12	0.0033
Ignition Furnace	24	0.110	-0.033	1.50	0.0132

Table 2.8: Results of t-tests and F-test for Mean Difference between Ignition Methods and Reflux Extraction Method for Asphalt Content Determination (*Prowell 1996*)

Test Method	n	Mean (%)	Standard (%)	T-Test		F-Test	
				Result	Prob> |T|	Result	Prob> |T|
Reflux	12	5.21	0.378	NA	NA	NA	NA
Ashing Furnace	12	5.42	0.313	NS	0.17	NS	0.27
Ignition Furnace	12	5.29	0.367	NS	0.61	NS	0.46

Table 2.9: Ignition Furnace Calibration Factor by Aggregate Type for Base Mixture Specimens (*Prowell 1996*)

Aggregate Source	**Mix Calibration Factor (AC, %)**
Shadwell Greenstone	-0.15
Grottoes River Gravel	-0.52
Boscobel Granite/Gneiss	-0.06
Bluefield Limestone	+0.05

Prowell (*2002*) investigated the impact of different types of ignition ovens (infrared and Standard Thermolyne) on the calibration factor of binder content due to aggregate loss. A number of mixtures were prepared with different sources of aggregates including granite, crushed gravel, limestone, and dolomite at two binder contents. Table 2.10 provides the summary of the correction factors determined using two types of ignition ovens. It was concluded that each method needs its own calibration factor (*Prowell 2002*).

Table 2.10: Correction Factors for Aggregate Loss (*Prowell 2002*)

Mixture	Aggregate Correction Factor, %	
	Standard Furnace	Infrared Furnace
9.5 mm NMAS Granite	0.07	0.01
9.5 mm NMAS Crushed Gravel	0.11	0.03
9.5 mm NMAS Limestone	0.24	0.14
9.5 mm NMAS Dolomite	0.66	0.51
19.0 mm NMAS Granite	-0.03	-0.13
19.0 mm NMAS Crushed Gravel	-0.02	0.04
19.0 mm NMAS Limestone	0.19	0.16
19.0 mm NMAS Dolomite	0.55	0.40

Table 2.11 summarizes the effect of the two types of ignition oven in term of accuracy (bias) and variability (standard deviation). It was found that measured binder content using two ignition types were very close to the actual values.

Table 2.11: Summary of Measured Asphalt Contents, Bias & Standard Deviations by Furnace (*Prowell 2002*)

Aggregate	NMAS	Actual P_b	Measured P_b			Bias (Measured – Actual)			Avg. Bias	Std. Dev.
			1	2	3	1	2	3		
Standard Furnace										
Dolomite	9.5	5.0	5.05	4.51	5.07	0.05	-0.49	0.07	-0.12	0.3177
Dolomite	19	4.3	4.24	4.22	4.24	-0.06	-0.08	-0.06	-0.07	0.0115
Granite	9.5	5.8	5.84	5.75	5.74	0.04	-0.05	-0.06	-0.02	0.0551
Granite	19	4.7	4.78	4.77	4.73	0.08	0.07	0.03	0.06	0.0265
Gravel	9.5	5.2	5.14	5.15	5.22	-0.06	-0.05	0.02	-0.03	0.0436
Gravel	19	4.7	4.76	4.81	4.70	0.06	0.11	0.00	0.06	0.0551
Limestone	9.5	4.2	4.17	4.09	4.17	-0.03	-0.11	-0.03	-0.06	0.0462
Limestone	19	4.2	4.15	4.21	4.09	-0.05	0.01	-0.11	-0.05	0.0600
								Avg.	-0.0292	0.0770
Infrared Furnace										
Dolomite	9.5	5.0	4.98	4.95	4.97	-0.02	-0.05	-0.03	-0.03	0.0153
Dolomite	19	4.3	4.29	4.30	4.27	-0.01	0.00	-0.03	-0.01	0.0153
Granite	9.5	5.8	5.78	5.77	5.70	-0.02	-0.03	-0.10	-0.05	0.0436
Granite	19	4.7	4.77	4.83	4.72	0.07	0.13	0.02	0.07	0.0551
Gravel	9.5	5.2	5.19	5.22	4.93	-0.01	0.02	-0.27	-0.08	0.1595
Gravel	19	4.7	4.68	4.70	4.50	-0.02	0.00	-0.20	-0.07	0.1102
Limestone	9.5	4.2	4.06	4.15	4.14	-0.14	-0.05	-0.06	-0.08	0.0493
Limestone	19	4.2	4.02	4.16	4.02	-0.18	-0.04	-0.18	-0.13	0.0808
								Avg.	-0.0479	0.0661

Prowell and Hurley (*2005*) investigated the accuracy of determining binder contents of mixtures containing high-loss aggregates (i.e., those that tend to lose mass excessively during ignition) from various sources and using four types of ignition ovens. They found considerable variation in correction factors for the four types of ovens investigated as illustrated in Figure 2.9.

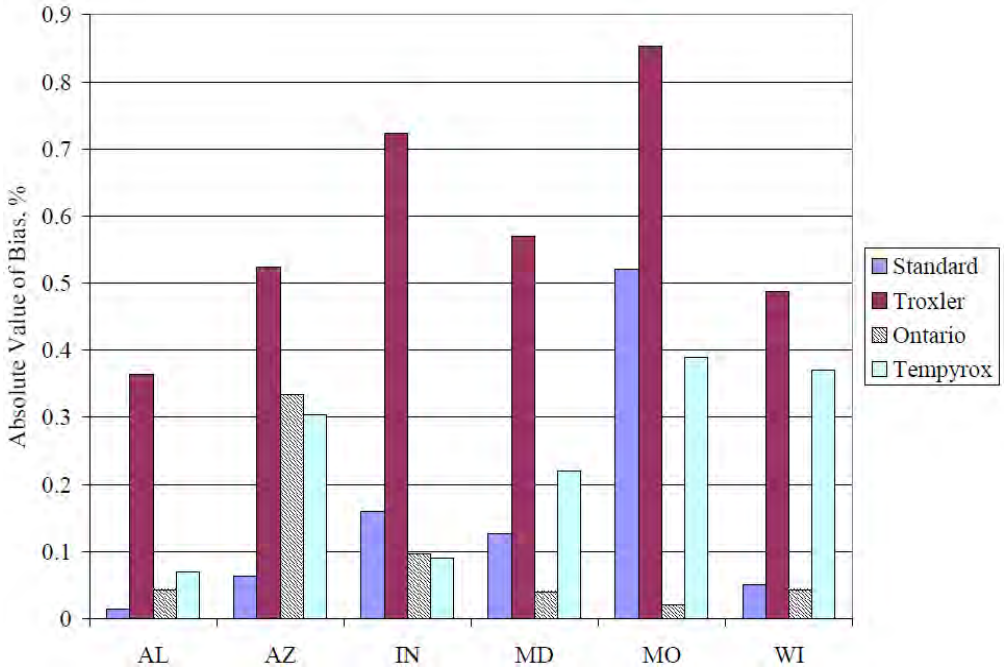


Figure 2.3: Summary of Correction Factors Bias (*Prowell and Hurely 2005*)

In the work by Brown and Murphy (*1994*) cited earlier, determining the binder content of RAP RAP using ignition ovens was also investigated. They used the average of four samples burned in ignition ovens to determine binder contents and compared the results with those determined using centrifuge extractions and nuclear gauge measurements. As indicated in Table 2.12, they found the binder content of the RAP to be approximately 0.5 percent higher than the binder contents determined using the other two methods.

Table 2.12: Comparison of Binder Content of HMAC Containing RAP Using Ignition Oven, Extraction and Nuclear Gauge Methods (*Brown and Murphy 1994*)

Project 3 – Test Variable: Measured AC Content					
Method	No. of Samples	Job Mix AC Content, percent	Average Measured AC Content, percent	Standard Deviation	SNK Grouping*
NAC Gauge	12	5.35	5.32	0.127	B
Ignition	12	5.35	5.87	0.337	A
Centrifuge	12	5.35	5.37	0.452	B
*Measured AC contents with the same letter are not significantly different at the 96 percent level of confidence					

Zhang (*1996*) carried out research to investigate the use of ignition ovens for the determining binder content of HMAC mixtures containing RAP. This work involved evaluation evaluating the performance of the ignition method for mixtures with RAP and developing a combined correction factor for these mixtures. In this study, the concept of a combined aggregate loss factor (weight loss factor) was introduced for mixtures with multiple aggregate types, or RAP, as shown in Equation 2.5.

$$p_c = p_m - \frac{rW_{AF}}{W_T} \quad (2.5)$$

Where:

p_c = corrected binder content of a mixture
p_m = measured binder content of a mixture by ignition method
r = weight loss factor, proposed test procedure
W_{AF} = weight of mineral aggregate remaining after ignition
W_T = total weight of mixture

Finally, ignition oven calibration procedures of the state agencies allowing RAS were reviewed. Appendix A summarizes the findings obtained from this effort.

2.5 QC/QA PROCEDURES FOR RAP AND/OR RAS

McDaniel et al. (*2000*) recommended no changes in QC/QA test procedures or the sampling process for mixtures with RAP. However, they recommended a higher sampling frequency for the purposes of monitoring compliance with the design gradation. They also encouraged careful processing and stockpiling of RAP to reduce variability.

King County Solid Waste Division (*KCSWD 2008*) developed specifications for RAS used in the HMAC for an overlay project constructed in 2009. The specifications included construction material quality control and verification testing. Aside from prescribing additional testing to determine if asbestos was present in the RAS derived from tear-off shingles, the specifications stipulated existing procedures. Specifically, these included test methods contained in the Materials Manual from the Washington State Department of Transportation (*WSDOT 2008*) for sampling RAS and determining the binder content, moisture content, and gradation of the RAS, all of which are slight variations of AASHTO procedures. Of particular note, the specifications stipulated use of AASHTO T 164 or T 308 (or both) for determining the binder of RAS.

Appendix B contains a summary of relevant information derived from specifications of various state agencies that allow RAS in HMAC. Again, aside from some agencies requiring additional testing to determine if asbestos is present in RAS, all of these stipulated existing test methods for RAS and mixtures with RAS. The summary does, however, indicate that sampling frequencies vary widely among agencies.

3.0 PRELIMINARY PROCEDURES

Prior to recommending procedures for use by ODOT, a task was undertaken to select a set of preliminary procedures, based on the findings from the literature review, for further evaluation in this project. This section provides a summary of the procedures selected, while Section 8 provides final recommendations based on further evaluation.

3.1 VIRGIN BINDER GRADE SELECTION PROCEDURE

AASHTO PP 53 (*AASHTO 2010*) was the only procedure found in the literature that specifically accounts for RAS binder properties when selecting a virgin binder grade for mixtures containing RAS. The approach utilizes blending charts in similar manner as that proposed by McDaniel and Anderson (*2001*), and documented in AASHTO M 323 (*AASHTO 2010*), except that percentage of binder replacement is used when constructing the charts (in lieu of percentage by weight of aggregate or mixture).

The other "procedures" found in the literature were actually prescriptive specifications that placed limitations on the quantity (by weight) of RAS allowed in mixtures so as to minimize the effects of the RAS binder. None were found to take into account the properties of the RAS binder.

For the purposes of this study, the procedure detailed in AASHTO PP 53 (*AASHTO 2010*) was selected for further evaluation.

3.2 RAS BINDER EXTRACTION/RECOVERY PROCEDURE

Section 2.2 indicates that a variety of procedures have been used to extract and recover binders from RAP as RAS. Several recommend a modified version of AASHTO TP 2, while the majority recommend AASHTO T 164 Method A (centrifuge method) for extraction and ASTM D 5404 (rotavapor method) for recovery. It is noted, however, that some prefer AASHTO T 170 (Abson method) for recovery. After consultation with ODOT personnel, the methods chosen for use and further evaluation in this study were AASHTO T 164 Method A for extraction and ASTM D 5404 for recovery.

3.3 BATCHING AND MIXING PROCEDURES

As indicated in Section 2.3, the literature review uncovered minimal information regarding explicit batching procedures for mixtures containing RAS, but it did reveal that established standard procedures do exist for batching HMAC without reclaimed materials, and NCHRP Report 452 (*McDaniel and Anderson 2001*) specifically takes into account incorporation of RAP. Taking into consideration the procedures contained in AASHTO T 245, T 247 and T 312 (*AASHTO 2010*), as well as in NCHRP Report 452 (*McDaniel and Anderson 2001*), the

preliminary procedures detailed in the following sections were developed for the purposes of this research effort.

3.3.1 Batching

The following batching procedure was developed for this research project. It includes steps for determining the binder content and residual aggregate gradation for each reclaimed material included in the mixture, and using these to determine batch quantities. The residual aggregate gradations are used in combination with virgin aggregate stockpile gradations to establish stockpile percentages that, when combined, match a target gradation (e.g., design aggregate structure) within acceptable tolerances. Reclaimed material batch quantities are determined taking into consideration the residual aggregate batch percentages (i.e., percentages of individual size fractions defined by the target gradation), total mass of aggregate for a given batch (or total mass of mixture for a given batch), and the binder content of each reclaimed material (or fractions thereof). The quantity of virgin binder to add to the batch is determined by subtracting the quantity of reclaimed binder from the total quantity of binder for the batch (i.e., it assumes that 100 percent of the reclaimed binder will contribute as binder in the mixture).

Batching Virgin Aggregate with Reclaimed Materials

Prepare and batch materials comprised of virgin aggregate and reclaimed materials (RAP, RAS, or RAP and RAS) as follows:

1. Determine the gradation of each virgin aggregate stockpile to be used in the mixture per AASHTO T 27 and T 11.
2. Determine the binder content (percent by total weight of mixture) of each reclaimed material (or fraction of each reclaimed material) to be used in the mixture per AASHTO T 308. If the mixture is to contain both RAP and RAS, designate the binder contents as $(P_{br})_{RAP}$ and $(P_{br})_{RAS}$, respectively. If the RAP and/or RAS are fractionated, designate each binder content so as to clearly distinguish each from one another (e.g., $(P_{br})_{CoarseRAP}$, $(P_{br})_{FineRAP}$, etc.).
3. Determine the gradation of the residue aggregate from each reclaimed material (or fraction of each reclaimed material) per AASHTO T 30.
4. Establish a trial target gradation (i.e., design aggregate structure) for the mixture.
5. Establish a trial binder content (P_b) for the mixture (percent by total weight of mixture).
6. Establish the trial stockpile percentage for each reclaimed material to be used in the mixture taking into account the restrictions for these percentages per ODOT Standard Specifications.
7. Develop a batch plan utilizing the aggregate gradations for each virgin aggregate stockpile and the residual aggregate gradations and percentages for each reclaimed material (or for each fraction of reclaimed material) such that the gradation of the blended aggregates (i.e., combined aggregate gradation) meets the trial target gradation within acceptable tolerances for any given sieve size. Accomplish this by iteratively adjusting the percentages of the virgin aggregate stockpiles (i.e., coldfeed percentages) while

holding the percentage(s) of the reclaimed material stockpile(s) constant. It may be necessary to also adjust the percentages of the reclaimed material stockpile(s) if the target gradation cannot be met (within acceptable tolerances) by adjusting only the percentages of the virgin aggregate stockpiles. The basic equation for accomplishing this is as follows:

$$P_i = \sum_{j=1}^{n} \left[p_{i_j} \times \frac{P_{S_j}}{100} \right] \tag{3.1}$$

Where:

P_i = percent of a given size fraction (e.g., 3/4" × 1/2") as a result of combining all stockpiles; where i represents the i^{th} size fraction in the target gradation

p_{ij} = percent of a given size fraction (e.g., 3/4" × 1/2") from a given stockpile (e.g., percent retained on the 1/2" sieve from the 3/4" - #4 stockpile)

P_{Sj} = stockpile percentage; $\Sigma P_{Sj} = 100$ percent, j = 1 to n

n = total number of stockpiles

Once the stockpile percentages are determined, the masses of individual size fractions from each stockpile are determined using the following equations:

Virgin aggregates or residual aggregates from reclaimed materials:

$$m_{i_j} = {}^{p_{i_j}}\!/_{100} \times {}^{P_{S_j}}\!/_{100} \times M_A \tag{3.2a}$$

or

$$m_{i_j} = {}^{p_{i_j}}\!/_{100} \times {}^{P_{S_j}}\!/_{100} \times \left[1 - {}^{P_b}\!/_{100}\right] \times M_T \tag{3.2b}$$

Reclaimed material batch mass adjusted to account for binder mass (NOTE 1):

$$m_{i_j} = \frac{\left[{}^{p_{i_j}}\!/_{100}\right] \times \left[{}^{P_{S_j}}\!/_{100}\right] \times M_A}{100 - [\![(P]\!]_{br})_{RAM_j}} \times 100 \tag{3.3a}$$

or

$$m_{i_j} = \frac{\left[{}^{p_{i_j}}\!/_{100}\right] \times \left[{}^{P_{S_j}}\!/_{100}\right] \times \left[1 - {}^{P_b}\!/_{100}\right] \times M_T}{100 - [\![(P]\!]_{br})_{RAM_j}} \times 100 \tag{3.3b}$$

Where:

m_{ij} = mass of a given size fraction (e.g., 3/4" × 1/2") from a given stockpile (e.g., 3/4" - #4 stockpile), grams; where i represents the

i^{th} size fraction in the target gradation, and j = 1 to the total number of stockpiles

p_{ij} = percent of a given size fraction (e.g., 3/4" × 1/2") from a given stockpile (e.g., percent retained on the 1/2" sieve the from the 3/4" - #4 stockpile)

P_{Sj} = stockpile percentage; ΣP_{Sj} = 100 percent

M_A = total mass of aggregate for a given batch (excluding binder), grams

M_T = total batch mass (i.e., including both the mass of binder and the mass of aggregate), grams

P_b = trial binder content for the mixture (virgin binder content plus reclaimed binder content), percent

$(P_{br})_{RAMj}$ = binder content of the j^{th} reclaimed material, percent (NOTE 1)

i = 1 to total number of size fractions

j = 1 to total number of reclaimed materials stockpiles

NOTE 1: Use the binder content for a given reclaimed material type in the equation to calculate the batch masses for the given material. For example, if RAP and RAS from separate stockpiles are included in the mixture, use $(P_{br})_{RAP}$ to calculate batch masses for the RAP and $(P_{br})_{RAS}$ to calculate batch masses for the RAS. If a reclaimed material is fractionated, use the respective binder contents of the fractionated materials to calculate batch masses (e.g., use $(P_{br})_{CoarseRAP}$ and $(P_{br})_{FineRAP}$ to calculate the batch masses for coarse RAP and fine RAP, respectively).

Determine the mass of virgin binder to add to the mixture as follows:

$$M_{virgin} = M_T - M_A - \sum_{j=1}^{r}\left[\left(\sum_{i=1}^{s} m_{i_j}\right) \times \frac{(P_{br})_{RAM_j}}{100}\right] \quad (3.4)$$

Where:

M_{virgin} = mass of virgin binder, grams

M_T = total batch mass, grams

M_A = total mass of aggregate for a given batch (excluding binder), grams

m_{ij} = mass of a given size fraction (e.g., 3/4" × 1/2") from a given reclaimed material stockpile (e.g., RAP), grams; where i represents the i^{th} size fraction in the target gradation, and j = 1 to the total number of reclaimed material stockpiles

$(P_b)_{RAMj}$ = binder content of the j^{th} reclaimed material, percent (NOTE 2)

r = total number of reclaimed material stockpiles

s = total number of size fractions in the target gradation

NOTE 2: The term in the square brackets in Equation 3.4 determines the mass of binder on the batched mass (quantity enclosed in the parentheses within the square brackets) for a particular type of reclaimed material. Therefore, use the binder content for a given reclaimed material type in the equation to calculate the mass of binder on the given material. For example, if RAP and RAS from separate stockpiles are included in the mixture, use $(P_{br})_{RAP}$ to calculate the mass of binder on the batched RAP and $(P_{br})_{RAS}$ to calculate the mass of binder on the batched RAS. If a reclaimed material is fractionated, use the respective binder contents of the fractionated materials to calculate the binder masses (e.g., use $(P_{br})_{CoarseRAP}$ and $(P_{br})_{FineRAP}$ to calculate the binder masses for the batched coarse RAP and batched fine RAP, respectively).

8. Dry a sufficient quantity of virgin aggregate and reclaimed materials to prepare the required number of batches. Maintain the materials in their separated sizes. Dry the virgin aggregate per AASHTO T 255. Dry the reclaimed materials (RAP and RAS) at 230±5°F for no more than two hours. Allow the materials to cool to room temperature (NOTE 3).

   NOTE 3: If batching of the materials will not immediately follow drying of the materials, place the materials into covered or sealed containers to prevent absorption of moisture. Maintain separation of the materials and label the containers appropriately (i.e., material type, source, size, etc.).

9. In separate pans for each type of material (i.e., virgin aggregate, RAP, and RAS), weigh the appropriate quantity of each separated size into the respective pans (i.e., virgin aggregate in a pan for only virgin aggregate, etc.) in accordance with the batch plan (NOTE 4). Ensure batch weights for individual components are within 0.1% of the planned batch weights.

   NOTE 4: Place the individual materials into separate piles in the pan to avoid mixing of separated sizes while batching. This allows removing a portion of a particular separated size if too much of the material is added without removing portions of other materials already in the pan.

10. Determine the total weight of each type of material (i.e., virgin aggregate, RAP, and RAS) and ensure that each total weight is within 0.1% of its planned total weight. If the batched total weight of any material is greater than 0.1% different from the planned total batch weight, discard the material in error and prepare a new batch of that material.

11. Sum the weights of the different materials and ensure the total weight (i.e., sum of weights of the individual materials) is within 0.2% of the planned total batch weight. If not, discard the materials and repeat Steps 9 through 11.

12. Place the batched materials into separate sealed containers to prevent absorption of moisture and label the containers appropriately (i.e., material type, sample number, etc). Maintain separation of the virgin aggregate from reclaimed materials and if both RAP and RAS are included in the batch as separate materials, maintain separation of the RAP from the RAS.
13. Prepare the required number of batches plus one extra (to be used for buttering the mixing bowl during the mixing process).

3.3.2 Mixing

As with batching procedures, minimal information was found in published literature regarding detailed mixing procedures for mixtures containing RAS, but some information was found for mixtures containing RAP, with the greatest detail provided by Johnson et al. (*2010*) and to a lesser extent by McDaniel and Anderson (*2001*). With consideration of the procedures provided in these two reports, but using AASHTO T 312 (*AASHTO 2010*) as a foundation, the following procedure was developed for use in this research effort.

It should be noted, however, that the following procedure explicitly identifies how to determine the mixing temperature range and what part of the range to use as a basis for heating all of the constituent materials (i.e., including the RAP and the RAS). McDaniel and Anderson (*2001*) recommended that RAP be heated to 110°C (230°F) for no more than two hours for sample sizes from 1 to 2 kilograms. Johnson et al. (*2010*) heated their materials (virgin aggregate, RAP, and RAS) to a temperature that, judging from its magnitude, appears to be based on a kinematic viscosity of the asphalt binder. In developing the procedure described below, and given that sufficiently large proportions of RAP and RAS were included in some of the laboratory-prepared mixtures investigated for this research effort, it was reasoned that all materials should be heated to the mixing temperature as determined for the unaged virgin binder to promote adequate activation (through heat) of the reclaimed binders. This, in turn, would promote blending of the virgin and reclaimed binders as well as promote dispersion of the blended binder. That is, it was reasoned that the RAP and RAS binders would need to be hot enough (and, consequently, of sufficiently low viscosity) to adequately coat the virgin aggregate particles. It should also be noted that the procedure was noted developed for the preparation of warm-mix asphalt mixtures containing RAP and RAS binders.

Mixing Virgin Aggregate and Reclaimed Materials with Virgin Binder

Prepare and mix the materials batched as described in Section 3.3.1 with virgin asphalt binder as follows:

1. Determine the mixing temperature range of the virgin asphalt binder per AASHTO T 312, or based on manufacturer recommendations.
2. Heat all constituent materials (i.e., virgin binder, virgin aggregate and, if included, RAP and/or RAS) as well as all miscellaneous mixing equipment (i.e., mixing bowls/buckets,

pans, spoons, spatulas, etc.) to the upper limit of the mixing temperature range determined in Step 1 (NOTE 1).

NOTE 1: Heating of the virgin binder and, if included, RAP and/or RAS, should be staged to minimize the duration required to bring these materials to the required temperature. Heating these materials to the temperature necessary for mixing tends to harden the asphalt binder(s) and more hardening typically occurs with longer durations at a given elevated temperature. Hence, the duration of heating should be minimized to minimize hardening of the binder(s). Materials comprised of the smallest proportion by weight will require the shortest duration, whereas materials with successively larger proportions will require successively longer durations. In any case, the virgin binder and materials containing asphalt binder (i.e., RAP or RAS) should be heated for only as long as is necessary to bring these materials to the required mixing temperature.

3. Charge the heated mixing bowl (or bucket) with the virgin aggregate and, if included, RAP and/or RAS. Thoroughly dry-mix the material(s) to obtain uniform dispersion of the material fractions.

4. Form a crater in the dry-blended materials and add the required amount of virgin asphalt binder into the crater (NOTE 2).

   NOTE 2: When adding the virgin binder, ensure that it pools in the crater, which provides provision for removing virgin binder without removing fine aggregate, RAP, or RAS particles in case too much virgin binder is added. Removal of a portion of the asphalt binder can be accomplished by dipping the end of a strip of paper towel into the pooled asphalt binder.

5. Begin mixing as soon as possible following addition of the virgin asphalt binder and continue mixing to obtain a mixture with a uniform distribution of binder; use the minimum duration necessary to achieve this condition (NOTE 3).

   NOTE 3: For some mechanical mixers, if utilized, it may be necessary to stop the apparatus partway through the process and scrape the coated and uncoated fine particles from the bottom and inner perimeter of the mixing bowl (or bucket).

6. Immediately after mixing, use a spoon (or scraper, or spatula, etc.) to transfer the mixture from the mixing bowl (or bucket) to a metal pan for further processing (e.g., short-term aging). Thoroughly scrape the bottom and inner perimeter of the mixing bowl (or bucket) to remove as much material as possible while the bowl and mixture are hot.

7. Discard the first mixture prepared in this way as it is intended to butter the mixing bowl (or bucket). Repeat Steps 4 through 6 for all remaining mixtures.

3.4 IGNITION OVEN CALIBRATION FACTOR PROCEDURE

As indicated in Section 2.4, none of the studies reviewed specifically addressed calibrating ignition ovens for mixtures containing RAS. However, a review of State DOT procedures (Appendix A) revealed that some states include provision for mixtures containing RAS. None of these include significant deviations from the basic methodology contained in ODOT TM 323. Hence, for the purposes of this study, ODOT TM 323 is recommended as the preliminary procedure for determining ignition oven calibration factors.

3.5 QC/QA PROCEDURES

Aside from increasing sampling frequencies for reclaimed materials, especially for evaluating the properties and consistency of RAS, nothing was found in the literature review to suggest testing procedures currently used for HMAC (with or without RAP) cannot be used for mixtures containing RAS. Given that current procedures have been used for decades for mixtures containing RAP, and that RAS is fundamentally similar in nature to RAP (albeit with a much harder binder, a higher proportion of finer aggregate, and includes cellulose and/or glass fibers and possibly a higher proportion of deleterious materials), no changes to current QC and QA procedures are recommended for the purposes of conducting this research effort.

4.0 EXPERIMENT PLANS

A significant part of this research effort involved investigation of both laboratory-prepared and plant-produced HMAC mixtures containing RAP and RAS. This section documents the experiment plans developed for the laboratory study utilizing the laboratory-prepared mixtures and the pilot studies utilizing the plant-produced materials. The experiment plans were developed prior to conducting the studies. It also describes the materials, mix designs, and methods used during the studies.

4.1 LABORATORY STUDY

The plan for the laboratory study was developed with two primary aims. The first was to investigate the physical properties of blended binders composed of various proportions of virgin and reclaimed binders with the intent of gathering evidence so as to satisfy the first three objectives listed in Section 1.3. Briefly, these were to develop recommendations for: 1) a virgin binder grade selection process for mixtures containing RAP and/or RAS; 2) a method for recovering binder from asphalt shingles; and 3) a batching and mixing procedure for mixtures containing RAP and/or RAS. The second aim was to determine ignition oven calibration factors of mixtures with and without RAP and/or RAS so as to gather evidence to satisfy the fourth objective listed in Section 1.3 (i.e., to develop recommendations for a procedure for determining ignition oven calibration procedures for mixtures containing RAS or RAP and RAS).

Table 4.1 displays the proportions of reclaimed binders and the total percentage of virgin binder replacement utilized to fabricate mixtures for the laboratory study. As indicated, up to 25 percent of RAP binder and up to 30 percent RAS binder was utilized to provide up to 55 percent virgin binder replacement, where total virgin binder replacement is shown in bold typeface. Thus, the base experiment design consisted of two factors (i.e., percentage of RAP binder and percentage of RAS binder) with three levels for each factor (i.e., RAP binder percentages of 0, 15, and 25 percent and RAS binder percentages of 0, 15, and 30 percent) for a total of nine different combinations. This allowed statistical comparisons to be made between virgin and blended binders and between mixtures containing only virgin materials with those having varying percentages of binder derived from RAP and RAS.

Characterization of the materials involved conducting tests on the as-received materials, on binders extracted and recovered from the as-received materials, and on mixtures prepared in the laboratory using the various proportions of virgin and reclaimed binders as well as on binders extracted and recovered from these mixtures. As indicated in Table 4.2, characterization of the as-received materials involved testing the virgin binder, burning the RAP and RAS mixtures in an ignition oven to determine binder contents, extracting, recovering, and testing the RAP and RAS binders, and conducting sieve analyses on the aggregates recovered from the RAP and RAS. For each material and for each type of test, the plan called for three tests to be conducted so that the mean and standard deviation for each property could be determined.

Table 4.1: Base Experiment Design for the Laboratory Study

Total percentage of virgin binder replacement shown in bold typeface		RAP Binder Percentage (Percentage of Virgin Binder Replaced by RAP Binder)		
		0	15	25
RAS Binder Percentage (Percentage of Virgin Binder Replaced by RAS Binder)	0	**0**	**15**	**25**
	15	**15**	**30**	**40**
	30	**30**	**45**	**55**

Table 4.2: Characterization of As-Received Materials

	Number of Tests		
Test	**Virgin Binder**	**RAS**	**RAP**
Binder content:			
Ignition oven	---	3	3
Quantitative extraction	---	3	3
Binder recovery	---	3	3
Binder flexural stiffness	3	3	3
Binder rheological properties	3	3	3
Sieve analysis	---	3	3

The plan also included tests on mixtures prepared with various proportions of virgin and reclaimed binder as well as tests on the blended binders extracted and recovered from these mixtures as shown in Table 4.3. As indicated, the plan included extraction, recovery, and testing of the blended binders, and burning the mixtures in an ignition oven to determine ignition oven calibration factors. It as indicates that two tests were planned for binder extraction, recovery, and characterization, and three tests were planned for the work involving ignition oven calibration factors so as to determine the mean and standard deviation for each property evaluated.

Table 4.3: Test Matrix for the Laboratory Study

	Reclaimed Binder Proportions								
RAP binder, percent	0	15	25	0	15	25	0	15	25
RAS binder, percent	0	0	0	15	15	15	30	30	30
Total binder replacement, percent	0	15	25	15	30	40	30	45	55
Binder selection procedure testing (loose-mix specimens):									
• Extraction/recovery	2	2	2	2	2	2	2	2	2
• Flexural stiffness	2	2	2	2	2	2	2	2	2
• Rheological properties	2	2	2	2	2	2	2	2	2
• **Total number of specimens**	**2**	**2**	**2**	**2**	**2**	**2**	**2**	**2**	**2**
Ignition oven calibration factor testing (loose-mix specimens):									
• Binder content	3	3	3	3	3	3	3	3	3
• **Total number of specimens**	**3**	**3**	**3**	**3**	**3**	**3**	**3**	**3**	**3**

4.2 PILOT STUDIES

Pilot studies were planned to satisfy the last two objectives of this research effort (listed in Section 1.3). More specifically, the plan was to conduct the studies with the aim of evaluating QC/QA procedures including mix design verification, and to evaluate mixture performance. In particular, the findings from these studies, together with the findings from the literature review, were to be used for developing recommendations for 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). This section provides brief descriptions of the two projects followed by a description of the experiment plan for the pilot studies including the materials, mix designs, and methods utilized.

4.2.1 Projects Investigated

Two pilot studies were conducted as part of this research effort. One pilot study was conducted on an off-ramp of Interstate 5 at the south end of Salem in the western part of the state, and the other was conducted on highway US 20 just east of Bend in the central part of the state. The locations were selected to study the sections in two significantly different environments with the I-5 section in the mild climate of the Willamette Valley, and the US 20 section in the much harsher climate east of the Cascade Mountains. The following paragraphs provide brief descriptions of the two projects.

I-5 Battle Creek – North Jefferson Project

The overall project involved repaving approximately 5 miles of the northbound and southbound lanes of Interstate 5 from the Battle Creek Road overcrossing near milepoint 249 to the North Jefferson Interchange near milepoint 244. The portion of this project relevant to this research effort involved cold plane removal and replacement of the top 3 inches of the HMAC pavement on the northbound Commercial Street off-ramp. The length of this work was about 1 mile, from approximately the north end of the gore area at the I-5 exit to the point at which the off-ramp merges with Commercial Street. HMAC with RAP was placed as the wearing course in the righthand (eastern) lane and shoulder of this two-lane off-ramp, whereas HMAC with RAP and RAS was placed as the wearing course in the lefthand (western) lane and shoulder. Roughly 2,300 tons of each mixture was placed in this portion of the overall project. The mixture with RAP was placed on the night of August 12, 2010, whereas the mixture with RAP and RAS was placed the night of August 13, 2010.

US20 Purcell Boulevard – Arnold Ice Caves Project

The overall project involved cold plane removal and replacement of existing HMAC along a 2.7-mile stretch of US20 from Purcell Boulevard in Bend to about a quarter-mile east of the Powell Butte Highway turn-off (from approximately milepoint 2.3 to approximately milepoint 5.0). The portion of this project relevant to this research effort was between milepoints 2.9 and 5.0 where the top 2 inches the wearing course was removed and replaced. HMAC with RAP and RAS was placed in the westbound lane, whereas HMAC with RAP was placed in the eastbound lane. Roughly 2,660 tons of each mixture was placed in this portion of the overall project. The

mixture with RAP was placed on the night of August 30, 2010, whereas the mixture with RAP and RAS was placed the night of August 31, 2010.

4.2.2 Experiment Plan

Table 4.4 lists the tests planned for the materials obtained from the pilot studies. As indicated, these included tests to characterize the binders from the as-received materials (i.e., virgin binder and reclaimed binders from the RAP and RAS) and the blended binders from the plant-produced mixtures. In addition, the plan included tests to characterize the volumetric properties, stiffness, and fatigue resistance of the plant-produced mixtures.

Table 4.4: Test Matrix for Pilot Studies

	As-Received Materials				Plant-Mixed Materials	
Test(s)	**Virgin Binder**	**RAP Binder**	**RAS Binder**		**RAP Mix**	**RAP/RAS Mix**
Extraction/Recovery for Binder Grade (AASHTO T 164 & ASTM D 5404)	---	2	2		2	2
Mixture Binder Content (AASHTO T 164 & T 308)	---	2 ea.	2 ea.		2 ea.	2 ea.
Binder Grade (AASHTO T 313 & T 315)	2	2	2		2	2
Residual Aggregate Gradation (AASHTO T 30)	---	---	---		2	2
Volumetric Properties (AASHTO T 166, T 209, and WAQTC TM 8)	---	---	---		3	3
Dynamic Modulus, Fatigue (AASHTO T 321)	---	---	---		3	3

4.3 MATERIALS

All materials used in this research effort consisted of the materials used to construct the pavement sections for the two pilot studies. These included constituent materials, loose (uncompacted), plant-produced mixtures, and specimens extracted from the in situ pavement sections. The constituent materials and loose, plant-produced mixtures were obtained from the plants prior to and during construction of the pavement sections, whereas the specimens extracted from the in situ pavements sections were obtained a few hours after compaction of the wearing courses. All materials utilized in the laboratory study were those used to construct the pavement sections for the I-5 Battle Creek – North Jefferson project. The following sections provide further details of the materials used in this research effort.

4.3.1 I-5 Battle Creek – North Jefferson Project

For the I-5 Battle Creek – North Jefferson project, the constituent materials consisted of virgin aggregates from a single source (crushed, river-run gravel fractionated into three primary sizes – 1/2" × #4, #4 × #8, and #8 minus), baghouse fines derived from the same aggregate source, reclaimed asphalt pavement, reclaimed asphalt singles, and virgin binder. Sufficient quantities of these materials were obtained during a single visit to the plant while the project was underway.

Table 4.5 lists relevant properties of the virgin aggregates and reclaimed materials used for the mixtures investigated in this research effort. The virgin binder was modified to meet ODOT's specification of a PG 70-22ER binder. It had a specific gravity of 1.034, a mixing temperature range of 340-353°F, and a compaction temperature range of 317-327°F.

Table 4.5: Basic Properties of the Materials Used for the I-5 Project

	Stockpile				
	1/2" × #4	#4 × #8	#8 minus	RAP	RAS
Gradation[1]					
Sieve Size	Percent Passing				
3/4"	100	100	100	100	100
1/2"	97	100	100	98	99
3/8"	61	99	100	91	99
1/4"	13	71	100	78	98
#4	4	44	99	70	97
#8	1	12	82	56	96
#16	1	7	57	43	81
#30	1	5	40	32	63
#50	1	4	24	25	56
#100	---	---	---	20	50
#200	1.1	2.2	7.8	15.1	41
Specific Gravity and Absorption[2]					
Bulk	2.618	2.592	2.530	2.591	---
SSD	2.670	2.649	2.611	---	---
Apparent	2.761	2.749	2.753	2.773	---
Absorption	2.0	2.2	3.2	---	---
Binder Content[3]	---	---	---	5.4	19.8

[1]AASHTO T 27 and T 11 for virgin aggregates and T 30 for residual aggregates from RAP and RAS (*AASHTO 2010*)

[2]AASHTO T 84 and 85 (*AASHTO 2010*) for virgin aggregates; ODOT TM 319 for RAP and RAS (*ODOT 2011*)

[3]AASHTO T 308 (*AASHTO 2010*)

On each night of paving the portion of the project relevant to this research effort, plant-mixed materials were obtained from the plant discharge sampling chute, and cores and beams were extracted from the in situ pavement following compaction. In each pavement section, the cores were obtained from five randomly-selected locations whereas the beams were extracted from a single location.

4.3.2 US20 Purcell Boulevard – Arnold Ice Caves Project

For the US20 Purcell Boulevard – Arnold Ices Caves project, the constituent materials consisted of virgin aggregates from a single source (crushed, sedimentary gravel fractionated into three primary sizes – 1/2" × #4, #4 × #8, and #8 minus), lime, reclaimed asphalt pavement, reclaimed asphalt shingles, and virgin binder. All materials were obtained from the plant during one of the two nights of paving the portions of the project relevant to this research effort.

Table 4.6 lists relevant properties of the virgin aggregates and reclaimed materials used for the mixtures investigated in this research effort. The virgin binder was modified to meet ODOT's specification of a PG 70-28ER binder. It had a specific gravity of 1.038, a mixing temperature range of 342-355°F, and a compaction temperature range of 319-329°F.

Table 4.6: Basic Properties of the Materials Used for the US20 Project

	Stockpile				
	1/2" × #4	#4 × #8	#8 minus	RAP	RAS
Gradation[1]					
Sieve Size	Percent Passing				
3/4"	100	100	100	100	100
1/2"	93	100	100	98	99
3/8"	64	100	100	91	99
1/4"	18	93	100	77	98
#4	6	54	100	66	96
#8	2	5	79	45	93
#16	2	3	50	31	77
#30	2	3	34	23	59
#50	2	2	24	18	51
#100	2	2	17	14	44
#200	1.4	1.8	11.7	10.1	35.7
Specific Gravity and Absorption[2]					
Bulk	2.714	2.750	2.728	2.750	---
SSD	2.766	2.808	2.718	---	---
Apparent	2.864	2.920	2.945	2.773	---
Absorption	1.9	2.1	2.8	---	---
Binder Content[3]	---	---	---	4.8	18.5

[1]AASHTO T 27 and T 11 for virgin aggregates and T 30 for residual aggregates from RAP and RAS (*AASHTO 2010*) (*AASHTO 2010*)

[2]AASHTO T 84 and 85 (*AASHTO 2010*) for virgin aggregates; ODOT TM 319 for RAP and RAS (*ODOT 2011*)

[3]AASHTO T 308 (*AASHTO 2010*)

During construction operations, plant-mixed materials were obtained from the plant discharge sampling chute, and cores and beams were obtained from the pavement following compaction. Cores were obtained from each pavement section at five randomly-selected locations whereas the beams were obtained from a single location within each section. Section 5 provides further details of these materials.

4.4 MIX DESIGNS

This section summarizes the mix designs for the RAP-only and RAP/RAS mixtures placed on the I-5 Battle Creek – North Jefferson project. These were used as a basis for determining batch quantities for fabrication of the mixtures used in the laboratory study. The mix designs for the US20 Purcell Boulevard – Arnold Ice Caves project are also summarized for archival purposes.

4.4.1 I-5 Battle Creek – North Jefferson Project

Tables 4.7 and 4.8 summarize the mix designs for the RAP-only and RAP/RAS mixtures, respectively. Both were designed to meet the requirements for a Level 4, 1/2-inch, dense-graded mixture (*ODOT 2008*). It should be emphasized that the HMAC supplier combined the RAP and RAS into a single stockpile (80 percent RAP and 20 percent RAS, by weight) and, consequently, this is reflected in the mix design for the RAP/RAS mixture (Table 4.8).

Table 4.7: Mix Design for the RAP-only Mixture Placed on the I-5 Project

Stockpile		1/2" × #4	#4 × #8	#8 minus	Baghouse	RAP	RAS
Stockpile Percentage		26.0	29.0	24.0	1.0	20.0	---
Bulk Specific Gravity (G_{sb})		2.637	2.570	2.544	2.785	2.591	---
Percent Binder Content		---	---	---	---	5.8	---
Virgin Binder		Grade		Mixing Temp. Range		Comp. Temp. Range	
		PG 70-22ER		340 - 353°F		317 - 327°F	
Sieve Size	Percent Passing	Mixture Volumetric Properties					
1"	100	Percent Asphalt Binder by Weight of Mixture (P_b)					5.8
3/4"	100						
1/2"	98	Theoretical Maximum Specific Gravity (G_{mm})					2.449
3/8"	83						
1/4"	60	Combined Aggregate Bulk Specific Gravity (G_{sb})					2.587
#4	49						
#8	31	Air Void Content (V_a), %					4.0
#16	22						
#30	16	Voids in Mineral Aggregate (VMA), %					14.4
#50	11						
#100	8	Voids Filled with Asphalt (VFA), %					72
#200	6.2						
		Dust-to-binder Ratio (P_{200}/P_{be})					1.4

Table 4.8: Mix Design for the RAP/RAS Mixture Placed on the I-5 Project

Stockpile		1/2" × #4	#4 × #8	#8 minus	Baghouse	RAP/RAS (80%/20%)
Stockpile Percentage		30.0	30.0	24.0	1.0	15.0
Bulk Specific Gravity (G_{sb})		2.637	2.570	2.544	2.785	2.669
Percent Binder Content		---	---	---	---	8.9
Virgin Binder		Grade	Mixing Temp. Range		Comp. Temp. Range	
		PG 70-22ER	340 - 353°F		317 - 327°F	
Sieve Size	Percent Passing	Mixture Volumetric Properties				
1"	100	Percent Asphalt Binder by Weight of Mixture (P_b)				5.9
3/4"	100					
1/2"	98	Theoretical Maximum Specific Gravity (G_{mm})				2.446
3/8"	83					
1/4"	59	Combined Aggregate Bulk Specific Gravity (G_{sb})				2.600
#4	49					
#8	31	Air Void Content (V_a), %				4.0
#16	22					
#30	16	Voids in Mineral Aggregate (VMA), %				15.0
#50	11					
#100	8	Voids Filled with Asphalt (VFA), %				73
#200	6.3					
		Dust-to-binder Ratio (P_{200}/P_{be})				1.3

Due to the similarity of the mix designs in terms of aggregate gradation, total binder contents, and volumetric properties, the mix design for the RAP-only mixture (Table 4.7) was used as the basis for developing batch quantities for the laboratory-prepared samples. Hence, using the aggregate gradation and total binder content listed in Table 4.7, in combination with results of tests to determine binder contents and gradations of the as-received RAP and RAS (as identified in Table 4.2), batch quantities for each of the nine combinations listed in Table 4.1 were developed. Appendix C provides the batch quantities for the nine mixtures investigated in the laboratory study.

4.4.2 US20 Powell Butte – Arnold Ice Caves Project

Tables 4.9 and 4.10 summarize the mix designs for the RAP-only and RAP/RAS mixtures placed on the US20 Purcell Boulevard – Arnold Ices Caves project, respectively. Both mixtures were designed to meet the requirements for a Level 3, 1/2-inch, dense-graded mixture (*ODOT 2008*). It should be noted that the HMAC supplier combined the RAP and RAS into a single stockpile (78 percent RAP and 22 percent RAS, by weight) and, consequently, this is reflected in the mix design for the RAP/RAS mixture (Table 4.10).

Table 4.9: Mix Design for the RAP-only Mixture Placed on the US20 Project

Stockpile		1/2" × #4	#4 × #8	#8 minus	Lime	RAP
Stockpile Percentage		34.5	0.0	34.5	1.0	30.0
Bulk Specific Gravity (G_{sb})		2.714	2.750	2.728	2.150	2.750
Percent Binder Content		---	---	---		4.8
Virgin Binder		Grade		Mixing Temp. Range		Comp. Temp. Range
		PG 70-28ER		345 - 359°F		319 - 329°F
Sieve Size	Percent Passing	Mixture Volumetric Properties				
1"	100	Percent Asphalt Binder by Weight of Mixture (P_b)				6.3
3/4"	100					
1/2"	97	Theoretical Maximum Specific Gravity (G_{mm})				2.551
3/8"	85					
1/4"	64	Combined Aggregate Bulk Specific Gravity (G_{sb})				2.722
#4	57					
#8	42	Air Void Content (V_a), %				4.1
#16	28					
#30	20	Voids in Mineral Aggregate (VMA), %				15.8
#50	14					
#100	11	Voids Filled with Asphalt (VFA), %				75
#200	7.5					
		Dust-to-binder ratio (P_{200}/P_{be})				1.5

Table 4.10: Mix Design for the RAP/RAS Mixture Placed on the US20 Project

Stockpile		1/2" × #4	#4 × #8	#8 minus	Lime	RAP/RAS (78%/22%)
Stockpile Percentage		39.0	0.0	39.0	1.0	21.0
Bulk Specific Gravity (G_{sb})		2.714	2.750	2.728	2.150	2.724
Percent Binder Content		---	---	---	---	7.6
Virgin Binder		Grade		Mixing Temp. Range		Comp. Temp. Range
		PG 70-28ER		345 - 359°F		319 - 329°F
Sieve Size	Percent Passing	Mixture Volumetric Properties				
1"	100	Percent Asphalt Binder by Weight of Mixture (P_b)				6.5
3/4"	100					
1/2"	97	Theoretical Maximum Specific Gravity (G_{mm})				2.545
3/8"	84					
1/4"	63	Combined Aggregate Bulk Specific Gravity (G_{sb})				2.714
#4	56					
#8	43	Air Void Content (V_a), %				3.9
#16	28					
#30	20	Voids in Mineral Aggregate (VMA), %				15.7
#50	14					
#100	11	Voids Filled with Asphalt (VFA), %				75
#200	7.5					
		Dust-to-binder ratio (P_{200}/P_{be})				1.5

4.5 METHODS

As indicated in Tables 4.2, 4.3, and 4.4 (Sections 4.1 and 4.2) a variety of test methods were employed during this research effort. These are described in further detail below. Also described is the batching and mixing procedures employed to prepare the nine combinations of laboratory-prepared mixtures with the binder proportions listed in Table 4.1.

Binder Content

Binder contents of the as-received materials (i.e., RAP and RAS) and the laboratory-prepared mixtures were determined through use of ignition ovens and by quantitative extraction. Detemination of binders contents using ignition ovens was performed in accordance with AASHTO T 308 (*AASHTO 2010*) whereas determination of binder contents via quantitative extraction was performed in accordance with AASHTO T 164 (*AASHTO 2010*).

Binder Properties

The virgin binder and the binders recovered from the as-received RAP and RAS, as well as the blended binders recovered from the laboratory-prepared mixtures, were evaluated to determine flexural stiffness and rheological properties. Recovery of extracted binders was performed in accordance with ASTM D 5404 (*ASTM 2010*). Flexural stiffness and rheological properties of the virgin and recovered binders were performed in accordance with AASHTO T 313 and AASHTO T 315 (*AASHTO 2010*), respectively.

Material Gradation

Particle size distribution (gradation) of the as-received materials and the aggregate recovered from the ignition oven tests were performed for mix design purposes and for developing the ignition oven calibration factor procedure. Sieve analyses of the as-received virgin aggregate fractions were performed in accordance with AASHTO T 11 and T 27 (*AASHTO 2010*) whereas sieve analyses of the aggregates recovered from the ignition oven tests were performed in accordance with AASHTO T 30 (*AASHTO 2010*).

Volumetric Properties

Cores and beams extracted from the compacted pavements were tested to determine bulk specific gravity and theoretical maximum specific gravity in accordance with AASHTO T 166 and T 209 (*AASHTO 2010*), respectively. In addition, mat density was measured at each core location (prior to extracting the cores) in accordance with WAQTC TM 8 (*ODOT 2011*).

Dynamic Modulus and Fatigue

Beams extracted from the compacted pavements were tested for dynamic modulus and fatigue in accordance with AASHTO T 321 (*AASHTO 2010*). Dynamic moduli were determined for each specimen at loading frequencies of 0.1, 0.2, 0.5, 1, 2, 5, 10, and 15 Hertz using a controlled-strain level of 100 microstrain. All tests were conducted in a controlled-temperature incubator set at 68°F (20°C).

Immediately following dynamic modulus testing of a particular specimen, it was tested for fatigue at a loading frequency of 10 Hertz and at a temperature of 68°F (20°C). Dynamic modulus (stiffness) and dissipated energy were recorded for each loading cycle and the test was terminated when the stiffness of the specimen reached 50 percent of its initial stiffness. Two sets of three specimens each (grouped so that the average air void contents of each set were approximately equal) were tested in this way with one set tested using an intial strain level of 200 microstrain and the other set using an intial strain level of 400 microstrain.

It should be noted that Table 4.4 indicates the plan called for three modulus and fatigue tests for each mixture, whereas six tests per mixture were actually conducted. The same is true for the tests used to determine the volumetric properties of the mixtures. This doubling of the number of tests conducted on the mixtures came about by adding a second initial strain level for the fatigue tests after the experiment plan had been developed.

Batching and Mixing Procedures

No standard procedures for batching and mixing HMAC mixtures incorporating RAS were found at the time the literature review was conducted. Consequently, new procedures were developed, as previously indicated in Section 3.3, and samples for use in the laboratory study were fabricated in accordance with these procedures.

5.0 RESULTS

Various tests were conducted on the constituent materials, laboratory-prepared mixtures, and field samples as described previously in Section 4. This section presents the results from these tests. Although only the materials from the I-5 Battle Creek – North Jefferson project were used in the laboratory study, tests were conducted on the constituent materials from both projects and, hence, the results from these tests are presented first.

5.1 CONSTITUENT MATERIALS

Tests were conducted on the constituent materials to establish baseline values for the critical temperatures of the virgin, RAP, and RAS binders. In addition, binder contents of the RAP and RAS materials and particle size distributions of the aggregates extracted from the RAP and RAS materials were determined for the purposes of establishing batch quantities of the constituent materials to meet the mix design target values previously listed in Section 4.4. All tests on the constituent materials were conducted at the ODOT Materials Laboratory.

5.1.1 Critical Temperatures of the Binders

The as-received virgin binder and binders extracted and recovered from the as-received RAP and RAS were tested to determine flexural stiffness and rheological properties in order to verify virgin binder grades and to determine actual critical temperatures of the reclaimed materials. Table 5.1 lists the critical temperatures determined from these tests, and the Superpave binder grades per AASHTO M 320 (*AASHTO 2010*) based on the tests.

Table 5.1: Critical Temperatures and Superpave Grades of the As-Received Virgin and Reclaimed Binders

Project	Binder Source	High Critical Temperature (°C)	Low Critical Temperature (°C)	Superpave Grade	Purchased Virgin Binder Grade
I-5	Virgin	71	-26	PG 70-22	70-22ER
	RAP	85	-12	PG 82-10	---
	RAS	119	---[1]	---[2]	---
US20	Virgin	78	-31	PG 76-28	70-28ER
	RAP	85	-19	PG 82-16	---
	RAS	151	---[1]	---[2]	---

[1]Extracted/recovered binder had too high of viscosity to pour samples for testing

[2]High critical temperature exceeded maximum in AASHTO M 320

5.1.2 Binder Contents and Aggregate Gradations of the Reclaimed Materials

Binder contents of the reclaimed materials were determined during the extraction process as well as by burning the mixtures in an ignition oven. Particle size distributions of the extracted aggregates were also determined (to be used for determining batch quantities). Table 5.2 lists the binder contents of the reclaimed materials while Table 5.3 lists the gradations of the extracted aggregates.

Table 5.2: Binder Contents of the Constituent Reclaimed Materials

Project	Material	Binder Content (%)		
		Quantitative Extraction		Ignition Oven
I-5	RAP	6.6[a], 6.8[b]		7.8
	RAS	23.8[b]		18.7
US20	RAP	5.8[a]		4.7
	RAS	16.4[b]		18.5

[a]Rotovapor, [b]Centifuge only

Table 5.3: Gradations of the Aggregates Extracted from the Reclaimed Materials

Sieve Size	Percent Passing				
	I-5			US20	
	RAP	RAS		RAP	RAS
1"	100	100		100	100
3/4"	100	100		100	99
1/2"	98	100		98	99
3/8"	93	100		90	99
1/4"	82	98		73	98
#4	77	97		60	96
#8	64	96		37	93
#16	53	80		26	77
#30	43	60		19	59
#50	36	53		14	51
#100	31	46		12	44
#200	20.8	38.5		8.7	35.7

5.2 LABORATORY STUDY

The laboratory study was conducted to investigate the physical properties of blended binders composed of various proportions of virgin and reclaimed binders as well as to investigate the effect of these proportions on ignition oven calibration factors for mixtures containing the reclaimed materials. Only the materials from the I-5 Battle Creek – North Jefferson project were included in the laboratory study. The following sections present the results obtained from laboratory tests conducted on the as-received materials and on the laboratory-prepared mixtures investigated (as described previously in Section 4.1).

5.2.1 Mixing Procedure Evaluation

In developing the preliminary mixing procedure (see Section 3.3.2), it was assumed that it would be best to combine and thoroughly dry-mix all of the virgin aggregate with all of the reclaimed materials prior to adding virgin binder (and, thus, simulate the sequence that would typically occur during an actual plant mixing process). However, given that the preliminary procedure is for fabricating mixtures in the laboratory, a simple investigation was conducted to determine if more thorough and uniform coating of virgin aggregate and reclaimed particles could be obtained by first adding virgin binder to either the coarse fraction (plus #4 material) or the fine fraction (minus #4 material) followed by adding the other fraction. Specifically, the investigation considered the following sequences of adding materials during the mixing process:

1. Add virgin binder to the fine fraction, mix for a specified duration, and then add the coarse fraction.
2. Add virgin binder to the coarse fraction, mix for a specified duration, and then add the fine fraction.
3. Combine coarse and fine fractions prior to adding virgin binder.

The investigation utilized a mixture with 55 percent binder replacement (i.e., the mixture with greatest proportion of reclaimed binder investigated in the laboratory study) since it would be most difficult to obtain thorough and uniform coating of virgin aggregate particles with this mixture. Assessment of mixing efficacy was made by visual observation.

Table 5.4 lists observations made on the mixed materials as well as an informal assessment of the relative effectiveness of mixing for the three trials. As indicated, both trials where the coarse and fine fractions were added separately resulted in uncoated fractions and, consequently, a poor ranking relative to the trial where the coarse and fine fractions were blended together prior to adding the binder.

5.2.2 Properties of Blended Binders

Blended binders were extracted and recovered from the laboratory-fabricated mixtures and tested for rheological properties to determine the high and low critical temperatures of the blended binders. Table 5.5 lists the critical temperatures of the blended binders determined from these tests. Note that the blended binders obtained from the two mixtures with the highest percentages of virgin binder replacement (i.e., 45 and 55 percent) were too stiff to pour the beam for testing in the Bending Beam Rheometer; hence, the low critical temperatures of the binders from these two mixtures could not be determined.

Table 5.4: Informal Assessment of Mixing Procedure Effectiveness

Sequence		Observations	Relative Effectiveness*
1.	Binder added to fine fraction followed by adding the coarse fraction	• Fine fraction completely coated, but clustered in ball-shaped conglomerates • Bulk of coarse fraction uncoated	Poor
2.	Binder added to coarse fraction followed by adding the fine fraction	• Coarse fraction completely coated • Bulk of fine fraction uncoated • Poor uniformity	Poor
3.	Binder added to blended coarse and fine fractions	• Good coating of fine fraction • Bulk of coarse fraction coated with small proportion not completely coated	Good

*By visual assessment based on listed observations

Table 5.5: Critical Temperatures of the Blended Binders Recovered from the Lab-Prepared Mixtures

Total Percent Virgin Binder Replacement	Percent Virgin Binder Replaced By		Sample No.	High, Low Critical Temperature	Average High, Low Critical Temperature
	RAP Binder	RAS Binder			
0	0	0	1	75, -28	75.5, -28.0
			2	76, -28	
15	15	0	1	78, -22	80.5, -21.5
			2	83, -21	
15	0	15	1	93, -16	87.5, -18.5
			2	82, -21	
25	25	0	1	87, -17	89.0, -16.5
			2	91, -16	
30	0	30	1	91, -17	95.5, -13.5
			2	100, -10	
30	15	15	1	90, -15	88.5, -17
			2	87, -19	
40	25	15	1	96, -12	90.5, -16.0
			2	85, -20	
45	15	30	1	106*	110.0*
			2	114*	
55	25	30	1	116*	112.0*
			2	108*	

*Low critical temperature could not be determined since the binder was too stiff to create the beam to be tested in the Bending Beam Rheometer

5.2.3 Ignition Oven Calibration Factors

Binder contents of laboratory-prepared mixture specimens were determined by quantitative extraction and by ignition in an oven to assist in developing a procedure for determining ignition oven calibration factors for mixtures containing reclaimed materials. Table 5.6 lists the results from these tests. Note that the mixtures with 40 percent or more virgin binder replacement are not included as it was decided by ODOT personnel to eliminate these mixtures from this part of the investigation.

Table 5.6: Laboratory-Prepared Mixture Specimen Binder Contents

Total Percent Virgin Binder Replacement	Percent Virgin Binder Replaced By		Sample No.	Binder Content[1], percent				
	RAP Binder	RAS Binder		Mixture Specimen[2]	Extraction		Ignition Oven[3]	
					Indiv.	Avg.	Indiv.	Avg.
0	0	0	1	5.81	5.99	5.93	6.60	6.62
			2		6.00		6.55	
			3		5.81		6.71	
15	15	0	1	5.80	6.74	6.59	6.64	6.55
			2		6.43		6.47	
			3		---		6.55	
15	0	15	1	5.79	6.69	6.58	6.56	6.44
			2		6.47		6.26	
			3		---		6.56	
			4		---		6.36	
25	25	0	1	5.81	6.98	6.78	6.56	6.50
			2		6.58		6.47	
			3		---		6.46	
30	0	30	1	5.80	6.28	6.32	6.37	6.36
			2		6.35		6.56	
			3		---		6.16	
30	15	15	1	5.80	7.40	6.84	6.45	6.46
			2		6.27		6.48	
			3		---		6.44	

[1]By total weight of mixture

[2]Percent binder added during mixture fabrication process

[3]Excludes correction factor

5.3 PILOT STUDIES

The pilot studies were conducted with the principal aims of evaluating QC/QA procedures and to evaluate mixture performance. Tests were conducted on loose-mix materials obtained from the mixing plants, on the in situ (compacted) mats, and on samples extracted from the compacted mats.

In addition, although not originally part of the experiment plan, a crack survey was undertaken along the I-5 project prior to construction of the pilot study overlays. The pavement sections were surveyed again following the first winter to determine if cracking had occurred. Although a pre-construction crack survey was not conducted along the US 20 project, a post-construction survey was conducted following the first winter the pavement sections were in service (again, to determine if cracking had occurred).

The following sections present the results obtained from the tests on plant-mixed and field-compacted materials followed by a summary of the crack surveys.

5.3.1 Properties of Plant-Mixed Materials

Loose-mix samples were obtained from the plants and tested to determine binder contents of the mixtures and rheological properties of the blended binders for the purposes of determining critical temperatures. Table 5.7 presents the results from these tests. Note that the results for the US 20 RAP-only binder blend indicate a high critical temperature 10°C lower than that for the virgin binder (Table 5.1). Similarly, the results for the US 20 RAP/RAS binder blend indicate a high critical temperature 4°C lower than that for the virgin binder.

Table 5.7: Pilot Study Mixture Binder Contents and Binder Critical Temperatures

Project	Mixture	Specimen No.	Binder Content[1], percent				High, Low Critical Temperatures, °C	
			Extraction		Ignition Oven[2]			
			Indiv.	Avg.	Indiv.	Avg.	Indiv.	Avg.
I-5	RAP-only	1	5.44	5.51	6.24	6.26	78, -27	72, -28
		2	5.58		6.28		75, -27	
		3	---		---		64, -30	
	RAP/RAS	1	5.43	5.37	6.23	6.23	79, -25	80, -26
		2	5.30		6.22		80, -26	
US 20	RAP-only	1	5.53	5.55	6.78	6.74	66, -31	68, -29
		2	5.71		6.66		68, -29	
		3	5.42		6.77		71, -29	
	RAP/RAS	1	6.04	5.89	6.73	6.70	75, -28	74, -28
		2	5.73		6.67		73, -29	

[1]By total weight of mixture

[2]Excludes correction factor

5.3.2 Properties of Field-Compacted Mixtures

Cores were obtained from the pavements at the locations where the nuclear density gauge tests were conducted for the purposes of comparing core densities determined in the laboratory to those determined by the nuclear density gauges. In addition, beams were extracted from the shoulders of the pavements and tested for dynamic modulus and fatigue to assess relative performance of the mixtures.

In-Place Density

Nuclear density gauge tests were conducted by both ODOT personnel and paving contractor personnel at locations selected randomly along each pavement of both projects. Pavement cores were obtained from the test locations following the nuclear density gauge tests. Table 5.8 lists the results of these tests.

Table 5.8: In-Place Density of the Pilot Study Pavements

				Nuclear Gauge Density, lb/ft^3			Pavement Core	
Project	**Mixture**	**Location**	**Station**	**ODOT**	**Con-tractor**		**Bulk Sp. Grav.**	**Density, lb/ft3**
I-5	RAP-only	1	282+00	---	136.2		2.201	137.3
		2	275+27	---	144.5		2.322	144.9
		3	267+13	---	144.2		2.295	143.2
		4	259+61	---	142.4		2.291	143.0
		5	245+85	---	139.0		2.241	139.8
	RAP/RAS	1	278+95	---	141.6		2.279	142.2
		2	272+48	---	140.5		2.269	141.6
		3	253+05	---	136.9		2.195	137.0
		4	243+53	---	141.2		2.269	141.6
		5	239+18	---	133.8		2.160	134.8
US 20	RAP-only	1	198+11	149.8	150.3		2.399	149.7
		2	195+85	146.4	146.6		2.354	146.9
		3	194+00	147.5	149.6		2.367	147.7
		4	191+87	145.5	146.4		2.325	145.1
		5	189+70	147.4	147.8		2.347	146.5
	RAP/RAS	1	199+65	146.7	147.2		2.312	144.3
		2	197+85	144.3	144.3		2.276	142.0
		3	195+80	145.9	148.3		2.307	144.0
		4	193+70	143.8	144.6		2.268	141.5
		5	191+85	147.7	149.0		2.338	145.9

Mechanical Properties

Beams cut from the shoulders of the pavements from both projects were trimmed to testing size and tested to determine bulk specific gravity, dynamic moduli, and fatigue properties. Prior to fatigue testing, the beams were divided into two groups of three specimens each for each mixture type such that the two groups of a particular mixture type had approximately equal average bulk specific gravities. Following fatigue testing, specimens were tested for theoretical maximum specific gravity so that the air void content could be determined.

Table 5.9 lists the dynamic modulus test results while Table 5.10 summarizes of the fatigue test results. The latter lists the number of load cycles required to cause a 50 percent reduction in stiffness (dynamic modulus) relative to the initial stiffness of the mixture (E_0) for the purposes of comparing the results obtained from the various mixtures using the phenomenological approach (*Pell 1962; Epps and Monismith 1969; Pell and Cooper 1975*).

Table 5.9: Dynamic Moduli of Field-Compacted Mixtures

Project	Mixture	Sample No.	Stiffness, ksi, at a loading frequency of							
			0.1 Hz	0.2 Hz	0.5 Hz	1 Hz	2 Hz	5 Hz	10 Hz	15 Hz
I-5	RAP-only	1	158	232	356	438	552	745	934	1,099
		2	156	217	350	450	547	727	934	1,053
		3	172	240	371	474	549	762	967	1,034
		4	173	249	389	494	611	782	1,037	1,068
		5	173	226	372	476	593	819	1,029	1,134
		6	223	292	387	452	535	670	823	888
		Avg.	176	243	371	464	565	751	954	1,046
		St. Dev.	24.4	26.8	15.8	20.8	30.0	50.6	78.4	85.2
	RAP/ RAS	1	95	125	194	247	310	434	537	658
		2	95	132	190	255	317	447	563	617
		3	79	110	176	228	279	397	476	530
		4	122	162	260	316	400	531	664	744
		5	114	148	225	296	350	477	566	628
		6	125	171	249	327	425	556	702	777
		Avg.	105	141	216	278	347	474	585	659
		St. Dev.	18.1	23.1	34.2	40.3	56.4	60.6	83.6	90.0
US 20	RAP-only	1	83	103	174	226	286	382	510	525
		2	*	100	164	205	256	342	437	509
		3	113	153	237	307	394	539	656	753
		4	120	163	261	337	388	505	708	757
		5	113	160	229	302	386	540	690	726
		6	140	189	289	384	486	654	835	867
		Avg.	114	145	226	294	366	494	640	690
		St. Dev.	20.7	35.7	48.7	67.4	82.8	114.7	144.0	142.1
	RAP/ RAS	1	71	94	144	185	235	319	415	463
		2	77	111	165	212	266	347	419	479
		3	77	104	156	204	256	344	426	495
		4	*	167	258	350	432	601	730	803
		5	101	138	228	283	351	491	619	708
		6	*	138	194	278	328	432	547	629
		Avg.	81	125	191	252	311	422	526	596
		St. Dev.	13.2	27.1	44.5	62.5	73.8	109.1	130.1	139.9

*Test terminated due to significant reduction in stiffness on initial loading

Table 5.10: Four-Point Beam Fatigue Test Results of Field-Compacted Mixtures

Project	Mix-ture	Initial Tensile Strain ($\times 10^{-6}$)	Specimen No.	Percent Air Voids	Average Percent Air Voids	Cycles to 50% E_0	Average Cycles to 50% E_0
I-5	RAP-only	200	1	4.3	4.2	242,388*	330,943
			2	3.8		466,218*	
			4	4.4		284,222	
		400	3	4.1	4.0	9,036	8,138
			5	4.1		13,352	
			6	3.9		2,025	
	RAP/ RAS	200	1	8.9	8.1	679,687	613,453
			2	7.8		456,979	
			3	7.7		703,694	
		400	4	7.8	8.2	21,769	17,889
			5	8.8		20,208	
			6	8.0		11,691	
US 20	RAP-only	200	1	4.8	5.5	3,830,831	3,079,846
			2	7.0		2,817,157	
			4	4.7		2,591,550	
		400	3	7.0	5.8	31,322	30,171
			5	5.9		30,245	
			6	4.6		28,945	
	RAP/ RAS	200	1	9.1	9.0	2,541,705	2,523,840
			2	9.7		2,993,252	
			3	8.2		2,036,564	
		400	4	7.7	9.0	18,714	19,268
			5	9.0		16,214	
			6	10.3		22,877	

*The tests were terminated at approximately 68% and 67% of E_0, respectively, due to equipment failure. The cycles to 50% of E_0 listed were derived from regression models.

5.3.3 Field Performance

Detailed crack surveys were conducted along the portion of the I-5 project investigated as part of this research effort prior to construction of the two study sections to document the locations of cracks in the existing pavement. Surveys were conducted prior to and following grinding operations. It was thought that this information could assist in distinguishing between thermal cracking and reflection cracking (i.e., environmental- versus load-related cracking) should cracks appear in the study sections at some future date. Details of the crack surveys are provide in Appendix D.

Informal surveys were conducted approximately eight months following construction (and following the first winter of service) at all four study locations. No cracking was detected in any of the four pavement sections during these surveys.

6.0 ANALYSIS OF RESULTS

6.1 LABORATORY STUDY

6.1.1 Properties of Blended Binders

Figure 6.1 graphically illustrates the results presented in Tables 5.1 and 5.5 (i.e., the critical temperatures of the as-received binders and blended binders, respectively). The diamond symbols indicate the critical temperatures of the individual samples, whereas the numeric values in bold typeface indicate the average critical temperatures. The following sections provide results of various analyses conducted using these data.

Low Critical Temperature

The low critical temperatures of the blended binders increased steadily with increasing reclaimed binder content up to 25 percent. With further increases in reclaimed binder content, the low critical temperatures remained about the same, with the exception of that for the blend with no RAP binder and 30 percent RAS binder (i.e., 0% RAP / 30% RAS).

Figure 6.2, which shows the mean low critical temperature and corresponding 95 percent confidence interval (utilizing Fisher's least significant differences) for each total virgin binder replacement level, illustrates these observations in greater detail. Moreover, it shows statistically significant differences between low critical temperatures of blended binders at all replacement levels relative to the low critical temperature of the virgin binder extracted from the laboratory-prepared mixture. It also shows that statistically significant differences did not exist between low critical temperatures of the blended binders at virgin binder replacement levels between 15 and 40 percent (indicated by the horizontal bar showing homogenous groups).

Although the results shown in Figure 6.2 indicate significant differences between the low critical temperatures of the blended binders relative to that of the virgin binder, they do not indicate if these differences would constitute an increase in Superpave grade as determined by AASHTO M 320 (*AASHTO 2010*). Consequently, the data were analyzed using a Student's t-test to determine if the differences were greater than 6 or 12°C (i.e., one or two Superpave grades). Table 6.1 displays the results of these analyses.

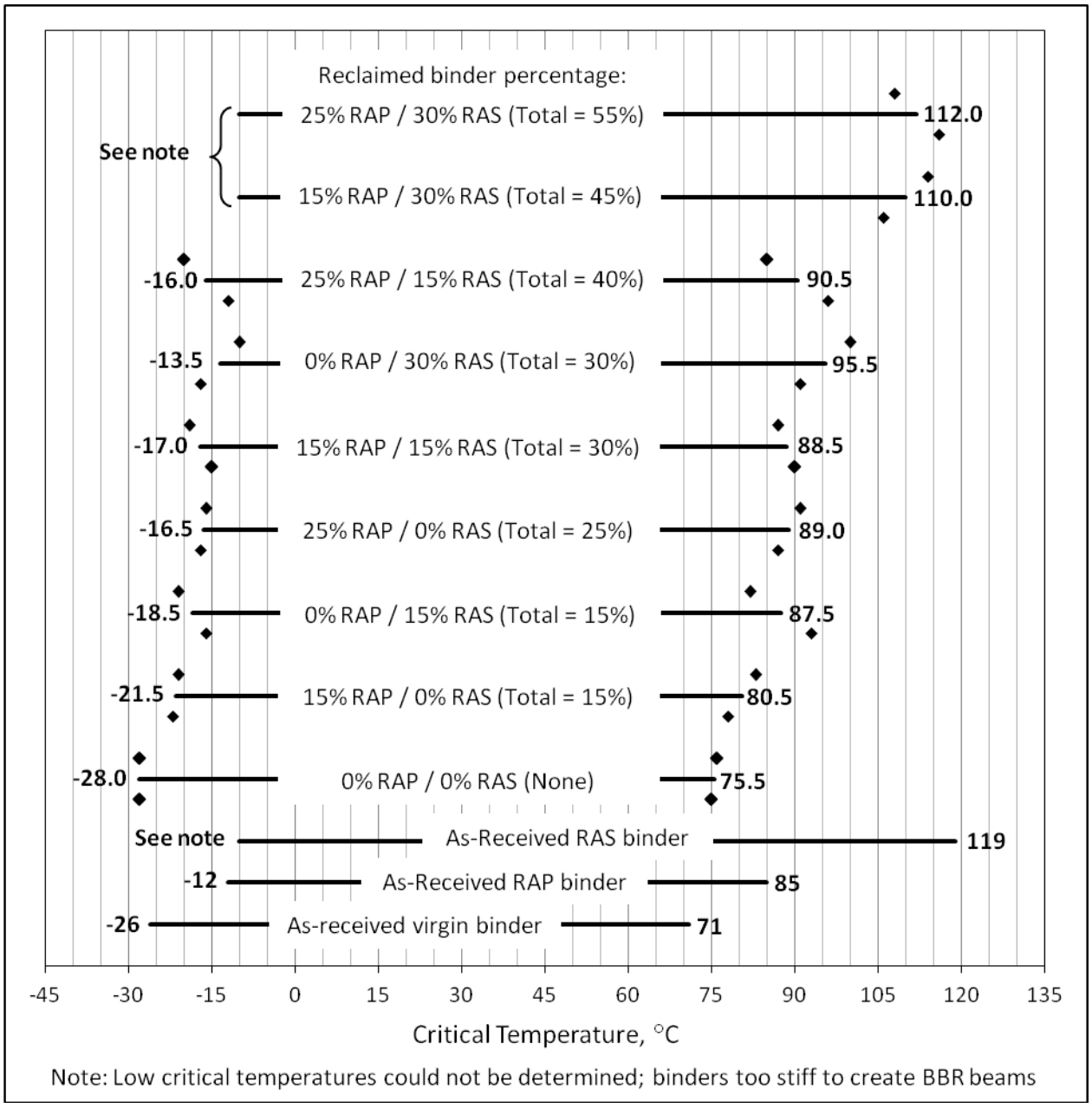


Figure 6.1: Critical Temperatures of the As-Received Binders and the Blended Binders Recovered from the Lab-Fabricated Mixtures

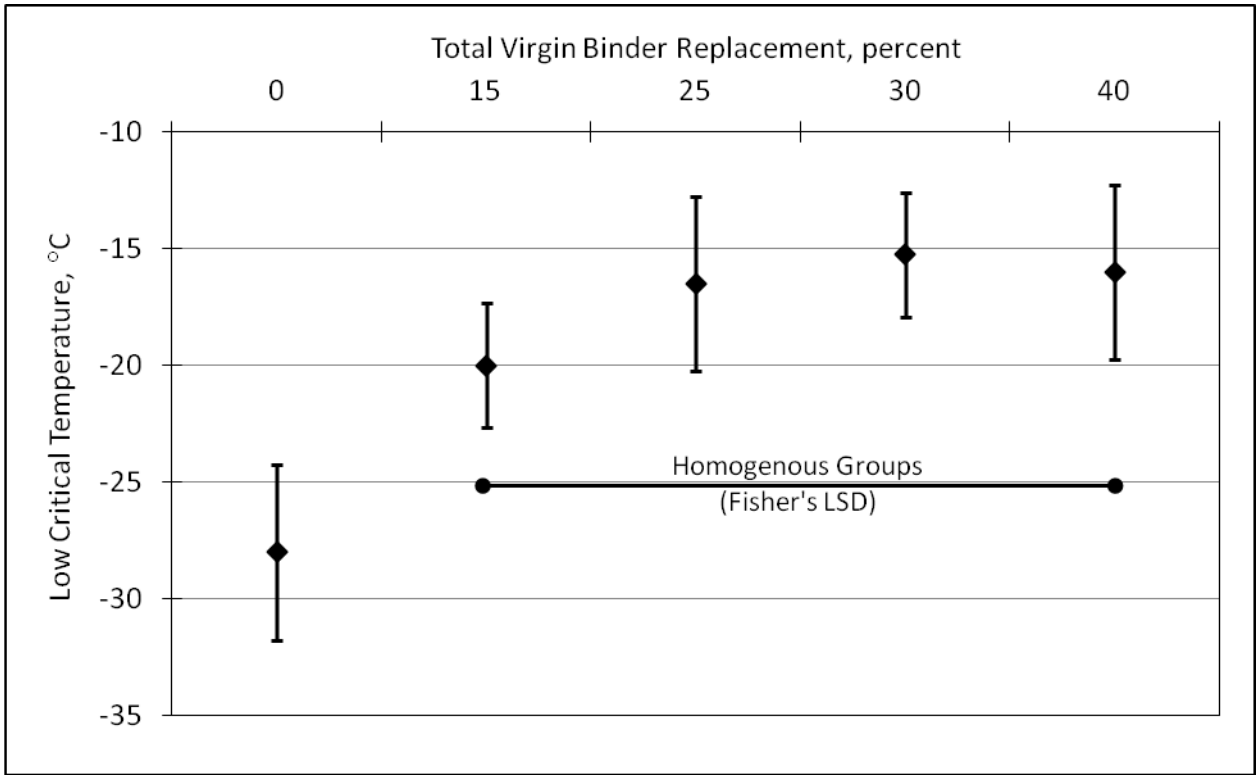


Figure 6.2: Comparison of Low Critical Temperatures versus Total Percent Binder Replacement using Fisher's Least Significant Difference Intervals

Table 6.1: Statistical Comparison (Student's t-test) of the Low Critical Temperatures of the Combined Blended Binders Relative to that of the Virgin Binder

Total Virgin Binder Replacement, percent	Is difference* > 6°C (i.e., at least one Superpave grade)? (p-value)	Is difference* > 12°C (i.e., at least two Superpave grades)? (p-value)
15	No (0.2113)	No (0.9959)
25	Yes (0.0041)	No (0.7887)
30	Yes (0.0401)	No (0.4042)
40	No (0.1362)	No (0.5000)

*Difference equals the mean low critical temperature of the blended binder minus the mean low critical temperature of the virgin binder; evaluation based on a significance level of 0.05.

A significance level of 0.05 (i.e., confidence level of 95 percent) was used as the criterion to determine if a difference existed. Hence, if the p-value listed in Table 6.1 was less than 0.05, then there existed sufficient evidence to reject the null hypothesis of the difference being less than 6°C or less than 12°C. Based on this criterion, it can be seen that the blends constituting

total virgin binder replacement levels of 25 and 30 percent increased the low temperature component of the Superpave binder grade by one grade, whereas those with replacement levels of 15 and 40 percent did not. Further, none of the replacement levels resulted in an increase of more than one grade. It is not clear why the replacement levels of 25 and 30 percent resulted in a one-grade increase while the replacement level of 40 percent did not, but further discussion is provided in Section 7.1.

Given that three of the four blends shown in Table 6.1 and Figure 6.2 contained both RAP binder and RAS binder, further analysis was conducted to determine if significant differences existed between low critical temperatures based on the type of reclaimed binder used for partial virgin binder replacement. Figure 6.3 displays the results of this analysis. It shows the mean low critical temperature and corresponding 95 percent confidence interval (utilizing Fisher's least significant differences) for each blend of reclaimed binders in relation to one another and to the virgin binder.

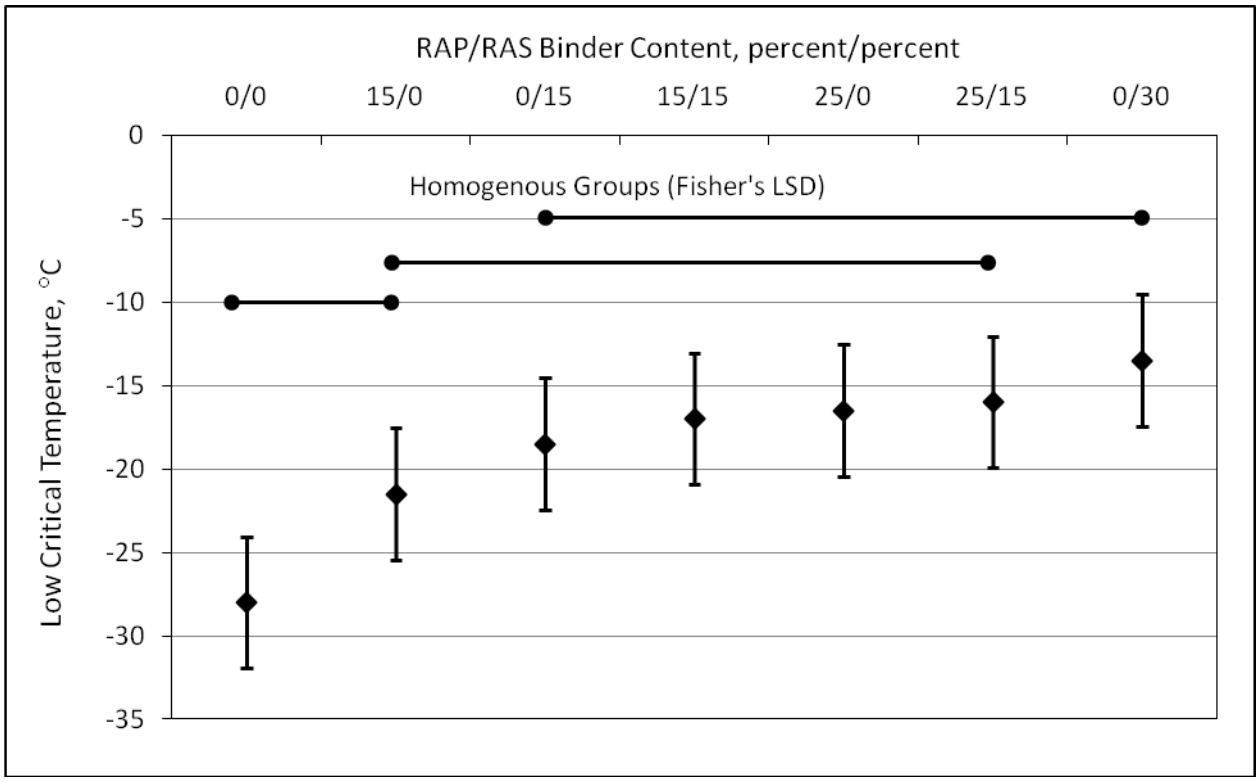


Figure 6.3: Comparison of Low Critical Temperatures versus RAP/RAS Binder Replacement Levels using Fisher's Least Significant Difference Intervals

Several inferences can be drawn from the results displayed in Figure 6.3 as listed below. In all cases, the inferences are drawn based on a confidence level of 95 percent.

- The low critical temperature of the blend with 15 percent RAP binder and no RAS binder (shown as 15/0) was not significantly different from that of the virgin binder. For all other blends, the difference was significant.

- Although the low critical temperature of the blend containing no RAP binder and 15 percent RAS binder (shown as 0/15) was greater than that of the blend containing 15 percent RAP binder and no RAS binder (shown as 15/0), the difference was not significant.

- Significant differences did not exist between low critical temperatures of blends containing up to 25 percent RAP binder and up to 15 percent RAS binder.

- The low critical temperature of the blend containing no RAP binder and 30 percent RAS binder (shown as 0/30) was significantly different from that of the blend containing 15 percent RAP binder and no RAS binder (shown as 15/0), but it was not significantly different from the low critical temperatures of the other blends.

Additional analyses were conducted using a Student's t-test to determine if the differences shown in Figure 6.3 were greater than 6 or 12°C (i.e., one or two Superpave grades). Based on a significance level of 0.05 as the criterion for determining significant differences, the findings shown in Table 6.2 were obtained from these analyses. As indicated, only the blend containing 25 percent RAP binder and no RAS binder (i.e., 25% RAP/ 0% RAS) resulted in an increase of one Superpave grade, but not two. It is not known why only this combination resulted in a one-grade increase while the others did not, but further discussion is provided in Section 7.1.

Table 6.2 : Statistical Comparison (Student's t-test) of the Low Critical Temperatures of the Individual Blended Binder Combinations Relative to that of the Virgin Binder

Reclaimed Binder Blend	Is difference* > 6°C (i.e., at least one Superpave grade)? (p-value)	Is difference* > 12°C (i.e., at least two Superpave grades)? (p-value)
15% RAP / 0% RAS	No (0.2113)	No (0.9959)
0% RAP / 15% RAS	No (0.1482)	No (0.7887)
15% RAP / 15% RAS	No (0.0648)	No (0.6667)
25% RAP / 0% RAS	Yes (0.0041)	No (0.7887)
25% RAP / 15% RAS	No (0.1362)	No (0.5000)
0% RAP / 30% RAS	No (0.0679)	No (0.2746)

*Difference equals the mean low critical temperature of the blended binder minus the mean low critical temperature of the virgin binder; evaluation based on a significance level of 0.05.

High Critical Temperature

The trend for the high critical temperatures of the blended binders shown in Figure 6.1 mirrors that for the low temperature results where results at both temperature ranges can be compared. That is, it reveals a steady increase in high critical temperature up to a virgin binder replacement level of 25 percent followed by little change with further increases in reclaimed binder content up to the 40 percent replacement level. Above this replacement level, the results indicate a pronounced increase in high critical temperature.

These observations are illustrated in greater detail in Figure 6.4, which displays the mean high temperature and corresponding 95 percent confidence interval (utilizing Fisher's least significant differences) for each total virgin binder replacement level. It indicates that the high critical temperatures of the blends with 25 percent or more reclaimed binder were significantly different from that of the virgin binder extracted and recovered from the laboratory-fabricated mixture. It also indicates that there were no significant differences between high critical temperatures for the blends with total virgin binder replacement levels between 15 and 40 percent.

The results shown in Figure 6.4 also indicate a noteworthy jump in high critical temperature of about 20°C when the total virgin binder replacement was increased from 40 percent to 45 percent, but a further 10 percent increase did not have a significant effect. That is, the high critical temperatures of the blends with 45 and 55 percent reclaimed binder had significantly higher high critical temperatures than did the blends with 40 percent or less reclaimed binder, but no significant difference existed between the high critical temperatures of the blends with 45 and 55 reclaimed binder. This suggests a threshold of 40 percent virgin binder replacement, beyond which the high critical temperature of the blended binder is overwhelmingly dominated by the stiffness of the reclaimed binder(s). This is not to say the high critical temperature of the blended binder is not significantly influenced by the stiffness of the reclaimed binder(s) below this threshold, only that the impact was lower below the threshold than above it.

Student's t-tests were also conducted to determine which, if any, of the differences shown in Figure 6.4 were greater than 6, 12, or 18°C (i.e., one to three Superpave grades). Using a significance level of 0.05 as the criterion for establishing whether or not significant differences existed, the results listed in Table 6.3 were obtained. They indicate that the high critical temperatures of most of the blended binders at replacement levels greater than 15 percent resulted in an increase of one Superpave grade, but only those with 45 and 55 percent replacement levels resulted in more than one grade increase. It is not clear why the blend with a replacement level of 40 percent resulted in a one-grade increase while the blends with 25 and 30 percent did not, but Section 7.1 discusses this in further detail.

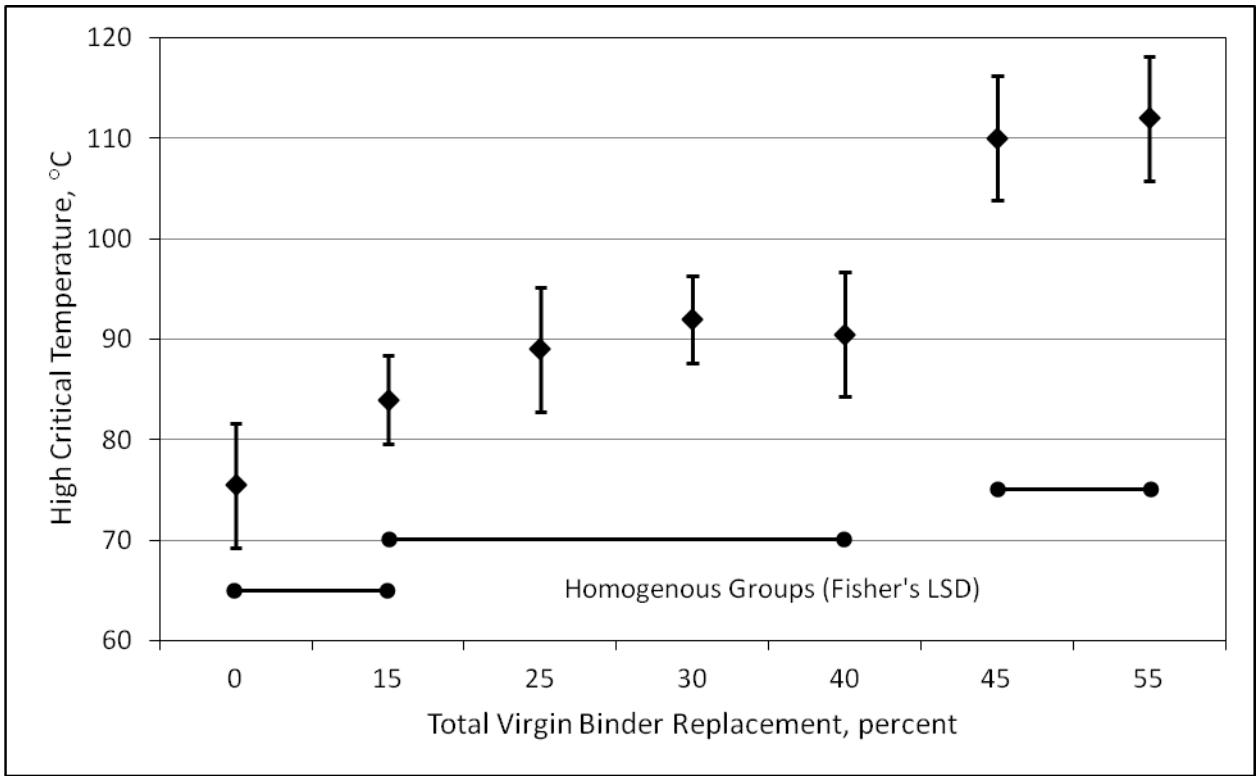


Figure 6.4: Comparison of High Critical Temperatures versus Total Percent Binder Replacement using Fisher's Least Significant Difference Intervals

Table 6.3: Statistical Comparison (Student's t-test) of the High Critical Temperatures of the Combined Blended Binders Relative to that of the Virgin Binder

Total Virgin Binder Replacement, percent	Is Difference* > 6°C (i.e., at least one Superpave grade)? (p-value)	Is Difference* > 12°C (i.e., at least two Superpave grades)? (p-value)	Is Difference* > 18°C (i.e., at least three Superpave grades)? (p-value)
15	No (0.3664)	No (0.9445)	No (0.9818)
25	Yes (0.0340)	No (0.2713)	No (0.9196)
30	Yes (0.0336)	No (0.1726)	No (0.6302)
40	No (0.1224)	No (0.3207)	No (0.6793)
45	Yes (0.0097)	Yes (0.0153)	Yes (0.0274)
55	Yes (0.0085)	Yes (0.0130)	Yes (0.0222)

*Difference equals the mean low critical temperature of the blended binder minus the mean low critical temperature of the virgin binder; evaluation based on a significance level of 0.05.

Additional analysis was conducted to determine if differences existed between high critical temperatures of the blended binders based on the type of reclaimed binder used for partial virgin binder replacement. Figure 6.5 provides the results of this analysis showing the mean low critical temperature and corresponding 95 percent confidence interval (utilizing Fisher's least significant differences) for each blend of reclaimed binders in relation to one another and to the virgin binder. Inferences that can be drawn from these results are as follows:

- The high critical temperature of the blend with 15 percent RAP binder and no RAS binder (shown as 15/0) was not significantly different from that of the virgin binder. For all other blends, the difference was significant.

- The high critical temperature of the blend containing no RAP binder and 15 percent RAS binder (shown as 0/15) was greater than that of the blend containing 15 percent RAP binder and no RAS binder (shown as 15/0), but the difference was not significant.

- Significant differences did not exist between high critical temperatures of blends containing up to 25 percent RAP binder and up to 15 percent RAS binder.

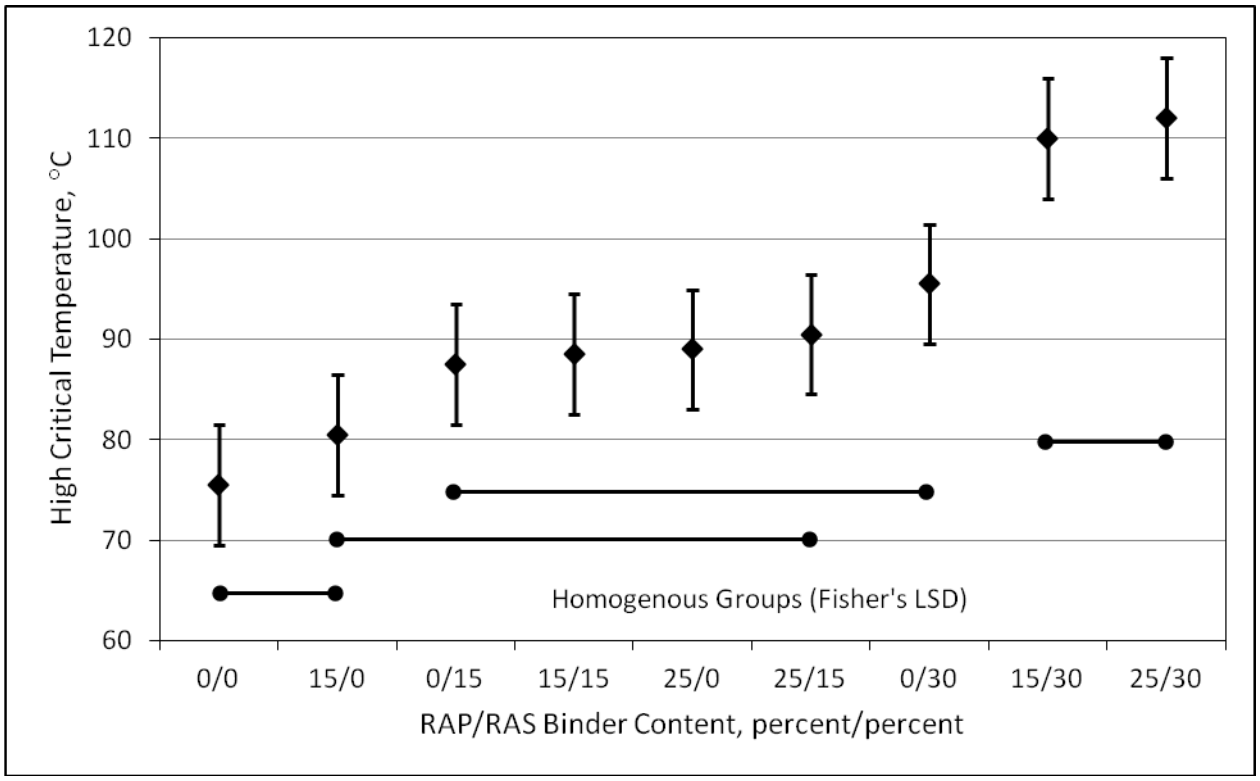


Figure 6.5: Comparison of High Critical Temperatures versus RAP/RAS Binder Replacement Levels using Fisher's Least Significant Difference Intervals

- The high critical temperature of the blend containing no RAP binder and 30 percent RAS binder (shown as 0/30) was significantly different from that of the blend containing 15 percent RAP binder and no RAS binder (shown as 15/0), but it was not significantly different from the high critical temperatures of the other blends.

- The above inferences exactly match those drawn from the results shown in Figure 6.3 for the low critical temperature comparisons.

- The high critical temperatures of the blends with 45 and 55 percent reclaimed binder were significantly higher than those of all other blends, but not significantly different from one another.

Finally, Table 6.4 lists of the results of Student's t-tests conducted to determine if the differences shown if Figure 6.5 were greater than 6, 12, or 18°C (i.e., one to three Superpave grades). Again, a significance level of 0.05 was used as the criterion for determining significant differences. As shown, the majority of blends resulted in an increase of one Superpave grade, but only those with virgin binder replacement levels of 45 or 55 percent resulted in more than one grade increase; and, in fact, these two replacement levels resulted in an increase of at least three grades. It is not clear why the blend with 25 percent RAP binder and 15 percent RAS binder did not result in a one-grade increase while two of the blends with lower total virgin binder replacement levels did, but Section 7.1 discusses this in further detail.

Table 6.4: Statistical Comparison (Student's t-test) of the High Critical Temperatures of the Individual Blended Binder Combinations Relative to that of the Virgin Binder

RAP/RAS Content, percent/percent	Is Difference* > 6°C (i.e., at least one Superpave grade)? (p-value)	Is Difference* > 12°C (i.e., at least two Superpave grades)? (p-value)	Is Difference* > 18°C (i.e., at least three Superpave grades)? (p-value)
15% RAP / 0% RAS	No (0.5700)	No (0.9392)	No (0.9811)
0% RAP / 15% RAS	No (0.1794)	No (0.4679)	No (0.7887)
15% RAP / 15% RAS	Yes (0.0189)	No (0.2113)	No (0.9523)
25% RAP / 0% RAS	Yes (0.0286)	No (0.2113)	No (0.9082)
25% RAP / 15% RAS	No (0.1131)	No (0.2948)	No (0.6530)
0% RAP / 30% RAS	Yes (0.0422)	No (0.0998)	No (0.3172)
15% RAP / 30% RAS	Yes (0.0092)	Yes (0.0145)	Yes (0.0256)
25% RAP / 30% RAS	Yes (0.0081)	Yes (0.0123)	Yes (0.0208)

*Difference equals the mean low critical temperature of the blended binder minus the mean low critical temperature of the virgin binder; evaluation based on a significance level of 0.05.

Blending Charts

The critical temperatures obtained from tests on the recovered binders were also used to evaluate the effectiveness of blending charts in predicting the critical temperatures of the blended binders. This was accomplished through use of Equation 2.2 shown in Section 2.1.1, which can be used with known properties of the virgin and recovered RAP binders to determine the percentage of RAP to add to a mixture in order to achieve a target grade of the blended binder. Equation 2.2 can be rearranged to provide the critical temperature of the blended binder as a function of the critical temperatures of the virgin and RAP binders and the percentage of RAP binder as shown in Equation 6.1:

$$T_{Blend} = T_{Virgin} + \frac{\%RAP}{100}(T_{RAP} - T_{Virgin}) \quad (6.1)$$

where:

T_{Blend} = critical temperature of the blended binder;
T_{Virgin} = critical temperature of the virgin binder;
T_{RAP} = critical temperature of the recovered RAP binder; and
%RAP = percentage of RAP binder in the blend.

The second term to the right of the equal sign provides the incremental increase in critical temperature relative to the critical temperature of the virgin binder arising from the RAP binder assuming that the increase varies linearly between the critical temperatures of the virgin and RAP binders. If the incremental increase due to the RAS binder also varies linearly between the critical temperatures of the virgin and RAS binders, then a third term can be added to Equation 6.1 to account for this additional incremental increase, as is shown in Equation 6.2, to determine the critical temperature of a blend containing both RAP and RAS binders:

$$T_{Blend} = T_{Virgin} + \frac{\%RAP}{100}(T_{RAP} - T_{Virgin}) + \frac{\%RAS}{100}(T_{RAS} - T_{Virgin}) \quad (6.2)$$

where:

T_{Blend} = critical temperature of the blended binder;
T_{Virgin} = critical temperature of the virgin binder;
T_{RAP} = critical temperature of the recovered RAP binder;
T_{RAS} = critical temperature of the recovered RAS binder;
%RAP = percentage of RAP binder in the blend; and
%RAS = percentage of RAS binder in the blend.

Table 6.5 lists the measured high critical temperatures determined from rheological tests on the blended binders recovered from the laboratory-fabricated mixtures. It also lists the predicted high critical temperature (T_{Blend}) for each blend of binders containing reclaimed binders determined using Equation 6.2. Separate predictions of T_{Blend} were determined using 1) the high

critical temperature of the as-received virgin binder, and 2) the virgin binder recovered from the laboratory-fabricated mixture without reclaimed binders.

Table 6.5: Measured versus Predicted High Critical Temperatures of the Blended Binders Recovered from the Laboratory-Fabricated Mixtures

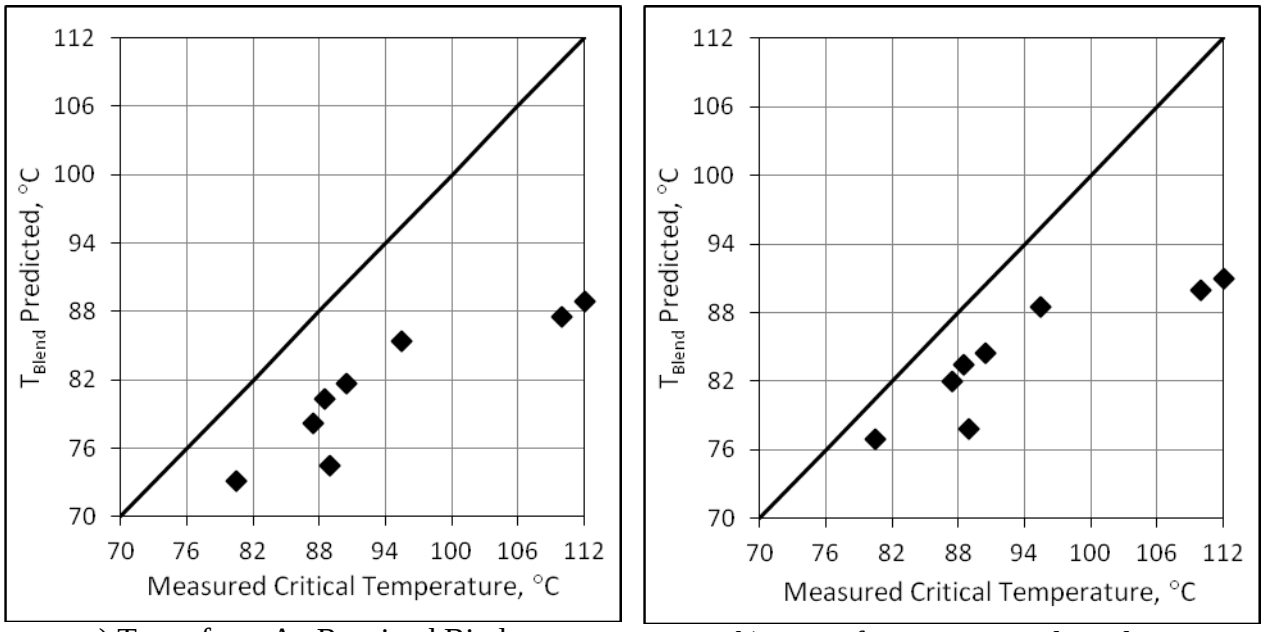
Percentage of reclaimed binder in the blend		Measured high critical temperature of the blend (°C)	Predicted T_{blend}* (°C) using the high critical temperature of the	
RAP Binder	RAS Binder		As-received virgin binder	Recovered virgin binder
15	0	80	73	77
0	15	88	78	82
25	0	89	74	78
0	30	96	85	89
15	15	88	80	84
25	15	90	82	84
15	30	110	88	90
25	30	112	89	91

*Determined using Equation 6.2

As indicated, Equation 6.2 predicted high critical temperatures lower than those determined through measurements conducted on the blended binders. Figure 6.6 presents the results graphically and illustrates the magnitude of differences between the predicted and measured values.

A similar analysis was conducted for the low critical temperatures. Unfortunately, since the low critical temperature of the RAS binder could not be determined, the analysis could be performed for only two of the blends; namely, those not containing RAS binder. Nevertheless, Table 6.6 lists the measured and predicted low critical temperatures. As indicated, and as with the results for the high critical temperatures, Equation 6.2 predicted low critical temperatures lower than those determined through measurements conducted on the blended binders, particularly for the blend containing 25 percent RAP binder.

The outcomes presented herein appear to be significantly incongruent with those observed by others (e.g., *McDaniel et al 2000*, and *Bonaquist 2011*). Further discussion is provided in Section 7.1.



a) T_{Virgin} from As-Received Binder

b) T_{Virgin} from Recovered Binder

Figure 6.6: Comparison of Predicted and Measured High Critical Temperatures of the Blended Binders Recovered from the Laboratory-Fabricated Mixtures

Table 6.6: Predicted versus Measured Low Critical Temperatures of the Blended Binders Recovered from the Laboratory-Fabricated Mixtures

Percentage of reclaimed binder in the blend		Measured low critical temperature of the blend (°C)	Predicted T_{blend}* (°C) using the low critical temperature of the	
RAP Binder	RAS Binder		As-received virgin binder	Recovered virgin binder
15	0	-22	-24	-26
25	0	-16	-22	-24

*Determined using Equation 6.2

6.1.2 Ignition Oven Calibration Factors

The data listed in Table 5.6 were analyzed to determine if the binder contents derived from burning the mixtures in an ignition oven were significantly different from one level of virgin binder replacement to another. This was accomplished using a one-way analysis of variance (ANOVA) with uncorrected binder content via the ignition oven test as the dependent variable and reclaimed binder content as the single factor with various levels. Table 6.7 displays the results from the ANOVA and indicates a p-value of 0.1813. The results provide strong evidence that there was not a statistically significant difference in uncorrected binder content via ignition oven test from one virgin binder replacement level to another (including no replacement) at a confidence level of 95 percent (i.e., p-value > 0.05).

Table 6.7: ANOVA Results for Determining Significance of Virgin Binder Replacement Level on Uncorrected Binder Content Determined by Ignition Oven

Source	Sum of Squares (Type III)	df	Mean Square	F-ratio	p-value
Between groups	0.1259	5	0.02518	1.79	0.1831
Within groups	0.1824	13	0.01403		
Total (Corrected)	0.3083	18			

Figure 6.7 illustrates this graphically showing the individual means and corresponding 95 percent confidence intervals for each level of reclaimed binder content. Since all of the confidence intervals embrace the grand mean, none of the mean values can be said to be different from the grand mean and, hence, not different from one another.

Despite this, it is difficult to ignore the trend in binder contents obtained from the ignition oven tests. The highest binder content was obtained from the mixture with no reclaimed materials (shown as 0/0) and the lowest was obtained from the mixture with no RAP binder and the greatest percentage of RAS binder (i.e., the mixture with 30 percent RAS binder shown as 0/30). Note also the three lowest binder contents were obtained from the mixtures with RAS binder and that the mixtures with only RAP binder had slightly higher binder contents, but still lower than that of the mixture without reclaimed binder.

Figure 6.7 also shows the binder contents used in fabricating the mixtures, as well as the grand mean of these binder contents. A paired t-test was conducted with a null hypothesis of no difference in mean binder contents (i.e., mean uncorrected binder content via ignition oven test minus mean batched binder content equals zero) against an alternate hypothesis of the difference in mean binder contents not equaling zero. This analysis provided a p-value of 7.205×10^{-15} (i.e., essentially zero) indicating strong evidence to reject the null hypothesis and accept the alternate hypothesis; or, in other words, to suggest a significant difference in binder contents obtained from ignition oven tests and those used to fabricate the mixtures (with almost 100 percent certainty).

The analysis also provided the mean difference in binder contents as well as the 95 percent confidence interval about this mean. As indicated in Figure 6.7, the mean difference was 0.68 percent and the 95 percent confidence interval was from 0.62 to 0.74 percent.

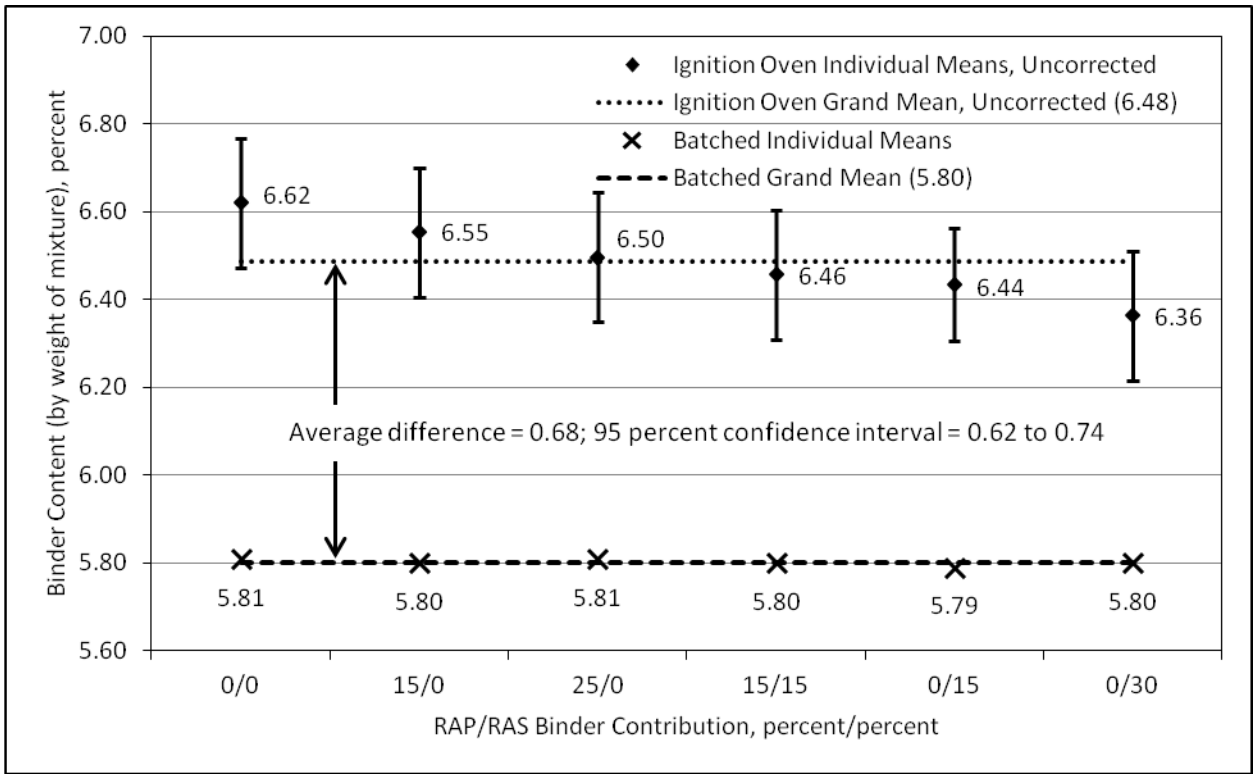


Figure 6.7: Differences between Batched Binder Contents and those Determined by Burning in an Ignition Oven

Similar analyses (i.e., paired t-tests) were conducted to determine the mean differences between batched binder contents and those obtained from the ignition oven tests (again, uncorrected) by segregating the results by type of reclaimed binder in the mixture (i.e., none, RAP and virgin binder only, and RAS and virgin binder only). The analyses explicitly excluded the results from tests on the RAP/RAS mixture in order to make comparisons between mixtures containing only virgin and RAP binders with those containing only virgin and RAS binders. Table 6.8 provides a summary of these analyses, including the results from above for the entire data set. As indicated, none of the differences were determined to be equal to zero at a 95 percent confidence level (all p-values < 0.05) providing strong evidence that the uncorrected binder contents determined from the ignition oven tests were significantly different from the binder contents used in fabricating the mixtures. Further, the mean differences ranged from 0.61 percent for the mixture with the RAS/virgin binder blend to 0.81 percent for the mixture with only virgin binder. Note also that only one of the 95 percent confidence intervals (the one for the mixture with the RAS/virgin binder blend) contained a value of 0.50 (i.e., the current correction factor applied to ignition oven test results).

Table 6.8: Paired t-test Results to Determine Mean Differences between Batched Binder Contents and Uncorrected Binder Contents Derived from Ignition Oven Testing

Type of Binder Blend	Paired t-test p-value	Is difference equal to zero?*	Mean difference (and 95 percent confidence interval), percent
All types	7.205×10^{-15}	No	0.68 (0.62 to 0.74)
Virgin binder only	3.387×10^{-3}	No	0.81 (0.61 to 1.01)
RAP & virgin binder only	2.383×10^{-6}	No	0.72 (0.64 to 0.80)
RAS & virgin binder only	6.084×10^{-5}	No	0.61 (0.46 to 0.76)

*Determined using a significance level of 0.05 (i.e., 95 percent confidence level); a difference not equal to zero indicates a significant difference between results at this significance level.

The binder contents of the various mixtures were also determined by extraction (see Table 5.6). These data were compared with the uncorrected binder contents derived from the ignition oven tests using a paired t-test with a null hypothesis of the mean differences equaling zero and an alternate hypothesis of the mean differences not equal to zero. The results of this analysis indicated a mean difference of 0.05 percent and a p-value of 0.6941 providing strong evidence of no statistically significant differences in mean binder contents between the two measurement methods at a 95 percent confidence level (i.e., p-value > 0.05). Hence, despite the apparent inconsistencies between some of the results listed in Table 5.6, the statistical analyses indicated that these were not significantly different.

6.2 PILOT STUDIES

6.2.1 Properties of Plant-Mixed Materials

Binder contents of the plant-mixed materials determined by extraction were compared with those derived from ignition oven tests using a paired t-test to determine if the differences were equal to zero (null hypothesis). These comparisons were made to test the reasonableness of the ignition oven test results under the assumption that the results from the extractions were more accurate in that loss of aggregate is not a factor with extractions if conducted properly.

Table 6.9 lists the results and indicates that significant differences did not exist between binder contents determined by the two methods for only one of the four mixtures evaluated (i.e., the RAP/RAS mixture on the US 20 project) at a 95 percent confidence level. Note, however, if the confidence level were reduced to 90 percent, significant differences between binder contents determined by the two methods would not exist between any of the mixtures evaluated. Hence, based on these analyses, there is less than a 10 percent chance that the binder contents determined using the ignition oven method were different from the binder contents determined through extractions, thereby providing strong evidence that the ignition oven results appear to be reasonable.

Table 6.9: Comparison of Extracted Binder Contents and Uncorrected Binder Contents Derived from Ignition Oven Testing

Project	Mixture	Sample No.	Binder Content, percent by wt.		Paired t-test p-value	Is difference equal to zero?[2]
			Extraction	Ignition[1]		
I-5	RAP-only	1	5.44	6.24	0.04238	No
		2	5.58	6.28		
	RAP/RAS	1	5.43	6.23	0.04434	No
		2	5.30	6.22		
US 20	RAP-only	1	5.53	6.78	0.01016	No
		2	5.71	6.66		
		3	5.42	6.77		
	RAP/RAS	1	6.04	6.73	0.09689	Yes
		2	5.73	6.67		

[1]Uncorrected
[2]Determined using a significance level of 0.05 (i.e., 95 percent confidence level); a difference not equal to zero indicates a significant difference between results at this significance level.

6.2.2 Properties of Field-Compacted Mixtures

In-Place Density

The results listed in Table 5.8 were compared to determine if differences in variability existed between the various methods of density measurements utilized during the construction of the pavements. That is, the standard deviations of the nuclear density gauge results determined by ODOT personnel were compared with those determined by contractor personnel, and the standard deviations of both sets of nuclear gauge results were compared with the standard deviations of the pavement core density results. Using a null hypothesis of equal standard deviations and an alternate hypothesis of unequal standard deviations, F-tests were performed to make these comparisons.

Table 6.10 lists the p-values obtained from the statistical comparisons, which represent the probability of the standard deviations of the two sets of density measurements compared not being significantly different. As indicated, all p-values significantly exceeded 0.05 providing strong evidence that none of the pairs of standard deviations were significantly different from one another at a 95 percent confidence level.

Table 6.10: Comparison of In-Place Density via Nuclear Density Gauges and Pavement Cores

Project	Mixture	F-test p-value[1]			Average Difference[2], lb/ft[3]			Standard Deviation of Differences[3], lb/ft[3]		
		ODOT versus Contr.	Core versus ODOT	Core versus Contr.	ODOT versus Contr.	Core versus ODOT	Core versus Contr.	ODOT versus Contr.	Core versus ODOT	Core versus Contr.
I-5	RAP-only	---	---	0.7514	---	---	0.4	---	---	0.8
	RAP/RAS	---	---	0.9927	---	---	0.6	---	---	0.4
US 20	RAP-only	0.8703	0.9125	0.9574	-0.8	-0.2	-1.0	0.8	0.6	0.8
	RAP/RAS	0.6114	0.8714	0.7278	-1.0	-2.1	-3.1	0.9	0.3	0.7

[1]Probability of the standard deviations of the two sets of density measurements compared not being significantly different
[2]Average of the differences between density measurements at each test location listed in Table 5.8
[3]Standard deviation of the differences between density measurements at each test location listed in Table 5.8

Table 6.10 also lists the average differences and standard deviations of the differences for each set of comparisons. Considering the average differences, all comparisons indicate differences of 1.0 lb/ft^3 or less except for two of the comparisons for the RAP/RAS mixture on the US 20 project. Note, however, the average difference between the ODOT and contractor results for this mixture was only 1.0 lb/ft^3. The results also indicate that the standard deviations of the differences of all comparisons were less than 1.0 lb/ft^3.

Mixture Stiffness

Figures 6.8 and 6.9 display the averages of the dynamic modulus results listed in Table 5.9 for the beams obtained from the I-5 and US 20 projects, respectively, up to the 10 Hz loading frequency; the results for the 15 Hz loading frequency are not shown (for brevity), but they do not alter the outcomes of the analysis. Each figure also shows the 95 percent confidence intervals about the means at each loading frequency.

The analysis of results for the two mixtures placed on the I-5 project (Figure 6.8) indicated significant differences between dynamic moduli at all loading frequencies at a 95 percent confidence level as evidenced by no overlap of the confidence intervals. Further, it showed that the RAP-only mixture had significantly higher moduli than the RAP/RAS mixture at all loading frequencies.

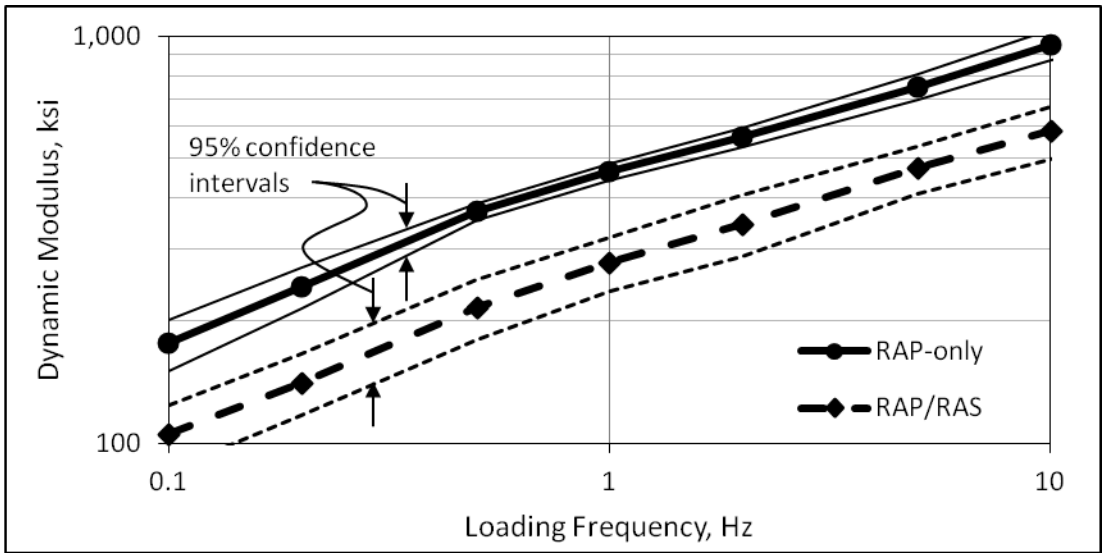


Figure 6.8: Dynamic Moduli of the In-Place Mixtures Placed on the I-5 Project

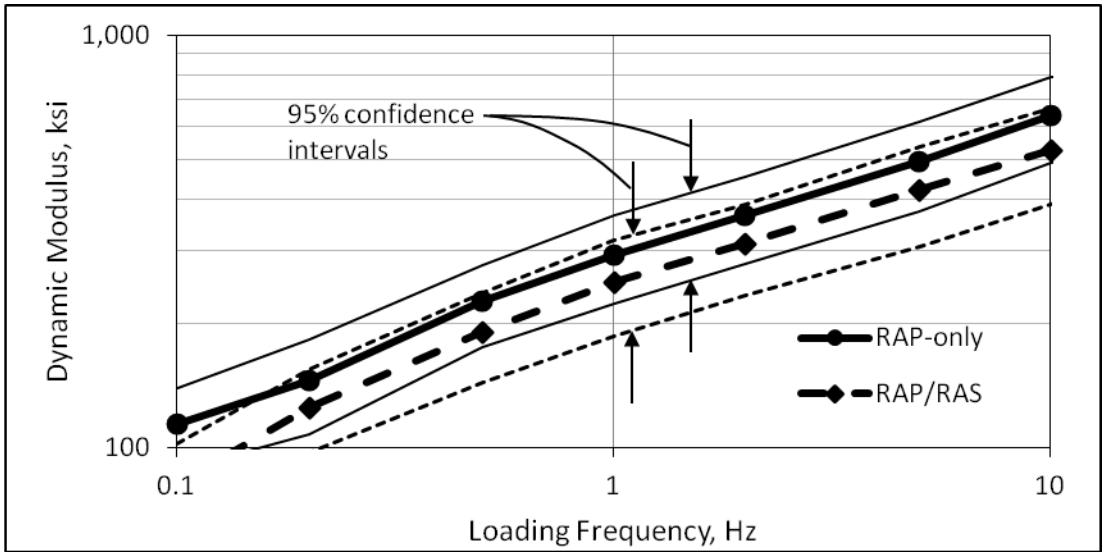


Figure 6.9: Dynamic Moduli of the In-Place Mixtures Placed on the US 20 Project

Similarly, Figure 6.9 shows that the RAP-only mixture placed on the US 20 project also had higher moduli than the RAP/RAS mixture. However, in this case, the moduli were not significantly different between the two mixtures at the 95 percent confidence level as evidenced by the overlap of confidence intervals.

At the request of ODOT personnel, the dynamic modulus results were compared with those from a previous ODOT project that involved a laboratory-based evaluation of dynamic moduli of dense-graded HMA (*Lundy et al. 2005*). In the previous study (herein referred to as SPR 610), mixtures were prepared using a single aggregate source and gradation, and four different binder grades (PG 64-22, PG 70-22, PG 70-28, and PG 76-22). Binder contents were 5.8% and 6.0% while air void contents were intentionally varied with targets of 3.0%, 4.0%, 5.0%, and 7.0%.

Sixteen different combinations were tested in accordance with AASHTO TP 62-03 to develop master curves for each combination.

Specific mixtures from the previous study were selected for comparison purposes by choosing only those mixtures that had similar binder grades and air void contents to the four mixtures placed during the pilot studies. Table 6.11 summarizes the properties of the mixtures used for making the dynamic moduli comparisons. As indicated, most of the mixtures had the same binder grade but, despite attempts to select mixtures with approximately equal air void contents, all of the mixtures selected from the SPR 610 study had lower air void contents relative to those from the pilot studies.

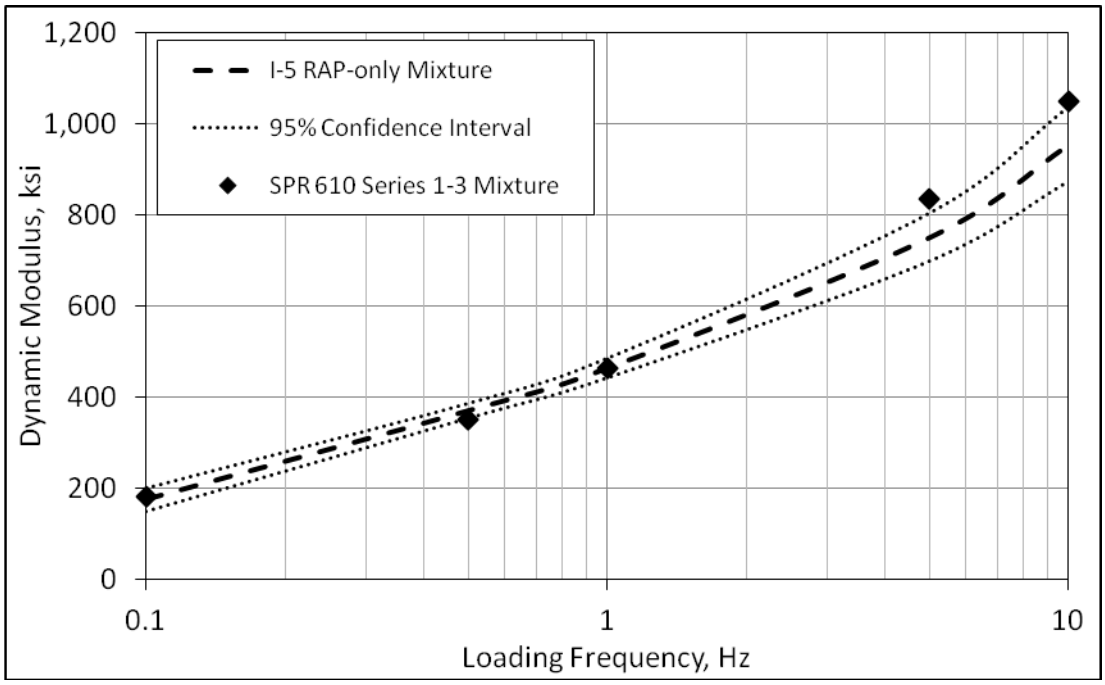
Table 6.11: Properties of the Mixtures Used for Comparing Dynamic Moduli

				Air Void Content, percent		
Mixture	Binder Content*, percent	Critical Temps (°C)	Binder Grade	Before Coring/ Sawing	After Coring/ Sawing	After Sawing
I-5 RAP-only	5.5/6.3	72, -28	PG 70-28ER	---	---	4.1
SPR 610 Series 1-3	5.8	---	PG 70-28	3.7	2.6	---
I-5 RAP/RAS	5.4/6.2	80, -26	PG 76-22ER	---	---	8.2
SPR 610 Series 2-4	5.8	---	PG 76-22	6.8	5.7	---
US 20 RAP-only	5.6/6.7	68, -29	PG 64-28ER	---	---	5.6
SPR 610 Series 4-3	6.0	---	PG 70-28	4.9	3.7	---
US 20 RAP/RAS	5.9/6.7	74, -28	PG 70-28ER	---	---	9.0
SPR 610 Series 2-3	5.8	---	PG 70-28	6.7	5.3	---

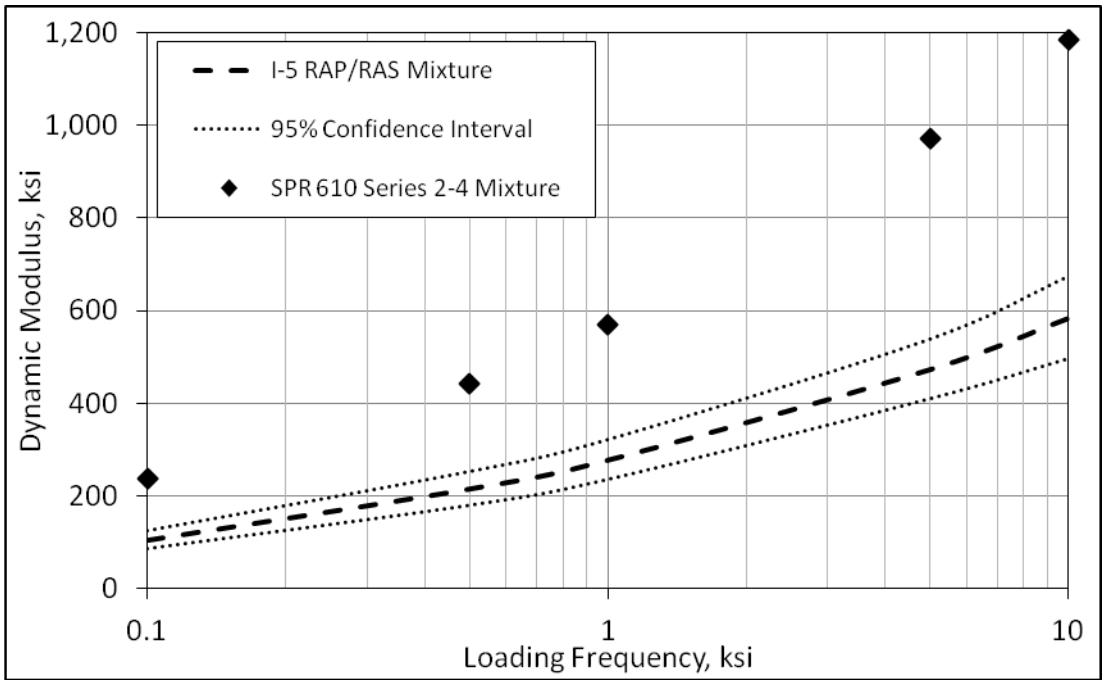
*By total weight of mixture. The binder contents via extraction and ignition oven tests are reported for the mixtures from the I-5 and US 20 pilot studies (see Table 5.7).

It is worthy to mention two additional differences that may have a bearing on the comparisons. Firstly, the specimens tested in this study were prisms (beams) and tested in four-point bending, whereas in the SPR 610 study the specimens were cylinders tested in repeated-load axial compression. Secondly, the comparisons included only those results from the SPR 610 study that were obtained from tests conducted at 21.1°C, whereas the tests performed on the mixtures from the pilot studies were conducted at 20°C.

Figures 6.10 and 6.11 display the comparisons graphically. Figure 6.10 shows the comparisons for the I-5 mixtures, while Figure 6.11 shows the comparisons for the US 20 mixtures. The figures include the 95 percent confidence intervals for the moduli obtained from the pilot study mixtures, but not for the moduli obtained from the SPR 610 mixtures since the report included only average values (i.e., variances were not provided).

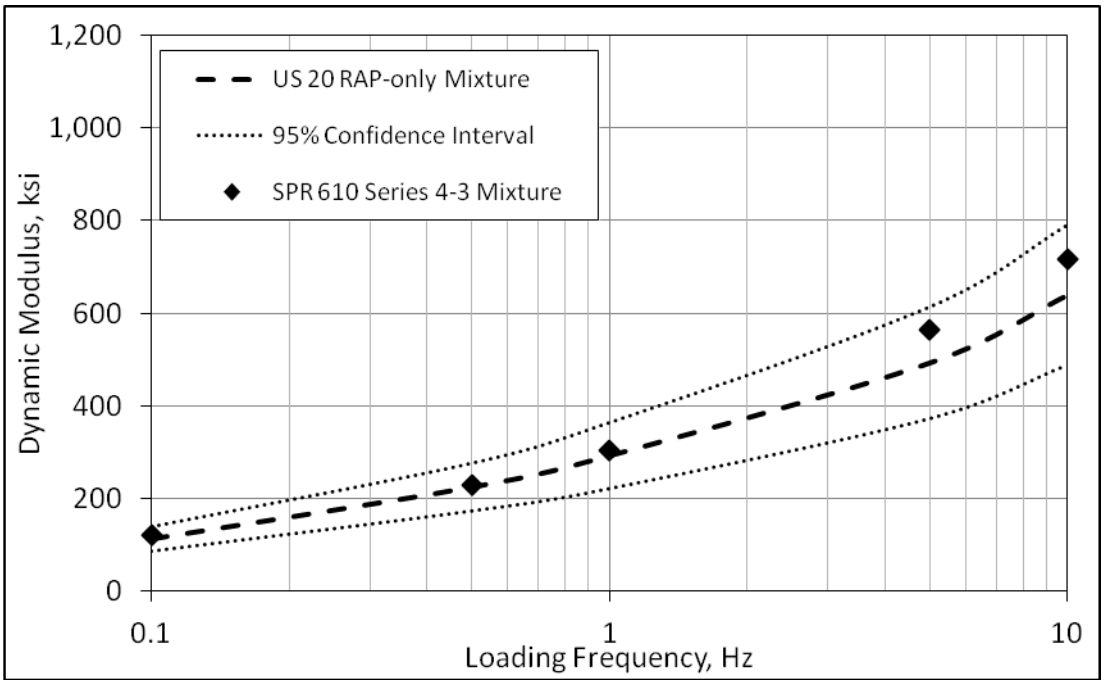


a) I-5 RAP-only mixture versus SPR 610 Series 1-3 mixture

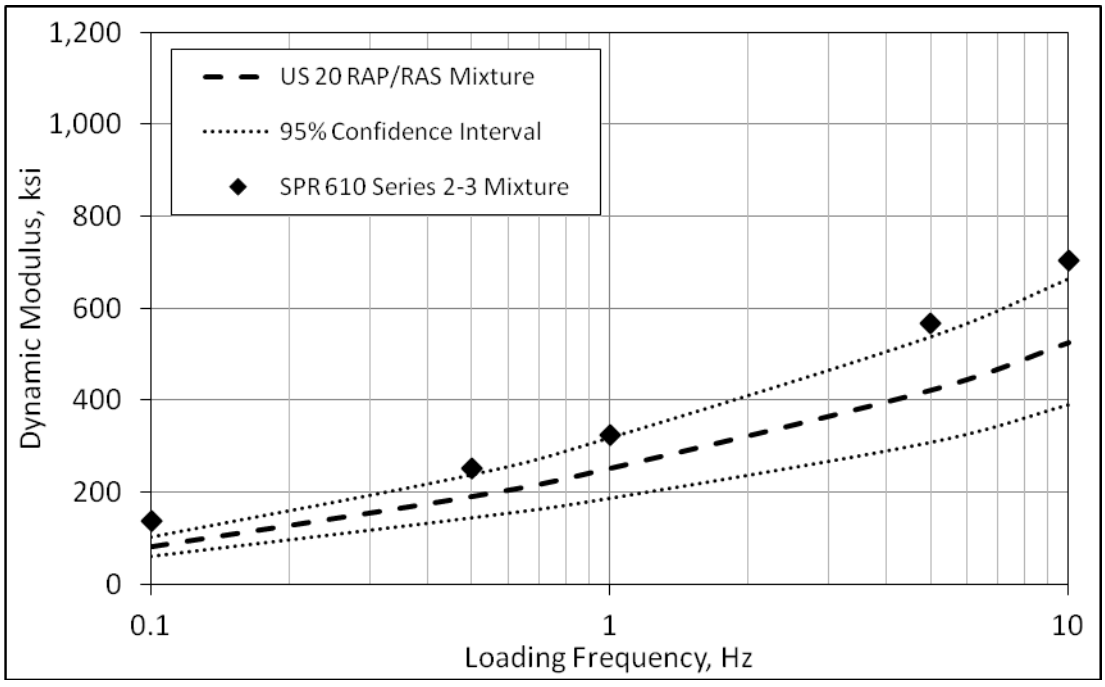


b) I-5 RAP/RAS mixture versus SPR 610 Series 2-4 mixture

Figure 6.10: Comparison of Dynamic Moduli: I-5 Pilot Study Mixtures versus SPR 610 Mixtures



a) US 20 RAP-only mixture versus SPR 610 Series 4-3 mixture



b) US 20 RAP/RAS mixture versus SPR 610 Series 2-3 mixture

Figure 6.11: Comparison of Dynamic Moduli: US 20 Pilot Study Mixtures versus SPR 610 Mixtures

Figures 6.10a and 6.11a show that there was close agreement between the moduli of the RAP-only mixtures and those obtained from the SPR 610 mixtures. At most loading frequencies, the results from the SPR 610 mixtures fall within the 95 percent confidence intervals for the results obtained from the pilot study mixtures indicating no statistically significant differences.

Figures 6.10b and 6.11b show that the RAP/RAS mixtures had lower moduli at all loading frequencies relative to those obtained from the SPR 610 mixtures. Although it cannot be stated with absolute certainty, Figure 6.10b suggests the likelihood of statistically significant differences between the results obtained from the two studies at a 95 percent confidence level, but Figure 6.11b suggests no statistically significant differences.

Fatigue Properties

Fatigue test results based on the phenomenological approach are shown in Figures 6.12 and 6.13 for the beams obtained from the I-5 and US 20 projects, respectively. The figures show the average number of cycles to a 50 percent reduction relative to initial stiffness (i.e., average cycles to 50% E_0 from Table 5.10) and the corresponding 95 percent confidence intervals about the averages for the two initial strain levels used during the tests. Note that, for display purposes, the results are intentionally plotted with a slight offset from the actual initial strain magnitudes used during testing. In all cases, the confidence intervals overlap indicating no significant differences in fatigue lives between the two types of mixtures placed along each project.

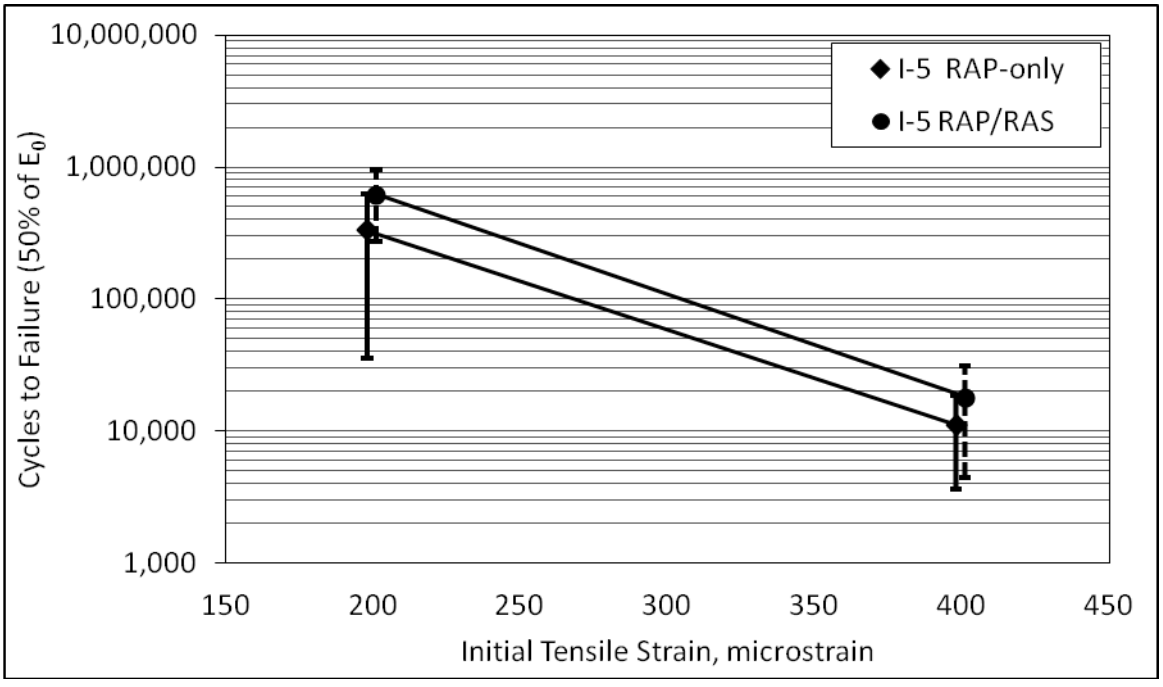


Figure 6.12: Fatigue Lives of the In-Place Mixtures Placed on the I-5 Project Based on the Phenomenological Approach

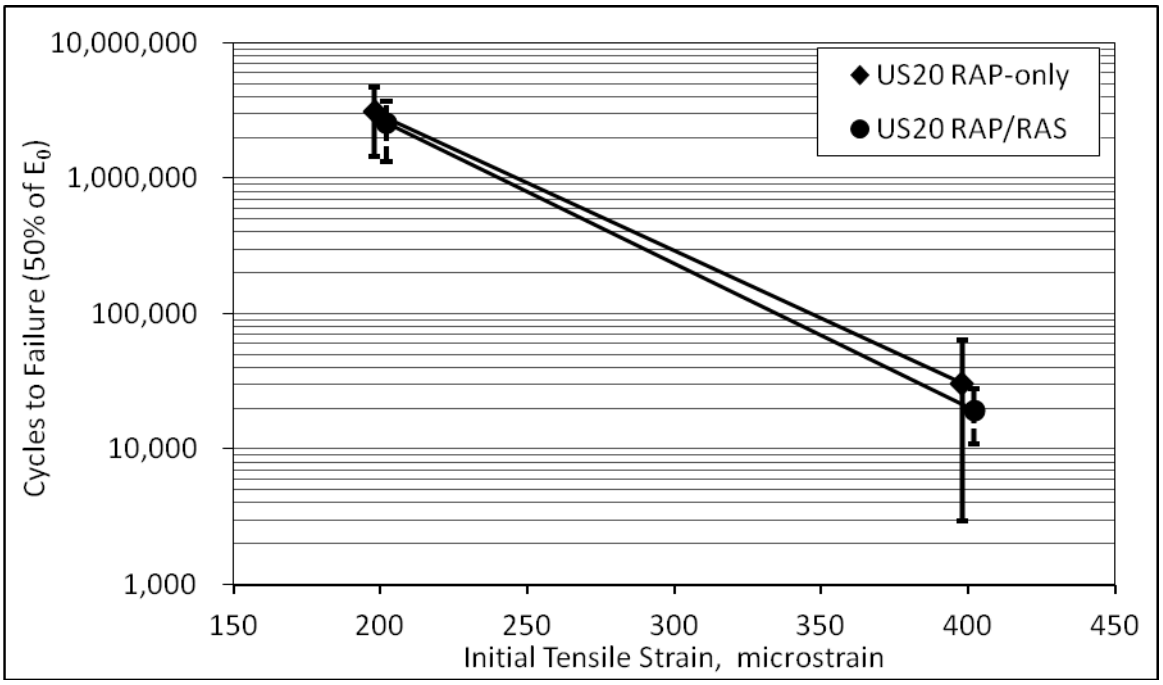


Figure 6.13: Fatigue Lives of the In-Place Mixtures Placed on the US 20 Project Based on the Phenomenological Approach

Comparing the results shown in Figures 6.12 and 6.13 it can be seen that there was no significant difference between mixture performance at the higher initial strain level. However, at the lower initial strain level, the mixtures from the US 20 project required a significantly higher number of cycles to induce a 50-percent reduction relative to initial stiffness suggesting a much higher resistance to fatigue cracking relative to the mixtures from the I-5 project. Section 7.3.2 provides further discussion of these findings.

7.0 DISCUSSION OF RESULTS

7.1 BLENDED BINDER CRITICAL TEMPERATURES

7.1.1 Laboratory-Fabricated Mixtures

Figure 6.1 provides compelling evidence that inclusion of reclaimed binders from RAP and/or RAS in the laboratory-fabricated mixtures resulted in blended binders with higher critical temperatures relative to those of the virgin binder used in the blend. By comparing average values, it would appear that the increases were significant and greater than 6°C (one Superpave grade) in most cases.

Figure 6.2 shows that the low critical temperatures of the blended binders, at all total virgin binder replacement levels evaluated, were indeed significantly different from that of the virgin binder at a 95 percent confidence level. However, Table 6.1 shows that only the mixtures with 25 or 30 percent reclaimed binder resulted in a blended binder where the low temperature component of the binder grade was one Superpave grade (i.e., 6°C) higher than that of the virgin binder, whereas those with either 15 or 40 percent reclaimed binder did not. This seems plausible for the blends with 15 percent total virgin binder replacement (i.e., either 15 percent RAP binder or 15 percent RAS binder), but improbable for the blend with 40 percent virgin binder replacement (which contained 25 percent RAP binder plus 15 percent RAS binder). It should be emphasized here that all blends shown in Figure 6.2 and Table 6.1 contained both RAP binder and RAS binder with the exception of the blend constituting 25 percent total virgin binder replacement, which did not contain any RAS binder.

Figure 6.3 and Table 6.2 provide comparisons of the low critical temperature results for the individual blended binder combinations. Figure 6.3 shows that all blends except for the one with 15 percent RAP binder resulted in blended binders with significantly higher low critical temperatures, at a 95 percent confidence level, than that of the virgin binder. However, Table 6.2 shows that only the blend with 25 percent RAP binder had a low critical temperature of at least one Superpave grade higher than that of the virgin binder.

Similar comparisons were made for the high temperature critical temperatures. The results shown in Figure 6.4 for the high critical temperatures almost exactly mirror those shown in Figure 6.2 for the low critical temperatures, except that a significant difference did not exist between the high critical temperature of the blends with 15 percent reclaimed binder and that of the virgin binder. Figure 6.4 also shows that the high critical temperatures of the blends with 45 percent or more reclaimed binder were significantly different from those of the blends containing lower virgin binder replacement levels. In addition, the results shown in Table 6.3 indicate a grade bump in the high temperature component of the binder grade for the same blends as those for the low temperature component shown in Table 6.1. Again, this seems plausible for the blends with 15 percent total virgin binder replacement, but improbable for the blend with 40 percent virgin binder replacement.

Similarly, the outcomes of the comparisons of the high critical temperatures (Figure 6.5) mirror those of the low critical temperatures (Figure 6.3). However, comparisons to determine if the differences resulted in a grade bump at the high end (Table 6.4) did not exactly match those for the low end (Table 6.2). That is, the blends with 30 percent reclaimed binder (either 15 percent each of RAP and RAS binder or 30 percent of RAS binder) resulted in a grade bump at the high end, but not at the low end.

The apparent irregularities in expected trends (i.e., increased impact due to increased virgin binder replacement level), elaborated upon above, can be summarized as follows:

- The blends with either 25 or 30 percent reclaimed binder resulted in a grade bump (i.e., increase of one Superpave grade relative to that of the virgin binder) for both the low and high temperature components, whereas the blend with 40 percent reclaimed binder did not (see Tables 6.1 and 6.3). However, this may be due to the larger variance in critical temperatures for the blend with 40 percent reclaimed binder relative to those for the blends with 25 or 30 percent reclaimed binder (see Table 5.5).

- The blend with 25 percent RAP binder resulted in a grade bump for the low temperature component, whereas blends with 30 percent or more reclaimed binder did not (see Table 6.2). For the high temperature component, the blend with 25 percent RAP binder also resulted in a grade bump, but the blend with 40 percent reclaimed binder (25 percent RAP binder and 15 percent RAS binder) did not. A larger variance in critical temperatures for the blend with 40 percent reclaimed binder (see Table 5.5) might explain the latter observation, but a similar argument does not appear to be justified for the former observation.

- The findings from the analyses suggest some type of mitigating effect occurred due to combining the RAP and RAS binders. Careful examination of Figures 6.3 and 6.5, and ignoring the results for the two blends with the highest virgin binder replacement levels in Figure 6.5, indicates insignificant increases in blended binder critical temperatures for the RAP/RAS blends relative to those with either just RAP binder or just RAS binder despite having equal or higher total virgin binder replacement levels. For example, the blend with 25 percent RAP binder and 15 percent RAS binder (shown as 25/15 in Figures 6.3 and 6.5) had nearly equal critical temperatures as those for the blend with 25 percent RAP binder. Again, the larger variance in critical temperatures for the 25/15 blend may partly explain this, but a similar observation can be made regarding the blend with 15 percent RAP binder and 15 percent RAS binder (i.e., 15/15) relative to either of the blends with half as much reclaimed binder.

Add to this the comparisons shown Table 7.1. On the I-5 project, the low critical temperatures of the blended binders recovered from the plant-produced mixtures were equal to or lower than that of the virgin binder, and the high critical temperature of the blended binder from the RAP-only mixture was nearly equal to that of the virgin binder. Similarly, only small differences existed between low critical temperatures of the blended binders recovered from the plant-produced mixtures placed on the US 20 project relative to that of the virgin binder, and the high critical temperatures were lower than that of the virgin binder.

Table 7.1: Summary of Critical Temperatures of As-Received Virgin Binders and Recovered Binders from Plant-Mixed Materials

Project	High, Low Critical Temperatures (°C)		
	Virgin Binder[1]	Plant-produced RAP-only Mixture[2]	Plant-produced RAP/RAS Mixture[2]
I-5	71, -26	72, -28	80, -26
US 20	78, -31	68, -30	74, -28

[1]As-received virgin binder (Table 5.1)

[2]Extracted/recovered binder (Table 5.7)

Given the percentages of reclaimed materials in these mixtures (see Tables 4.7 through 4.10), coupled with the stiffness of the reclaimed binders (see Table 5.1), most of these results appeared contrary to expectations (i.e., a harder blended binder relative to the virgin binder). An initial thought as to why this may have occurred centered on the extraction/recovery equipment and procedures, as these were new to the personnel performing the extractions and recoveries. With regard to extracting the binders from the mixtures, the technicians reported that the filters immediately downstream of the extractor unit readily clogged with fine material requiring the use of multiple filters when a mixture contained RAS, potentially resulting in incomplete extraction of the binder from the mixture. However, this did not satisfactorily explain the unexpected results for the mixtures with RAP shown in the above table. Another thought centered on the recovery process. Again, since new equipment was being used, it was suspected that the solvent (toluene) was not being completely removed during the distillation process, which could explain why the unexpected results shown in that above table appeared to affect both types of mixtures (i.e., those with RAP or both RAP and RAS).

This latter consideration appeared more plausible and prompted further investigation. The following section provides a brief description of the investigation followed by a summary of the findings.

7.1.2 WRI Study

Samples of binders and mixtures from both projects were submitted to Western Research Institute (WRI) for analysis to help determine the cause of the unexpected findings listed above in the preceding section. Table 7.2 provides a summary of the materials submitted. As indicated, these included binders extracted/recovered (at ODOT) from the plant-produced mixtures, virgin binders, plant-produced mixtures, and RAP and RAS stockpile samples. Infrared spectroscopic analysis was conducted on the samples of extracted/recovered binders to determine if residual solvent (toluene) from the extraction/recovery process conducted by ODOT was present in the materials. Automated Flocculation Titrimetry (AFT) analysis was conducted using the virgin binders and the binders extracted/recovered at WRI from the plant-produced and stockpile mixtures to determine if the softening of the virgin binder, when blended with RAP and/or RAS binder, was the result of increased compatibility of the materials. The following sections provide brief descriptions of these analyses and summaries of the findings, whereas Appendix E contains the final report of the investigation provided by WRI.

Infrared Spectroscopic Analysis

The binders extracted/recovered by ODOT from the plant-produced mixtures (i.e., samples identified as 10-4969, 10-4098A, 10-4134A, and 10-4612C in Table 7.2) were analyzed using Fourier transform infrared spectroscopy (FTIR) to determine how much infrared light was absorbed by the samples over a range of frequencies. Since molecules absorb specific frequencies based upon their structure, the technique can be used to identify the presence of a particular chemical in the sample.

According to the report provided by WRI, infrared absorbance at wavelengths (i.e., inverse of frequencies) of 693 cm^{-1} and 727 cm^{-1} can be used to detect the presence of toluene. The report acknowledges that absorbance at other wavelengths can be attributed to toluene, but emphasizes that interference by the presence of asphalt binder does not occur at a wavelength of 693 cm^{-1}. It also indicates that the absorbance at a wavelength of 727 cm^{-1} is typically sharper than at a wavelength of 693 cm^{-1}, but the former includes interferences related to the asphalt binder. Hence, the absorbance at a wavelength of 693 cm^{-1} can provide a clear indication of the presence of toluene, whereas the absorbance at a wavelength of 727 cm^{-1} can provide additional evidence, albeit potentially confounded by the presence of asphalt binder.

Figure 7.1 summarizes the results of the analyses conducted by WRI. It shows the absorbance of infrared light by the four extracted/recovered binder samples plus that by a RAS binder sample doped with toluene. Based on these results and according to the report provided by WRI, none of the four extracted/recovered binders analyzed indicated the presence of toluene. The following paragraphs provide further details in support of this outcome.

Table 7.2: Samples Submitted to Western Research Institute (WRI)

Project	Sample ID	Sample Description
I-5	10-4969	Extracted/recovered binder from RAP-only (RO) mixture placed on the I-5 project
	70-22ER	Virgin binder used with RAP-only (RO) and RAP/RAS (RR) on the I-5 project (tank sample)
	I5-RAP	RAP used on the I-5 project (stockpile sample)
	I5-RAS	RAS used on the I-5 project (stockpile sample)
	I5-RO-Mix	HMA containing RAP-only (RO) placed on the I-5 project (plant-mixed field sample)
	I5-RR-Mix	HMA containing RAP and RAS (RR) placed on the I-5 project (plant-mixed field sample)
US 20	10-4098A	Extracted/recovered binder from RAP/RAS (RR) mix placed on the US 20 project
	10-4134A	Extracted/recovered binder from RAP-only (RO) mix placed on the US 20 project
	10-4612C	Extracted/recovered binder from RAP-only (RO) mix placed on the US 20 project
	70-28ER	Virgin binder used with RAP-only (RO) and RAP/RAS (RR) on the US 20 project
	US20-RAP	RAP used on the US 20 project (stockpile sample)
	US20-RAS	RAS used on the US 20 project (stockpile sample)
	US20-RO-Mix	HMA containing RAP-only (RO) placed on the US 20 project (plant-mixed field sample)
	US20-RR-Mix	HMA containing RAP and RAS (RR) placed on the US 20 project (plant-mixed field sample)

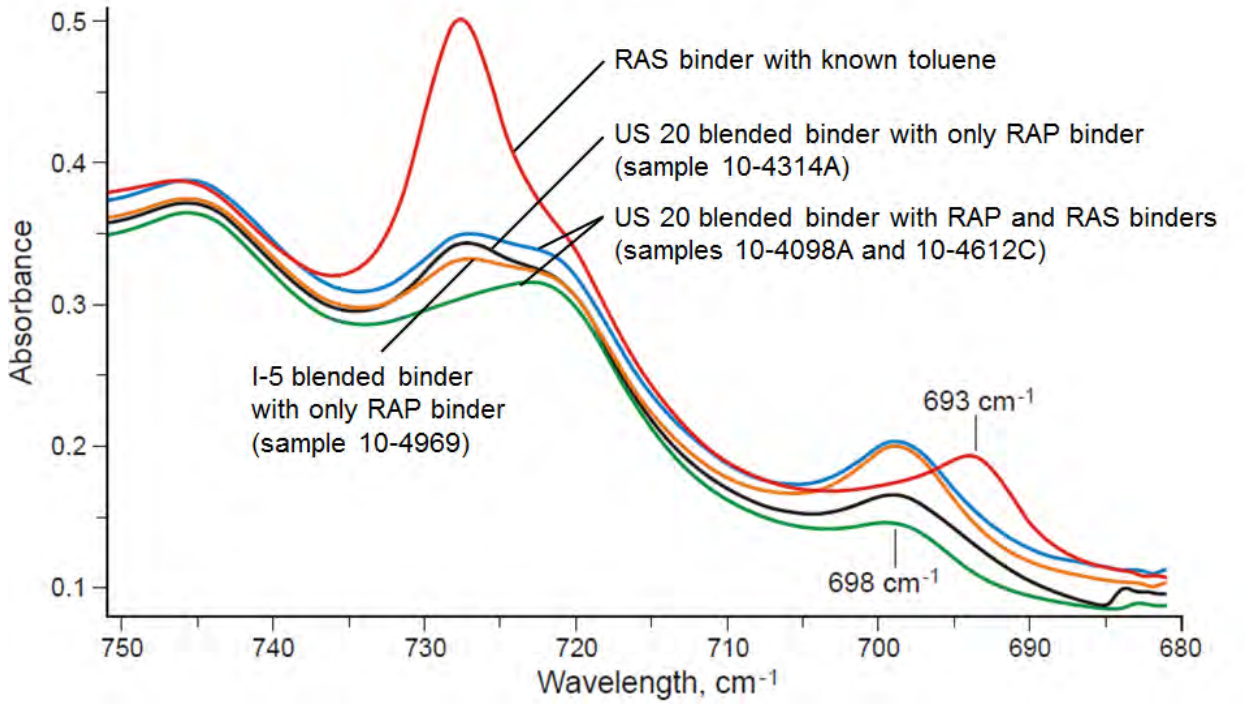


Figure 7.1: FTIR Spectra of Doped RAS Binder and Blended Binders

Considering first the results at a wavelength of 693 cm^{-1}, Figure 7.1 indicates that the absorbance by the extracted/recovered binders was much lower than that of the binder doped with toluene. The results also show absorbance peaked at a wavelength of 698 cm^{-1} for all four extracted/ recovered binders, possibly indicating the presence of toluene. However, the report from WRI indicates that the toluene would have had to be involved in hydrogen bonding with the asphalt binder to such an extent as to shift the absorbance to a greater wavelength which, to date, has not been observed. In addition, the peaks at the wavelength of 727 cm^{-1} did not correlate with those at the wavelength of 698 cm^{-1}, providing evidence that the peaks at the wavelength of 698 cm^{-1} were not related to the presence of toluene.

Gas chromatography-mass spectrometry (GC-MS) analysis was also conducted on the extracted/ recovered binder with the highest absorbance at the wavelength of 698 cm^{-1} (i.e., the one with the highest likelihood of containing toluene). Such analysis is widely used to detect the presence of a particular substance in a given sample and, according to the WRI report, can detect low molecular weight organic substances such as toluene at concentration levels as low as approximately 10 parts per million (an order of magnitude greater sensitivity than that of FTIR). The WRI report indicates that this analysis did detect toluene at a concentration of 0.05 percent, by weight, but such a concentration is much too low to have a softening effect on the rheological properties of asphalt binders. The report concluded that the softening observed in the virgin binder blended with reclaimed binders was due to something other than the presence of toluene.

AFT Analysis

Automated Flocculation Titrimetry (AFT) was conducted on the binders extracted and recovered (by WRI) from the plant-produced and stockpile mixtures as well as on the virgin binders to determine if increased colloidal stability (material compatibility) was responsible for the observed softening of the blended binders. Details of how AFT was conducted were not provided in the report by WRI, but it does contain an explanation of how to interpret the results (see Appendix E), which is synthesized below.

Table 7.3 summarizes the AFT data provided by WRI. The following provides a brief explanation of the parameters listed as well as how to interpret the results:

- P_a is an indication of asphaltene content. It also refers how likely they may be dispersed throughout the system. P_a decreases as asphaltene content increases (e.g., due to aging).

- P_o is an indication of the type of maltene fraction present in the system. It also indicates how well the fraction may disperse the alphaltenes. P_o increases with increasing solvent strength of the maltenes (i.e., increased ability to disperse the asphaltenes).

- P indicates the state of dispersion of the components in the system. P increases with increased dispersion indicating better compatibility of the components.

- δ_{floc}, calculated from the P value, is a solubility parameter corresponding to the start of flocculation of the asphaltenes.

- δ_{oil}, also calculated from the P value, is a solubility parameter directly related to the compatibility of the entire asphalt binder.

- Larger differences between δ_{floc} and δ_{oil} indicate greater compatibility.

- Increased compatibility results in softening of the asphalt binder.

Table 7.3: AFT Data Obtained from the Virgin and Blended Binders

		AFT Parameter Data				Wiehe Blending Numbers	
Project	Binder Blend	P_a	P_o	P		δ_{floc}	δ_{oil}
I-5	Virgin only	0.70	0.75	2.5		7.5	8.4
	Virgin + RAP	0.64	1.2	3.3		7.6	9.3
	Virgin + RAP + RAS	0.62	1.5	3.9		7.6	9.3
US 20	Virgin only	0.73	0.81	3.0		7.4	8.2
	Virgin + RAP	0.63	1.0	2.8		7.4	8.5
	Virgin + RAP + RAS	0.63	1.3	3.4		7.6	9.4

The results indicate that although the P_a parameter indicates higher concentrations of asphaltenes in the blended binders relative to the virgin binders, the P_o values indicate greater solvent strength of the maltenes (and, consequently, greater ability to disperse the alphaltenes). With the exception of the blend with only RAP binder from the US 20 project, the increased solvent

strength of the maltenes more than offset the stiffening effect due to increased asphaltene content as indicated by the increases in the P value.

These observations are corroborated by the Wiehe blending numbers, which show that while the δ_{floc} parameters remained essentially constant, there was a marked increase in the δ_{oil} parameters for the blended binders relative to the virgin binders. The increased differences between these parameters for the blended binders in relation to the respective virgin binders indicates that better compatibility between components (asphaltenes and maltenes) existed in the blended binders.

Conclusions

The following paraphrases the conclusions provided in the WRI report:

- The FTIR analysis of the four samples extracted at ODOT did not contain a sufficient amount of residual toluene to cause softening of the blended binders. The more sensitive GC-MS analysis identified only trace amounts of toluene and helped to resolve some initial concern over an anomalous absorbance at a wavelength of 698 cm^{-1} in the FTIR, providing conclusive evidence that the anomalous absorbance was not related to the presence of toluene.

- Results from AFT analysis indicated that there was indeed improved compatibility of the RAP-only and RAP/RAS binder blends relative to the neat, virgin binders. This improved compatibility was directly related to the softening of the blended materials. The improved compatibility was dominated by the increased solubility strength of the maltene fractions of the blended binders and the resulting improvement of the dispersion of the asphaltenes.

7.1.3 Blending Chart Efficacy

Efforts to correlate predicted critical temperatures through use of blending charts showed that the charts (actually, an equation representing the use of a blending chart) predicted much lower high critical temperatures than those determined from measurements on blended binders extracted and recovered from the laboratory-fabricated specimens. Table 6.5 provides the numerical summary while Figure 6.6 displays the results graphically. The same overall outcome was found for the predicted low critical temperatures, except that the differences between predicted and measured temperatures were much less than the differences for high critical temperatures.

The discussion about increased compatibility of the blended binders relative to the virgin binders in the preceding section cannot explain these discrepancies. In fact, the opposite effect appears to have occurred. Hence, there must be some other reason as to why the measured critical temperatures were so much higher than the predicted temperatures.

As discussed in detail in Section 2.1.1, Hajj et al (*2007*) found good agreement between predicted binder grades determined from blending chart analyses and those determined from measurements on blended binders when the blended binders were formulated by mixing virgin binders with binders extracted and recovered from RAP (see Table 2.4). Note, however, that they also compared predicted binder grades with grades determined from measurements on

binders extracted and recovered from mixtures formulated with the RAP. In comparing these results, the blending chart analyses, in all but one case, predicted binder grades one to two grades lower than those determined from measurements for the high-temperature component. For the low-temperature component, the blending chart analyses predicted grades one grade lower than those determine from measurements in nearly half of the cases.

These latter findings corroborate the findings presented herein (i.e., measured critical temperatures from extracted/recovered blended binders significantly exceeding predicted high critical temperatures and slightly exceeding predicted low critical temperatures). It is acknowledged that this is not necessarily a poor outcome for the high-temperature component, but it is for the low-temperature component. Perhaps more importantly, the findings presented herein did not provide strong evidence in support of using blending charts for the purposes asphalt binder grade selection.

This is not to say blending charts cannot be used for binder grade selection. Table 2.4 shows that good agreement was found between predicted and measured binder properties *when the evaluations were based on binders extracted and recovered from RAP and then mixed with virgin binder to formulate the blended binder* (rather than combining mixture components and then extracting and recovering the blended binder for evaluation purposes).

In a recent study for the Wisconsin Highway Research Program, Bonaquist (*2011*) demonstrated that the linear blending chart analysis included in the appendix of AASHTO M 323 can be extended to include binders from RAS and blends of RAP and RAS binders. Using virgin binder replacement levels of up to 50 percent, he found linear relationships between RAS binder content and the high, intermediate, low (stiffness) critical temperatures (the relationship between RAS binder content and the low critical temperature based on m-value was linear up to 30 percent replacement level, but non-linear beyond this replacement level).

In the same study, Bonaquist also compared the differences between blending chart analyses and measured values for blends with RAP binder. In these comparisons, blends of 50 percent RAP binder and 50 percent virgin binder were formulated and tested to determine critical temperatures (i.e., high, intermediate, low via stiffness, and low via m-value) of the blends. These, in turn, were used to extrapolate the critical temperatures for 100 percent RAP binder assuming linearity between critical temperature and RAP binder content (Bonaquist refers to this as the "blend approach" in the report). The extrapolated values were then compared with values determined from measurements conducted on the extracted and recovered RAP binders. In all cases, the differences between the extrapolated values (100 percent RAP via blend approach) and measured values (on extracted/recovered RAP binder) were within ±3°C and most were within ±2°C. Using these differences, he showed that the differences between measured critical temperatures and those determined using blending charts at a 50 percent virgin binder replacement level (using the RAP binders) was within ±1.5°C at worst, and most were within ±1°C.

The blend approach, described in the preceding paragraph, to estimate (extrapolate) the critical temperatures of the RAP binder using a 50/50 blend of RAP/virgin binder was extended to estimate critical temperatures of a RAS binder except, in this case, the blend ratio was 30 percent RAS binder to 70 percent virgin binder. Using the extrapolated critical temperatures for the RAS binders, blending charts were used to estimate critical temperatures of various blends of

RAP/RAS/virgin binders. Measurements were also conducted on actual blends of the three binder types. Figures 7.2, 7.3, and 7.4 display the comparisons between predicted critical temperatures determined from blending chart analyses and measured critical temperatures for the high, intermediate, and low temperatures, respectively. Note that Bonaquist used "continuous grade" as nomenclature for "critical temperature" in these charts (and throughout the report). The comparisons indicate reasonable agreement between the blending chart analysis and grades based on the AASHTO procedure for grading an asphalt binder (i.e., determined from measurements).

Bonaquist also conducted an extensive reliability analysis to evaluate Wisconsin's binder replacement criteria. It considered the variability of the design temperature at a given project location (using data from 170 weather stations throughout Wisconsin) as well as the variability of the binder supplied. Evaluations were conducted to determine the overall reliability of the low temperature performance grade, the reliability that the specified intermediate temperature grade was met, and the overall reliability that adding reclaimed binders increased the high temperature grade by one grade (from a PG 58 to a PG 64). From this analysis, it was determined that adding reclaimed binders decreases the reliability of the low temperature performance grade and increases the high temperature performance grade.

Based on the findings from the study, Bonaquist recommended modifications to Wisconsin's binder replacement criteria so as to treat RAP and RAS mixtures equally and provide high reliability that the blended binder will meet the design low temperature requirement. He also recommended modifications to AASHTO T 170 for recovering RAS binders for blending chart analysis and a procedure for blending chart analysis for mixtures with multiple reclaimed (recycled) binders.

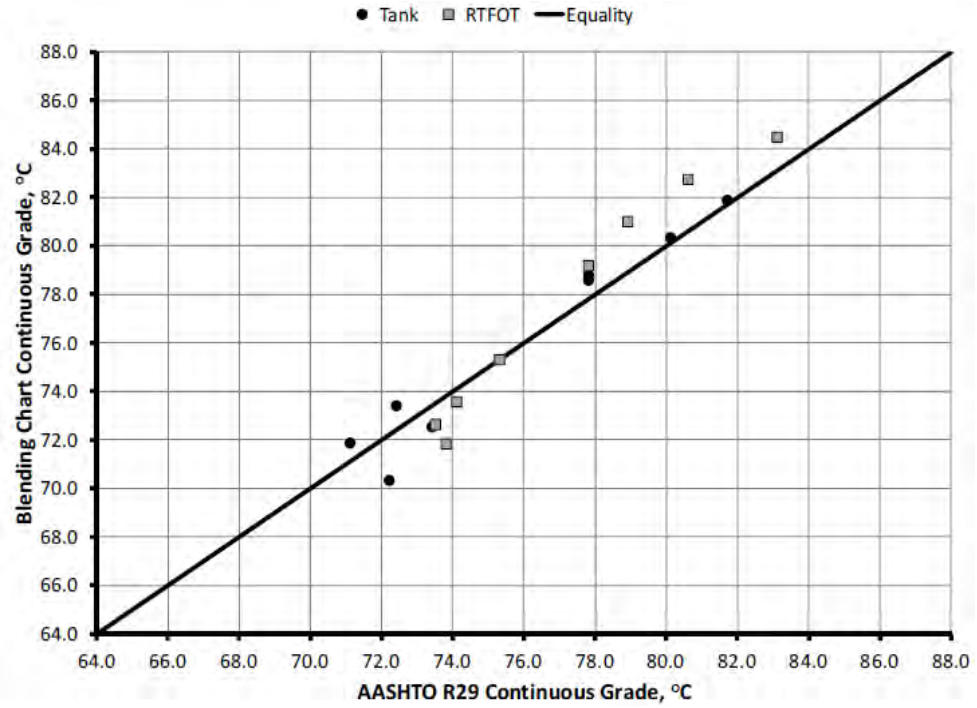


Figure 7.2: Predicted versus Measured High Critical Temperatures (*Bonaquist 2011*)

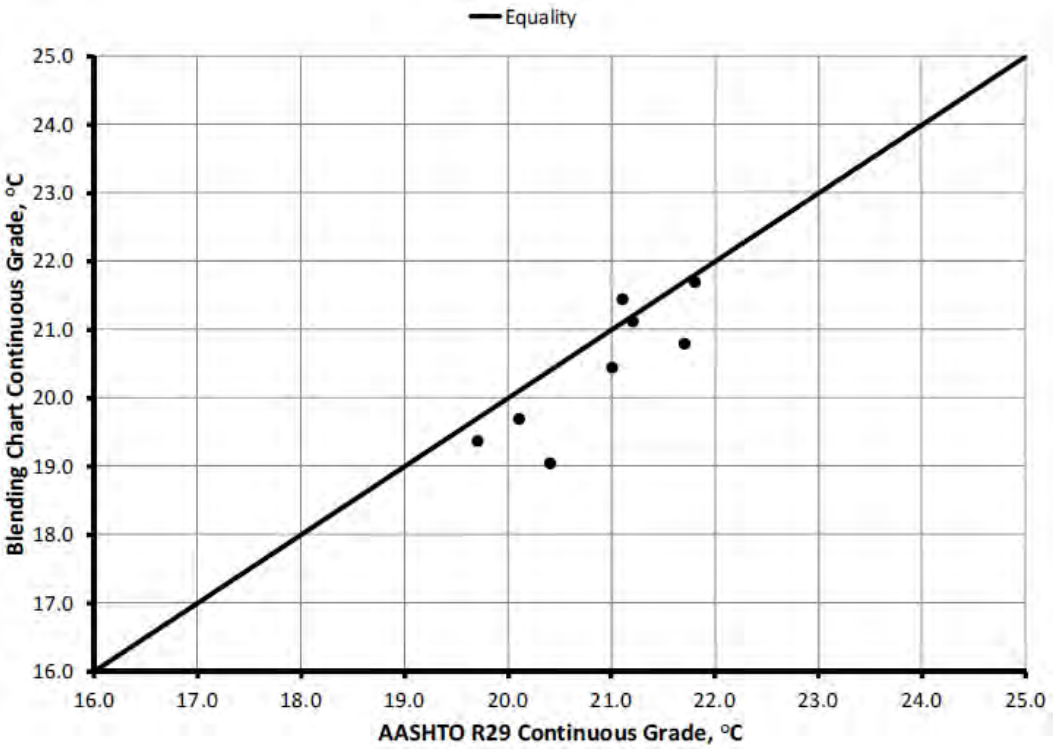


Figure 7.3: Predicted versus Measured Intermediate Critical Temperatures (*Bonaquist 2011*)

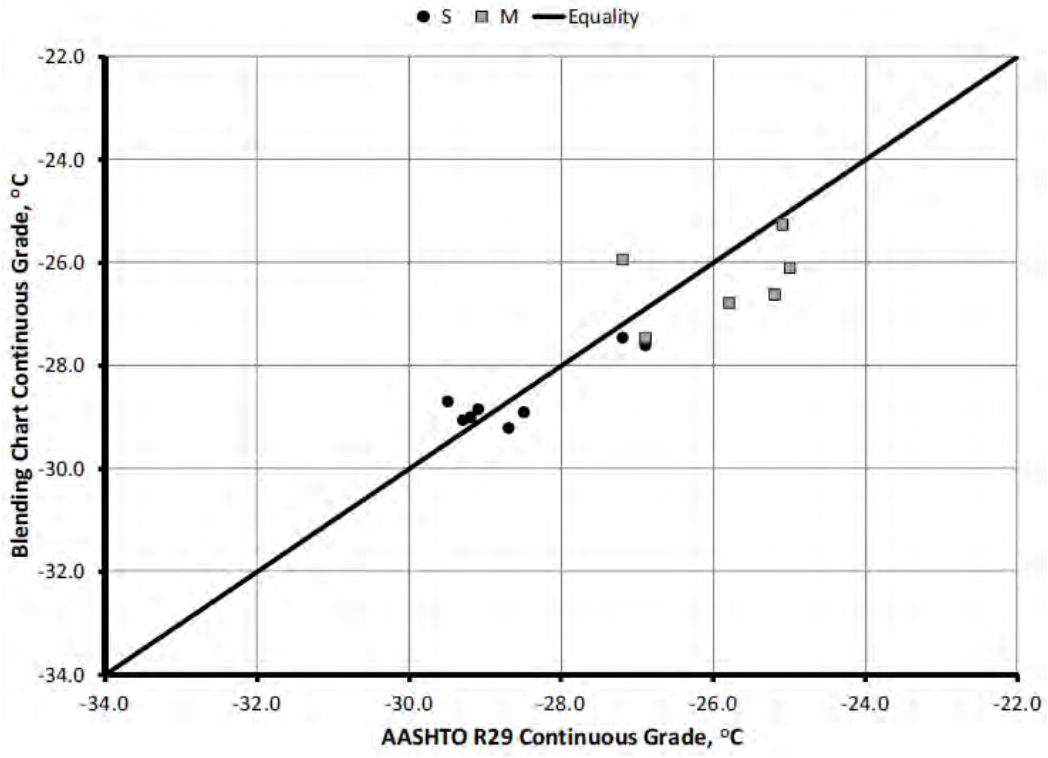


Figure 7.4: Predicted versus Measured Low Critical Temperatures (*Bonaquist 2011*)

The approach reported by Bonaquist (*2011*) provided very good agreement between predicted and measured critical temperatures for mixtures containing RAP binders or both RAP and RAS binders, whereas the approach used in this research effort did not. The following lists the principal differences between the two approaches:

- *Binder extraction/recovery*: Both studies used AASHTO T 164 Method A for extraction. A modified version of AASHTO T 170 was used for recovery in the Wisconsin study, whereas ASTM D 5404 was used in this study.

- *As-received RAP binder properties*: RAP binders were not aged in a PAV prior to determining the intermediate and low temperature properties in the Wisconsin study, whereas in this study they were.

- *As-received RAS binder properties*: In the Wisconsin study, the extracted/recovered RAS binders were blended with virgin binder using a 30/70 RAS binder to virgin binder ratio for the purposes of determining critical temperatures. The blend was aged in the RTFO and PAV as normal during the binder grading process. The results were used to extrapolate the critical temperatures for 100 percent RAS binder assuming linearity between critical temperatures and RAS binder content in the blend. In this study, attempts were made to grade the extracted/recovered RAS binders as if they were paving grade binders.

- *Sample preparation for evaluating blended binder properties*: In the Wisconsin study, virgin binders were blended with extracted/recovered binders to formulate samples for testing. In this study, mixtures of virgin and reclaimed (stockpile) materials were prepared and then the binders were extracted/recovered.

The differences listed are considerable and could explain why good agreement was not found in this study between predicted critical temperatures using blending analysis and measured critical temperatures.

7.2 IGNITION OVEN CALIBRATION FACTORS

Although there existed a clear trend in binder contents obtained from ignition oven tests that appeared to be associated with the type of reclaimed material included in the mixtures (Figure 6.6), the statistical analysis provided strong evidence to suggest that there was not a statistically significant difference in binder content from one virgin binder replacement level to another (Table 6.5). The difference, based on average values (i.e., not considering variance in the results), between the binder contents of the mixture with the highest binder content (the one without reclaimed binders) and the mixture with the lowest binder content (the one with 30 percent RAS binder) was only 0.26 percent.

Considering all of the results together (and considering variance in the results), the average difference between the mean uncorrected binder content determined via ignition oven testing and the mean batched binder content was 0.68 percent, with a 95 confidence interval ranging from 0.62 percent to 0.74 percent for these mixtures. In segregating the data by material type in the binder blend, the statistical analyses (Table 6.6) showed that the mixture with no reclaimed

materials had the greatest mean difference between measured and batched binder contents (0.81 percent), whereas the mixtures with only RAS binder had the least mean difference (0.61 percent), with a difference between these two means of only 0.20 percent.

Statistical comparisons showed significant differences between uncorrected binder contents via ignition oven testing and extracted binder contents for three of the four plant-produced mixtures (Table 6.7). Adjusting the binders contents obtained from the ignition oven test by subtracting 0.50 percent improved the outcome, but one difference remained significantly different (Table 6.8). However, statistical comparisons showed no difference between uncorrected binder contents via ignition oven testing and extracted binder contents for the laboratory-prepared mixtures. This analysis indicated a mean difference of only 0.05 percent. It is interesting to note that the greatest difference occurred with the mixture containing no reclaimed materials (see Table 5.6).

Given these findings, it is hard to justify a procedural change in the way ignition ovens are calibrated for mixtures containing reclaimed materials. In fact, the findings suggest procedural changes may be warranted for mixtures without reclaimed materials. However, further investigation would need to be conducted on a wider range of materials to justify any changes.

7.3 PROPERTIES OF FIELD-COMPACTED MIXTURES

7.3.1 In-Place Density

The results of F-test comparisons listed in Table 6.9 provide strong evidence to suggest no differences existed between standard deviations of nuclear density gauge measurements made by ODOT personnel and those of nuclear density gauge measurements made by contractor personnel. Further, the results also provide strong evidence to suggest no differences existed between standard deviations of nuclear gauge measurements and those of pavement core density measurements.

The comparisons in Table 6.9 also indicate that only small differences existed between the two sets of nuclear density gauge measurements made by ODOT and contractor personnel on the US 20 project (i.e., differences of 1.0 lb/ft^3 or less). They also indicate, in most cases, only small differences between nuclear gauge densities and pavement core densities (i.e., 1.0 lb/ft^3 or less for two-thirds of the comparisons). More importantly, however, the comparisons indicate that the standard deviations of the differences of all comparisons were less than 1.0 lb/ft^3, and that the standard deviations of the differences for the RAP/RAS mixtures were less than those for the RAP mixtures in most cases. In all cases, the standard deviations of the differences were much less than the criterion of 2.5 lb/ft^3 listed in ODOT TM 327. Granted, this criterion is to be applied to comparisons between core densities and nuclear gauge densities (as per ODOT TM 327), but it seems reasonable to apply it also to comparisons between nuclear gauge densities for the purposes of determining the applicability of using nuclear density gauges on RAP/RAS mixtures. Under this assumption, the comparisons clearly show that the variability in the differences between measurements made on the RAP/RAS mixtures was about the same as, or less than, the variability in the differences between measurements made on the RAP mixtures.

It is acknowledged that a limited set of comparisons were made during this study. However, based on the findings presented herein, no evidence was found to suggest the variability of density measurements made on mixtures containing RAP and RAS was different from that of density measurements made on mixtures containing only RAP. Hence, it would appear that use of nuclear gauges to measure the density of mixtures containing RAS seems completely reasonable.

7.3.2 Mechanical Properties

Mixture Stiffness

Figure 6.7 shows that a significant difference existed between the moduli of the two mixtures on the I-5 project. The results showed indicate the moduli of the RAP-only mixture were significantly higher than the moduli of the RAP/RAS mixture at all loading frequencies. Table 5.8 indicates that the density of the RAP-only mixture was slightly higher than that of the RAP/RAS mixture, which is also reflected in the air void content data shown in Table 5.10 (i.e., lower air voids for the RAP-only mixture). It would appear that these two interrelated factors outweighed the increased binder stiffness of the RAP/RAS mixture relative to that of the RAP-only mixture (Table 5.7).

For the mixtures on the US 20 project (Figure 6.8) there was not a significant difference between moduli for the two mixtures at any loading frequency. This was true even though the RAP-only mixture was slightly denser (Table 5.8) and had lower air voids (Table 5.10). It is also noted that the moduli of both mixture types from the US 20 project were very similar to the moduli of the RAP/RAS mixture from the I-5 project and, in fact, not significantly different at a 95 percent confidence level.

Figures 6.9 and 6.10 summarize comparisons between the dynamic moduli of the pilot study mixtures with those obtained during a previous study (*Lundy et al. 2005*). Rigorous statistical comparisons could not be conducted due to not knowing the variances of the dynamic moduli from the previous study. Nevertheless, the comparisons shown in Figures 6.9a and 6.10a provide strong evidence to suggest the dynamic moduli of the pilot study RAP-only mixtures were the same, or nearly the same, as those from the previous study. However, the comparisons shown in Figures 6.9b and 6.10b show that the pilot study RAP/RAS mixtures had lower dynamic moduli relative to those from the previous study.

Although there are no clear-cut reasons for these latter findings, differences in materials, mixtures properties, test parameters, etc. is one possibility. Another possibility is increased compatibility of the blended binders resulting in a softening effect. Section 7.1.2 explained this in detail and provided evidence to suggest that there was greater compatibility between binders in the RAP/RAS blend than between those in the RAP-only blend (see, in particular, the differences in the AFT P parameters in Table 7.3). However, Table 6.9 indicates that the RAP/RAS binder blends from both pilot study projects had higher critical temperatures than the RAP-only binder blends indicating that the RAP/RAS blends had higher stiffness. With these conflicting findings, it is difficult to pinpoint the likely reasons for the apparent differences shown in Figure 6.9b.

Nevertheless, despite the differences in mixture properties, specimen configurations, modes of testing, test temperatures, and binder types and properties, the dynamic moduli of the mixtures from the pilot studies were not significantly different from those of the mixtures from the previous study in three of the four comparisons. This suggests that the performance of the mixtures placed along the US 20 pilot study project (both with reclaimed materials) will perform similar to mixtures without reclaimed materials placed at the same thickness and compacted to a comparable density along the same stretch of road. It also suggests a similar outcome for the mixtures with reclaimed materials placed along the I-5 pilot study project. However, one might expect the RAP/RAS mixture to be less susceptible to cracking and more susceptible to permanent deformation relative to the RAP-only mixture or to a mixture without reclaimed materials placed at the same thickness and compacted to a comparable density.

Fatigue Properties

Figures 6.11 and 6.12 indicate that the RAP/RAS mixture had slightly better fatigue properties than the RAP-only mixture for the I-5 project, but slightly inferior fatigue properties than the RAP-only mixture on the US 20 project. However, statistical analyses showed no differences between fatigue properties of the two types of mixtures at a 95 percent confidence level for either project. Hence, based on these findings alone, there is no evidence to suggest that the RAP/RAS mixtures will develop fatigue cracking any sooner than the RAP-only mixtures at either project.

Comparing the results from the I-5 project with those from the US 20 project showed no significant difference in performance at the higher initial strain level. However, at the lower initial strain level, the mixtures from the US 20 project required a significantly higher number of cycles than the mixtures from the I-5 project to induce a 50-percent reduction in stiffness suggesting a much higher resistance to fatigue cracking. On average, the mixtures from the I-5 project had greater stiffness than those from the US 20 project (see Figures 6.7 and 6.8). In addition, the mixtures from the US 20 project had slightly softer blended binders than those from the I-5 project (see Table 5.7). Both of these factors could partially explain the apparent increased resistance to fatigue cracking of the mixtures from the US 20 project relative to those from the I-5 project. Modifier type and/or content in the virgin binder (to satisfy the elastic recovery criterion) are additional possibilities for the differences in performance in the fatigue test. It is also possible that the RAP and RAS binders contained modifiers, which could also partially explain the differences in performance.

On the other hand, the mixtures for the I-5 project were designed to meet the requirements of a Level 4 mix design whereas those for the US 20 project were designed to meet the requirements for a Level 3 mix design. Additionally, the test specimens from the I-5 project had lower air void contents relative to those from the US 20 project. Given these two factors, and with all else being equal, one would expect the mixtures from the I-5 project to require a higher number of cycles to induce a 50-percent reduction in stiffness (i.e., have a greater resistance to fatigue cracking).

As with other aspects of this study, these findings do not conveniently align with traditional expectations, which are largely based on unmodified binders and mixtures without RAP and/or RAS. Given that the mixtures contained RAP or a combination of RAP and RAS, both of which may have contained modifiers, and that the modifier type and content of the virgin binders are

unknown, it if difficult to pinpoint the likely reasons why the mixtures from the US 20 project performed better than those from the I-5 project in the fatigue test conducted at the lower initial strain level.

Irrespective, it is important to point out that resistance to fatigue cracking of a pavement is significantly influenced by the overall pavement structure, not just the cracking resistance of the wearing course layer. Given this, relative fatigue cracking resistance of the pavements at the two pilot study sites cannot be predicted from the results presented herein alone.

8.0 RECOMMENDED PROCEDURES

8.1 VIRGIN BINDER GRADE SELECTION

The findings presented herein did not provide strong evidence in support of using blending charts for the purposes asphalt binder grade selection. Section 7.1.3 discusses, in detail, potential reasons why good agreement was not found in this study between predicted critical temperatures using blending analysis and measured critical temperatures. In doing so, it also briefly synthesizes the findings from a comprehensive study conducted for the Wisconsin Department of Transportation (*Bonaquist 2011*), which demonstrated that blending chart analysis was very effective for the purposes of selecting a virgin asphalt binder grade when either RAP or RAS, or both, was incorporated in HMAC mixtures. Hence, given the success of the approach undertaken during the Wisconsin study, and lack of success with the approach undertaken in this study, the procedures detailed by Bonaquist (*2011*) should be seriously considered by ODOT for the purposes of selecting the virgin asphalt binder grade for mixtures incorporating RAS.

8.2 RAS BINDER EXTRACTION/RECOVERY

Based on the literature review, AASHTO T 164 Method A was recommended for extraction and ASTM D 5404 was recommended for recovery for the purposes of undertaking this project (Section 3.2). This required purchase of new extraction and recovery equipment, setting it up, and learning the specific procedures associated with the new equipment. In spite of some initial difficulties with regard to extracting RAS binder, ODOT personnel were able to successfully extract and recover binders from RAS for use on this project. Due to the nature of RAS, with high proportions of fine aggregate as well as cellulose and/or glass fibers (as may be the case with tear off shingles), extractions took much longer to complete relative to binder extractions from RAP, so efficiency is still a concern. Nevertheless, these two procedures are recommended for use by ODOT. However, ODOT should also consider the modified Abson recovery procedure proposed by Bonaquist (*2011*) as an alternative procedure for recoveries.

8.3 BATCHING AND MIXING

Section 3.3 provides batching and mixing procedures developed during this project and these were evaluated prior to fabricating mixture specimens for use in the study. Section 5.2.1 provides details of the evaluation, while Table 5.4 presents the results, which showed that the procedures listed in Section 3.3 to be effective in fabricating mixtures with RAP and RAS. Given this, the procedures in Section 3.3 are recommended for use by ODOT. Appendix F provides a detailed example for developing the batching plan according to the proposed batching procedure provided in Section 3.3.1.

8.4 IGNITION OVEN CALIBRATION FACTORS

Laboratory-prepared mixtures with various levels of virgin binder replacement and known total binder contents were burned in ignition ovens to determine the differences between the known

binder contents and those obtained from the incineration process. Binder contents from split samples of the mixtures were also determined by quantitative extraction. Statistical analyses of the results are presented in Section 6.1.2, while Section 7.2 discusses the findings from these analyses and provides compelling evidence to suggest significant procedural changes in the way ignition ovens are currently calibrated (i.e., according to ODOT TM 323) are not justified for mixtures containing RAP and/or RAS.

Based on the findings presented herein, therefore, fundamental changes to the methodology presented in ODOT TM 323 are not recommended at this time. However, given that this study showed the current procedure was used effectively for mixtures containing RAS or RAP and RAS, the language in ODOT TM 323 was modified to allow for this possibility. Appendix G contains the suggested modifications to the procedure. It also includes suggestions for some minor grammatical changes and a few suggestions for removing some language that appears to better placed in the Standard Specifications or the Manual of Field Test Procedures.

8.5 QUALITY CONTROL AND QUALITY ASSURANCE

Based on the findings from the literature review, no changes to current procedures were recommended for the purposes of conducting this study (Section 3.5). Hence, procedures currently specified by ODOT were employed during the construction of the two pilot studies undertaken as part of this project for both quality control (QC) and quality assurance (QA). During the two pilot studies, ODOT was specifically interested in evaluating procedures to assess binder contents and volumetric properties. In addition, although not currently specified by ODOT, performance (stiffness and fatigue) characteristics were also evaluated.

Evaluation of the applicability of using ignition ovens for determining binder contents for QC and QA purposes was evaluated through a combination of the laboratory study and the pilot studies. As detailed in Sections 6.1.2 and 7.2, no evidence was found to suggest that ignition ovens cannot be used for mixtures containing RAP or combinations of RAP and RAS based on the findings from the laboratory study. This involved comparisons of binders contents obtained from ignition oven tests on mixtures with various levels of virgin binder replacement as well as comparisons of binder contents based on ignition oven tests and quantitative extractions. Similar comparisons were made based on ignition oven tests and extractions conducted on the plant-produced mixtures placed on the pilot study projects (see Section 6.2.1). Although not as conclusive as the findings from the laboratory study, the findings from the analyses of these results provided strong evidence to suggest no differences existed between binder contents obtained from ignition oven tests and from quantitative extractions for three of the four mixtures used for the pilot studies.

Based on these findings, use of ignition ovens to determine binder contents of mixtures containing reclaimed materials (including RAP, RAS, or combinations of RAP and RAS) for quality control and quality assurance purposes is recommended. However, since the current procedure for calibrating ignition ovens does not include provision for mixtures containing RAS, this recommendation is predicated on acceptance of the proposed modifications to ODOT TM 323 (see Section 8.4).

Related to the use of ignition ovens for QC and QA purposes is the Independent Assurance (IA) parameter for asphalt binder content specified in ODOT's quality assurance program. Based on the foregoing arguments regarding the applicability of using ignition ovens for mixtures with RAP, RAS, or combinations of RAP and RAS, compelling evidence was not found in this study to justify modification of the IA parameter of 0.40 percent (see, in particular, the discussion in Section 7.2).

ODOT was also interested in evaluating the volumetric properties of the plant-produced mixtures during the pilot studies. Although originally planned, mix design verification was not undertaken as part of this study. However, the applicability of using nuclear density gauges for determining in-place density of the pavements incorporating RAS was evaluated. This was accomplished by comparing the variability associated with nuclear density gauge measurements and pavement core density measurements. Section 6.2.2 provides the comparisons of the results, while Section 7.3.1 provides further discussion. The findings from these comparisons provide strong evidence to suggest the variability associated with density measurements made on mixtures with RAP and RAS was not different from the variability associated with density measurements made on mixtures with only RAP. That is, there was no difference in the quality of in-place density measurements made on the two types of mixtures using nuclear density gauges. Hence, changes in the way in-place density is currently determined are not recommended.

9.0 CONCLUSIONS AND RECOMMENDATIONS

This study investigated several characteristics of laboratory-prepared and plant-produced hot-mix asphalt mixtures containing various proportions of RAP and RAS with the principal objectives of developing a procedure for selecting the virgin binder grade used in such mixtures as well as a procedure for determining ignition oven calibration factors for mixtures containing these materials. Other objectives included developing recommendations for procedures to effectively and efficiently recover asphalt binder from RAS, batch and mix reclaimed materials with virgin materials, and for quality control and quality assurance testing.

The study included a literature review to assist in developing experiment plans for the laboratory study and the two pilot projects undertaken in this research effort. Preliminary procedures were identified from the literature review and evaluated through testing of laboratory-fabricated mixtures, plant-produced loose mixtures, and samples obtained from the pavements constructed during the pilot studies. In-place density tests were also conducted at the time of construction of the pilot study pavement sections.

The laboratory study was conducted with two primary aims. The first was to investigate the physical properties of blended binders composed of various proportions of virgin and reclaimed binders with the intent of gathering evidence in order to satisfy the first three objectives listed in Section 1.3. The second aim was to determine ignition oven calibration factors of mixtures with and without RAP and/or RAS to gather evidence in order to satisfy the fourth objective listed in Section 1.3. The pilot studies were conducted to evaluate quality assurance procedures and to gather information regarding the relative performance of the mixtures placed on the projects. Based on the findings from these efforts, recommendations for the various procedures investigated during this study were developed.

Major conclusions drawn from this study are presented below. In addition, recommendations for further research are provided.

9.1 CONCLUSIONS

9.1.1 Virgin Binder Grade Selection Procedure

Mixtures with various proportions of RAP and RAS (including none) were batched and mixed such that the virgin binder replacement levels varied from 0 to 55 percent. Following mixing, the mixtures were subjected to short-term aging. The binders from these mixtures were then extracted/recovered and tested to determine the critical temperatures of the binders. Only the high and low critical temperatures were determined since ODOT does not evaluate binders for the intermediate critical temperature. High critical temperatures of the as-received virgin, RAP, and RAS binders were also determined. The low critical temperatures of the RAS binders could not be determined as the binders were too stiff to fabricate the bending beam rheometer samples, but the low critical temperatures of the virgin and RAP binders were successfully determined. In evaluating the low temperature properties, the binders were subjected to PAV aging. Using the

data from the tests on the as-received binders and the various proportions of the reclaimed binders in the blends, blending chart analyses were conducted to predict the high and low critical temperatures of the blended binders. These predicted temperatures were compared with temperatures obtained from the tests on the blended binders extracted/recovered from the mixtures. In all cases, these comparisons showed that the predicted temperatures were lower than the measured temperatures, and that the differences were greater for the high temperature comparisons.

Section 7.1 discusses, in detail, potential reasons why good agreement was not found in this study between predicted critical temperatures using blending chart analysis and measured critical temperatures. It short, the reasons appear to be associated with increased compatibility of the blended binders (Section 7.1.2), the process for grading reclaimed binders (especially RAS binders), and that blended binders extracted/recovered from blended mixtures were used in the comparisons (Section 7.1.3). It should be noted that issues with the binder recovery process (namely, incomplete removal of toluene solvent during distillation) was initially thought to be a potential reason (Section 7.1.1). However, as detailed in Section 7.1.2, further investigation dispelled this concern in that it showed the recovered binders contained on trace amounts of solvent, and not enough to affect the rheology of the binders.

Section 7.1 also briefly synthesizes the findings from a comprehensive study conducted for the Wisconsin Department of Transportation (*Bonaquist 2011*), which demonstrated that blending chart analysis was very effective for the purposes of selecting a virgin asphalt binder grade when either RAP or RAS, or both, was incorporated in the mixtures investigated in the study. In this study, blended binders were prepared by blending virgin binders with RAP and RAS binders extracted/recovered from the respective reclaimed materials. That is, the blended binders were not extracted/recovered for mixtures containing reclaimed materials. Hajj et al (*2007*) also demonstrated good agreement between predicted and measured critical temperatures for blends prepared in the same way as was done for the Wisconsin study, but poorer agreement when the blended binders were extracted/recovered from mixtures containing RAP.

Together, these findings lead to the conclusion that blending chart analysis is effective and can be used for virgin asphalt binder grade selection. However, the basis for this rests on the fact that evaluation of the efficacy of the process utilized blended binders that were prepared by extracting/recovering binders from reclaimed materials and then blending these with virgin binders. The findings also lead to the conclusion that preparing mixtures with reclaimed materials and then extracting/recovering the blended binder does not appear to be an appropriate means by which to prepare the blended binder specimens for use in evaluating the effectiveness of blending chart analysis.

9.1.2 Ignition Oven Calibration Procedure

AASHTO T 308 (ignition oven test) and AASHTO T 164 Method A (quantitative extraction) were used in this study for determining the binder contents of the mixtures investigated. Analysis of variance was used to determine if the binder contents of the laboratory-prepared mixtures derived from ignition oven tests were significantly different from one level of virgin binder replacement to another. Using a 95 percent confidence level, no statistically significant differences were found during this analysis. In addition, paired t-tests were used to compare

binders contents of the laboratory-fabricated mixtures derived from the two test methods (i.e., AASHTO T 308 versus AASHTO T 164 Method A). No statistically significant differences were found in mean binder contents between the two methods of measurement, again using a 95 percent confidence level. Binder contents of the plant-produced mixtures utilized in the pilot studies were also compared to determine if differences existed between mean binder contents obtained by the two test methods. This analysis found no significant differences, at a 95 percent confidence level, between the means for three of the four cases when corrected ignition oven test results were used.

The vast majority of these findings lead to the conclusion that ignition ovens can be used for mixtures containing RAS without the need for implementing procedural changes in the current ODOT method for determining ignition oven calibration factors (ODOT TM 323). However, the language in the method does need to be updated to account for the possibility of calibrating the ovens for mixtures containing RAS or combinations of RAP and RAS. Appendix G contains the suggested modifications to the procedure.

9.1.3 RAS Binder Extraction/Recovery

AASHTO T 164 Method A and ASTM D 5404 were used in this study for binder extraction and binder recovery, respectively. Personnel conducting the extraction procedure were faced with some initial difficulties in extracting binder from RAS. However, they were able to overcome the obstacles and utilize both methods on this project quite successfully. The principal conclusion to be drawn from their success is that the procedures appear to be appropriate for extracting and recovering binder from RAS.

9.1.4 Batching and Mixing Procedure

Explicit batching and mixing procedures for mixtures containing RAS were not found during the literature review. Consequently, taking into consideration the procedures described in AASHTO T 245, T 247, and T 312, as well as in NCHRP 452 (McDaniel and Anderson 2001), detailed batching and mixing procedures were developed for use during this study. Evaluation of the procedures confirmed their effectiveness and they were used successfully throughout the project. Hence, it can be concluded the procedures developed under this project are effective for producing laboratory-prepared mixtures containing RAS or combinations of RAP and RAS.

9.1.5 QC/QA Procedures

The efforts undertaken in this study specifically evaluated the applicability of using ignition ovens for determining binder contents of mixtures containing RAS, RAP, or combinations of RAP and RAS, and nuclear density gauges for determining in-place density of mixtures containing RAP or a combination of RAP and RAS. The applicability of using ignition ovens was discussed previously. However, related to the use of these ovens for QC and QA purposes is ODOT's Independent Assurance (IA) parameter for asphalt binder content. Based on the findings presented herein, compelling evidence was not found to justify modifying the current IA parameter of 0.40 percent. Hence, it can be concluded that, again based on the findings of this study, the current value can be used reliably for mixtures containing RAS, RAP, or combinations of RAP and RAS.

The applicability of using nuclear density gauges for determining in-place density of mixtures containing RAS was evaluated by comparing standard deviations of density gauge measurements made on the two types of mixtures used in each pilot study. Based on a 95 percent confidence level, no difference was found in the quality of the measurements. Hence, it can be conducted that, based on the findings presented herein, use of nuclear density gauges measurements are applicable for assessing the in-place density of mixtures containing combinations of RAP and RAS.

9.1.6 Mechanical Properties

Plant-produced, field-compacted mixture specimens were obtained from the pavements placed at both pilot study projects and tested for dynamic modulus and fatigue properties. Significant differences, at a 95 percent confidence level, were found between the stiffness characteristics of the two types of mixtures placed on the I-5 project, with those for the RAP-only mixture being higher than those for the RAP/RAS mixture. The higher stiffness characteristics of the RAP-only mixture were likely due to the substantially lower air void contents of the test specimens relative to those of the RAP/RAS mixture specimens. On the US 20 project no differences were found at a 95 percent confidence level between the stiffness characteristics of the two types of mixtures.

The stiffness characteristics of the mixtures placed along the two pilot studies were compared with those obtained from a previous study (*Lundy et al. 2005*) to test the reasonableness of the results obtained from the pilot study mixtures. Despite differences in mixture properties, specimen configurations, modes of testing, test temperatures, and binder types and properties, the dynamic moduli of the mixtures from the pilot studies were not significantly different from those of the mixtures from the previous study in three of the four comparisons. Based on these comparisons, it can be concluded that the stiffness characteristics of the mixtures placed along the pilot studies, as reported herein, are reasonable.

With regard to fatigue characteristics, no significant differences were found between the two types of mixtures placed along either when evaluated at a 95 percent confidence level. Based on these findings, coupled with the findings regarding stiffness characteristics, it can be concluded that the future performance of the two pavements placed along the I-5 project may differ slightly due to the difference in stiffness characteristics, but differences in the future performance of the two pavements placed along the US 20 is not likely.

Comparing the results from the I-5 project with those from the US 20 project showed no significant difference in performance at the higher strain level. However, at the lower strain level, the results suggest a much higher resistance to fatigue cracking for the mixtures placed along the US 20 project. Section 7.3.2 cites potential reasons in support of this finding, but also identifies factors to suggest better performance expectations from the mixtures placed along the I-5 project. Adding to this that overall pavement structure significantly influences resistance to fatigue cracking, a conclusion cannot be drawn regarding the expected fatigue cracking resistance of the pavements placed along the I-5 project relative to that of the pavements placed along the US 20 based the findings presented herein.

9.2 RECOMMENDATIONS

The attempt to validate the use of blending charts for the purposes of selecting virgin asphalt binder grades was unsuccessful during this project. Consequently, the laboratory investigations presented herein were not useful in satisfying the objective of developing a procedure for selecting a virgin asphalt binder grade for use in a mixture with reclaimed materials. However, in seeking answers as to why the efforts undertaken in this study were unsuccessful, additional review of recent literature uncovered the report by Bonaquist (*2011*), which does contain procedures that were used quite successfully in Wisconsin. Hence, it is recommended that ODOT consider investigating these procedures further.

In addition, even though strong evidence was provided in this study to conclude that procedural changes are not needed for calibrating ignition ovens for mixtures containing RAS, the data to arrive at this conclusion were derived from a limited number of materials. Hence, investigation of a broader range of materials is recommended to gain more confidence in the findings presented herein. The same argument can be used for use of nuclear density gauges to evaluate the in-place density of mixtures containing RAS. Finally, there remains the need to evaluate mix design verification procedures for mixtures containing RAS.

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APPENDIX A:
STATE DOT IGNITION OVEN CALIBRATION PROCEDURES FOR MIXTURES WITH RAS

Agency	Ignition Oven Calibration Procedure
Alabama	Recommends to determine asphalt content either using ALDOT-354 (Asphalt Content of Hot-Mix Asphalt by Nuclear Method or AASHTO T308 (Standard method for determination of Asphalt Content by Ignition Method)
Florida DOT	FM5-563 has not incorporated the language for RAP/RAS, and described procedure is general. Calibration factor for asphalt binder can be calculated as: CF [AC] = $(W_{L1}+W_{L2})/2$. Where: • CF [AC] = asphalt binder calibration factor, percent by total weight of mix. • W_{L1},W_{L2} = aggregate weight loss of the first & second calibration samples respectively, percent by weight of the total mix. W_{L1} & W_{L2} = AC_{actual}- $AC_{measured}$ (AC_{actual}, $AC_{measured}$ = percent asphalt before and after burning in the ignition oven, respectively).
Indiana DOT	ITM586-08T has not incorporated the language for the RAP/RAS in its procedure, and follows the standard procedure.
Minnesota DOT	MnDOT uses forced air ignition furnace. Combined aggregate calibration factor for mixture containing RAP is determined as: $C_f = C_1 \times P_1 + C_2 \times P_2 + \ldots + C_n \times P_n$ Where: • C_f = combined aggregate CF • P_i = Percent of aggregate of RAP calibration proportion in mixture • C_i = Calibration factor for aggregate (or RAP) proportion. • Determine the asphalt content calibration factor for RAP using procedure as for virgin materials

Agency	Ignition Oven Calibration Procedure
North Carolina DOT	Assume 0.5% calibration factor for RAP/RAS, and if combined calibration is less than 0.5 percent use the smaller one. Determine the moisture content of RAP/RAS and virgin materials before calculating binder content. The rest of procedure is the same as AASHTO T308.
South Carolina DOT	Calibration of RAP mixture for ignition oven is estimated from the average of the four sample (RAP only) mixture burned in the oven. The rest of the procedure is the same as for virgin materials.
Texas DOT	<u>Sample preparation</u> Prepare six samples containing RAP/RAS and virgin material, two as blank samples without binder or recycled materials, two samples with recycled materials at the design optimum binder content, and two samples each at ±0.5% of the design optimum asphalt content <u>Asphalt content correction factor</u> Determine asphalt content of ignited samples using following equation: $AC\% = [(W_s - W_A)/W_s] \times 100$ W_s = Total weight of the HMA sample prior to ignition W_A = Total weight of the aggregate remaining after ignition
Virginia DOT	Binder content correction factor for RAP is taken as the average of four samples as follows: $MCA = (\%AC_1 + \%AC_2 + \%AC_3 + \%AC_4) / 4$ Where: • MCA = Mixture Calibration Average • $\%AC_i$ = Difference between batched and measured binder content.

APPENDIX B:
SUMMARY OF SPECIFICATIONS FROM AGENCIES ALLOWING RAS

<table>
<tr><th>Agency</th><th>Tear-offs allowed?</th><th>Maximum RAS content</th><th>Maximum RAP/RAS content</th><th>Max. binder replacement</th><th>Virgin binder grade or adjustment</th><th>Testing frequency</th></tr>
<tr><td>AL</td><td>Yes</td><td>3% by wt. of aggr. for tear-offs; 5% by wt. of aggr. for manufacturer waste</td><td>25% for Plant-Mix Bit. Base; 20% for SMA/Superpave surface layers; 25% for other SMA/Superpave layers</td><td>Not specified (but specifies RAS shall contain approx. 20-30% binder)</td><td>PG 76-22; no adjustment found in special provision 08-0378(9)</td><td>First lot of mix production, and each 10,000 tons thereafter sampled; tested using T 319 (quant. extraction/recovery), T 202 (abs. visc.), T 240 (RTFO), and T 315 (rheol. props via DSR after RTFO)</td></tr>
<tr><td>FL Dev Spec (Dev334 RAS) 4/29/09</td><td>No</td><td>5% by wt. of aggr. (considered RAP in determining total RAP content in mix)</td><td>50% by wt. of aggr. for Traffic Levels A, B, and C mixtures (<10M ESALs); 30% by wt. of aggr. for Traffic Levels D and E mixtures (>=10M ESALs);</td><td>15% by wt. of aggr. when using PG 76-22 (see exception for max. binder replacement)</td><td>Table 334-2
Asphalt Binder Grade for Mixes Containing RAP
Percent RAP | Asphalt Binder Grade
< 20 | PG 67-22*
20-29 | PG 64-22
>= 30 | Recycling Agent
*Used in all mixtures unless specified otherwise in contract

Maintain the absolute viscosity of the recycled mixture within the range of 5,000 to 15,000 poises</td><td>One mixture sample during first 1,000 tons of production, and one per 4,000 tons of production thereafter</td></tr>
<tr><td>GA</td><td>Yes</td><td>5% by wt. of total mixture</td><td>40% (mainline and ramps) for drum plants, 25% for batch plants</td><td>Not specified</td><td>Recovered blended binder from mixture shall have an absolute viscosity between 6,000 & 16,000 poises</td><td>Tear-offs: One Polarized Light Microscopy test for asbestos per 1,000 tons of material stockpiled before mixing. Take a sample fom a lot of atleast 500 tons at beginning and one sample per week thereafter.</td></tr>
</table>

Agency	Tear-offs allowed?	Maximum RAS content	Maximum RAP/RAS content	Max. binder replacement	Virgin binder grade or adjustment	Testing frequency
IN	No	5% by wt. of total mixture for RAS-only mixtures; 3% for ESAL Cats 3, 4, and 5 (>3M)	25% RAP or 5% RAS by wt. of total mixture for ESALs < 3M (1% RAS = 5% RAP for substitutions); 15% RAP or 3% RAS by wt. of total mixture for ESALs >= 3M (does not appear to allow RAP/RAS combo for this ESALs >= 3M)	Not specified	15-25% RAP (ESALs < 3M), reduce by one grade; <15% RAP, use specified grade	One sample per sublot (1000 tons) per source of Dolomite, if lot exceed 2000 tons, then take a sample afterwards for every 2000 tons.
IA Dev Spec DS-09059 12/21/10	Yes	5% by wt. of aggr.	Up to 15% for surface courses; no limit for base and intermediate courses utilizing "Classified RAP", 20% for "Certified RAP", 10% for "Unclassified RAP"	30%	Not specified; mix design testing conducted by DOT, which indicates mix design adjustments may be required	Test the samples of either three randomly selected samples or 1 sample per 1000 ton lot whichever is greater. RAS Sample size should not be less than 20lbs.
MA	No	5% by wt. of total mixture for RAS-only mixtures	Based on maximum binder replacement.	40% for drum plants; 20% for mod. batch plants	<=25% binder repl.: PG 64-28; >25% binder repl.: PG 52-34	
MN	Yes	5% by total wt. of mixture	30% (>1M ESALs); 30% for wearing surface and 40% for non-wearing surface when <1M ESALs	30% (virgin/total >= 0.70)	Use specified grade for PG XX-28 and PG 52-34 independent of RAP content; Use specified grade for PG XX-34 with <=20% RAP; Use blending chart for PG XX-34 and >20%RAP. Percentage of RAS considered part of max. allowable RAP percentage.	1 sample per 500 tons for the 2000 tons of mixture production, 1 sample per 1000 tons afterwards. Extra test samples can be collected as requested by the project engineer while using RAP/RAS.
MO	Yes	ee max. binder terion)	Based on maximum binder replacement.	ing virgin grade	PG64-22,PG 52-28 or PG 58-28 when virgin/total between 0.60 and 0.70	1 sample per 1500 tons or 1 sample per lot whichever is greater.

Agency	Tear-offs allowed?	Maximum RAS content	Maximum RAP/RAS content	Max. binder replacement	Virgin binder grade or adjustment	Testing frequency
NH	Yes	Not specified (see max. binder replacement criterion)	Based on maximum binder replacement.	0.6% RAS binder content; up to 1.5% RAP/RAS binder content	Shall meet specified grade in special provision for project (contractor responsible for determining virgin binder grade)	RAS tested for gradation and binder content every 500 tons while stockpile is being built; RAP tested for gradation and binder content every 1,000 tons while stockpile is being built
NC	No	6% by wt. of total mixture	15% by wt. of total mixture (unless otherwise approved)	Not directly specified	PG76-22; one grade (high & low) below specified grade for 15-25% RAP/RAS; Engineer to determine grade when >25% RAP/RAS used	For RAP/RAS one split sample is needed for a lot of 750 tons, that should be taken at the beginning of the building stockpile and on weekly basis thereafter.
PA	No	5% by wt. of total mixture mandated	15% for wearing course	Not specified	Use specified grade for 5-15% RAP or 5% RAS; DOT to determine virigin binder grade if >15% RAP or >5% RAP plus 5% RAS	JMF Production of mixture having RAP/RAS greater than 140 tons, take minimum 1 sample per day . Determin AC,Gradation, theoretical max. specific gravity on collected sample.
SC	Not explicitly disallowed	3-8% by wt. of aggr.	20% for surface courses, 25% for intermediate course, and 30% for base courses. 15% when using batch plants and RAP/RAS introduced in hot elevator	Not specified	Recovered blended binder from mixture shall have an absolute viscosity less than 12,000 poises	From the RAP Stock pile,1 sample per 1000 tons, and minimum 3 test per stockpile.

<table>
<tr><th>Agency</th><th>Tear-offs allowed?</th><th>Maximum RAS content</th><th>Maximum RAP/RAS content</th><th>Max. binder replacement</th><th>Virgin binder grade or adjustment</th><th>Testing frequency</th></tr>
<tr><td>TX</td><td>Yes</td><td>5% by wt. of total mixture</td><td>Mixtures with fractionated RAP: 20% for surface courses, 30% for other layers
Mixtures with non-fractionated RAP: 10% for surface courses, 20% for other layers</td><td>35% for surface courses; 40% for other layers</td><td>Grade appears to based on M 320; no mention of adjustments found</td><td>Four lots would be built for the production of mixtures, first lot is of 1000 tons and remaining three ranges from 1000 to 4000 tons depends to the discretion of engineer. 1 sample per lot will be take for testing.</td></tr>
<tr><td>VA</td><td>Yes</td><td>5% by wt. of total mixture</td><td>Based on maximum binder replacement.</td><td>Combined RAP and RAS percentage shall not contribute more than 30% of the total asphalt content of the mixture.</td><td>One PG grade lower (both temperatures) for mixtures with 20% or more RAP/RAS content (25% for 25-mm base mixtures)</td><td>Asbestos: One Polarized Light Microscopy test per 100 tons. Contractor must take 1 sample per 1000 tons of lot or greater per day. Testing does not apply for if production less than 300tons.</td></tr>
<tr><td>WI</td><td>Yes</td><td>See max. binder replacement</td><td>Based on maximum binder replacement.</td><td><table><tr><th rowspan="2">Recycled Asphalt Material</th><th colspan="2">Max. binder replacement</th></tr><tr><th>Lower Layers</th><th>Upper Layer</th></tr><tr><td>RAS only</td><td>25%</td><td>20%</td></tr><tr><td>RAP/FRAP</td><td>40%</td><td>25%</td></tr><tr><td>RAS, RAP, and FRAP*</td><td>35%</td><td>25%</td></tr><tr><td colspan="3">*5% max. RAS by total wt. of aggr. blend</td></tr></table></td><td>Designated in contract. Contractor may replace virgin binder with recovered binder up to the maximum percentages shown under max. binder replacement. Greater replacement percentages allowed if the resultant binder meets grade specified in contract.</td><td></td></tr>
<tr><td>King Co., WA</td><td>Yes</td><td>Not specified</td><td>Not specified</td><td>Not specified</td><td>Not specified</td><td>Stockpiled RAS: once for first 50 tons produced, once every 250 tons thereafter</td></tr>
</table>

APPENDIX C:
BATCH QUANTITIES FOR LAB-FABRICATED MIXTURES

Mixture: 0% RAP Binder / 0% RAS Binder

Target Mixture, RAP, and RAS Gradations

Sieve Size	Target %Pass	RAP Grad.	RAS Grad.
3/4"	100	100	100
1/2"	98	98	100
3/8"	83	93	100
1/4"	60	83	98
#4	49	77	97
#8	31	64	96
#16	22	53	80
#30	16	43	60
#50	11	36	53
#100	8	30	46
#200	6.2	20.8	38.3
% Binder	**5.8**	**7.8**	**18.7**

Batch Percentages by Fraction

		Bin %	**0.00**	**0.00**			
					Virgin Aggr.		Combined
Fraction	Target (%)	RAP (%)	RAS (%)		BHF (%)	Aggr. (%)	Fraction
3/4" x 1/2"	2	0.0	0.0		0.0	2.0	2.0
1/2" x 3/8"	15	0.0	0.0		0.0	15.0	15.0
3/8" x 1/4"	23	0.0	0.0		0.0	23.0	23.0
1/4" x #4	11	0.0	0.0		0.0	11.0	11.0
#4 x #8	18	0.0	0.0		0.0	18.0	18.0
#8 x #16	9	0.0	0.0		0.0	9.0	9.0
#16 x #30	6	0.0	0.0		0.0	6.0	6.0
#30 x #50	5	0.0	0.0		0.0	5.0	5.0
#50 x #100	3	0.0	0.0		0.0	3.0	3.0
#100 x #200	2	0.0	0.0		0.0	1.8	1.8
#200 -	6.2	0.0	0.0		1.0	5.2	6.2
Total	100.0	0.0	0.0		1.0	99.0	100.0
% Binder Replacement		**0.00**	**0.00**				
% Binder	**5.8**	**0.00**	**0.00**		Virgin Binder, %		**5.80**

Batch Masses

Total batch mass, g	9000
Aggr. batch mass, g	8478

	Batch Mass, g				Combined
Fraction	RAP	RAS	BHF	Aggr.	Aggregate
3/4" x 1/2"	0.0	0.0	0.0	169.6	169.6
1/2" x 3/8"	0.0	0.0	0.0	1271.7	1271.7
3/8" x 1/4"	0.0	0.0	0.0	1949.9	1949.9
1/4" x #4	0.0	0.0	0.0	932.6	932.6
#4 x #8	0.0	0.0	0.0	1526.0	1526.0
#8 x #16	0.0	0.0	0.0	763.0	763.0
#16 x #30	0.0	0.0	0.0	508.7	508.7
#30 x #50	0.0	0.0	0.0	423.9	423.9
#50 x #100	0.0	0.0	0.0	254.3	254.3
#100 x #200	0.0	0.0	0.0	152.6	152.6
#200 -	0.0	0.0	84.8	440.9	525.6
Total	0.0	0.0	84.8	8393.2	**8478.0**

Gradation Check

Sieve Size	Batch Mass, g	% Ret.	Cumul. % Ret.	% Passing	Target Gradation	Difference
3/4"	0	0.0	0.0	100.0	100.0	0.0
1/2"	169.6	2.0	2.0	98.0	98.0	0.0
3/8"	1271.7	15.0	17.0	83.0	83.0	0.0
1/4"	1949.9	23.0	40.0	60.0	60.0	0.0
#4	932.6	11.0	51.0	49.0	49.0	0.0
#8	1526.0	18.0	69.0	31.0	31.0	0.0
#16	763.0	9.0	78.0	22.0	22.0	0.0
#30	508.7	6.0	84.0	16.0	16.0	0.0
#50	423.9	5.0	89.0	11.0	11.0	0.0
#100	254.3	3.0	92.0	8.0	8.0	0.0
#200	152.6	1.8	93.8	6.2	6.2	0.0
#200 -	525.6	6.2	100.0	0.0		
Total	**8478.0**	**100.0**				

Mixture: 15% RAP Binder / 0% RAS Binder

Target Mixture, RAP, and RAS Gradations

Sieve Size	Target %Pass	Batch RAP	RAS Grad.
3/4"	100	100	100
1/2"	98	98	100
3/8"	83	91	100
1/4"	60	78	98
#4	49	70	97
#8	31	56	96
#16	22	43	80
#30	16	32	60
#50	11	25	53
#100	8	20	46
#200	6.2	15.1	38.3
% Binder	**5.8**	**7.8**	**18.7**

Batch Percentages by Fraction

		Bin %	**11.15**	**0.00**			
			RAP	RAS	Virgin Aggr.		Combined
Fraction	Target (%)		Aggr. (%)	Aggr. (%)	BHF (%)	Aggr. (%)	Fraction
3/4" x 1/2"	2.0		0.2	0.0	0.0	1.8	2.0
1/2" x 3/8"	15.0		0.6	0.0	0.0	14.4	15.0
3/8" x 1/4"	23.0		1.2	0.0	0.0	21.8	23.0
1/4" x #4	11.0		0.7	0.0	0.0	10.3	11.0
#4 x #8	18.0		1.4	0.0	0.0	16.6	18.0
#8 x #16	9.0		1.2	0.0	0.0	7.8	9.0
#16 x #30	6.0		1.1	0.0	0.0	4.9	6.0
#30 x #50	5.0		0.8	0.0	0.0	4.2	5.0
#50 x #100	3.0		0.6	0.0	0.0	2.4	3.0
#100 x #200	1.8		1.1	0.0	0.0	0.7	1.8
#200 -	6.2		2.3	0.0	1.0	2.9	6.2
Total	100.0		11.2	0.0	1.0	87.9	100.0
% Binder Replacement			**14.99**	**0.00**			
% Binder	**5.8**		**0.87**	**0.00**	Virgin Binder, %		**4.93**

Batch Masses

Total batch mass, g	9000
Aggr. batch mass, g	8478

Fraction	Batch Mass, g RAP	RAS	BHF	Aggr.	Combined Aggregate
3/4" x 1/2"	25.1	0.0	0.0	146.4	169.6
1/2" x 3/8"	67.2	0.0	0.0	1209.7	1271.7
3/8" x 1/4"	129.5	0.0	0.0	1830.6	1949.9
1/4" x #4	75.3	0.0	0.0	863.2	932.6
#4 x #8	144.5	0.0	0.0	1392.8	1526.0
#8 x #16	133.5	0.0	0.0	640.0	763.0
#16 x #30	111.4	0.0	0.0	406.0	508.7
#30 x #50	66.2	0.0	0.0	362.8	423.9
#50 x #100	47.2	0.0	0.0	210.9	254.3
#100 x #200	52.2	0.0	0.0	104.5	152.6
#200 -	151.5	0.0	84.8	301.1	525.6
Aggr., g	925.2	0.0	84.8	7468.0	**8478.0**
Binder, g	78.3	0.0	443.7		**522.0**
Total, g	1003.5	0.0	7996.5		**9000.0**

Gradation Check

Sieve Size	Batch Mass, g	% Ret.	Cumul. % Ret.	% Passing	Target Gradation	Difference
3/4"	0	0.0	0.0	100.0	100.0	0.0
1/2"	169.6	2.0	2.0	98.0	98.0	0.0
3/8"	1271.7	15.0	17.0	83.0	83.0	0.0
1/4"	1949.9	23.0	40.0	60.0	60.0	0.0
#4	932.6	11.0	51.0	49.0	49.0	0.0
#8	1526.0	18.0	69.0	31.0	31.0	0.0
#16	763.0	9.0	78.0	22.0	22.0	0.0
#30	508.7	6.0	84.0	16.0	16.0	0.0
#50	423.9	5.0	89.0	11.0	11.0	0.0
#100	254.3	3.0	92.0	8.0	8.0	0.0
#200	152.6	1.8	93.8	6.2	6.2	0.0
#200 -	525.6	6.2	100.0	0.0		
Total	**8478.0**	**100.0**				

Mixture: 25% RAP Binder / 0% RAS Binder

Target Mixture, RAP, and RAS Gradations

Sieve Size	Target %Pass	Batch RAP	RAS Grad.
3/4"	100	100	100
1/2"	98	98	100
3/8"	83	91	100
1/4"	60	78	98
#4	49	70	97
#8	31	56	96
#16	22	43	80
#30	16	32	60
#50	11	25	53
#100	8	20	46
#200	6.2	15.1	38.3
% Binder	**5.8**	**7.8**	**18.7**

Batch Percentages by Fraction

		Bin %	**18.59**	**0.00**			
Fraction	Target (%)	RAP Aggr. (%)	RAS Aggr. (%)	Virgin Aggr. BHF (%)	Virgin Aggr. Aggr. (%)	Combined Fraction
3/4" x 1/2"	2.0	0.3	0.0	0.0	1.7	2.0
1/2" x 3/8"	15.0	1.0	0.0	0.0	14.0	15.0
3/8" x 1/4"	23.0	2.0	0.0	0.0	21.0	23.0
1/4" x #4	11.0	1.1	0.0	0.0	9.9	11.0
#4 x #8	18.0	2.4	0.0	0.0	15.6	18.0
#8 x #16	9.0	2.0	0.0	0.0	7.0	9.0
#16 x #30	6.0	1.8	0.0	0.0	4.2	6.0
#30 x #50	5.0	1.3	0.0	0.0	3.7	5.0
#50 x #100	3.0	1.1	0.0	0.0	1.9	3.0
#100 x #200	1.8	1.8	0.0	0.0	0.0	1.8
#200 -	6.2	3.9	0.0	1.0	1.3	6.2
Total	100.0	18.6	0.0	1.0	80.4	100.0
% Binder Replacement		**25.00**	**0.00**			
% Binder	**5.8**	**1.45**	**0.00**	Virgin Binder, %		**4.35**

Batch Masses

Total batch mass, g	9000
Aggr. batch mass, g	8478

Fraction	Batch Mass, g RAP	RAS	BHF	Aggr.	Combined Aggregate
3/4" x 1/2"	41.8	0.0	0.0	131.0	169.6
1/2" x 3/8"	112.1	0.0	0.0	1168.3	1271.7
3/8" x 1/4"	215.8	0.0	0.0	1750.9	1949.9
1/4" x #4	125.5	0.0	0.0	816.9	932.6
#4 x #8	240.9	0.0	0.0	1303.9	1526.0
#8 x #16	222.5	0.0	0.0	557.9	763.0
#16 x #30	185.7	0.0	0.0	337.5	508.7
#30 x #50	110.4	0.0	0.0	322.1	423.9
#50 x #100	78.6	0.0	0.0	181.8	254.3
#100 x #200	87.0	0.0	0.0	72.4	152.6
#200 -	252.6	0.0	84.8	207.9	525.6
Aggr., g	1542.6	0.0	84.8	6850.6	**8478.0**
Binder, g	130.5	0.0	391.5		**522.0**
Total, g	1673.1	0.0	7326.9		**9000.0**

Gradation Check

Sieve Size	Batch Mass, g	% Ret.	Cumul. % Ret.	% Passing	Target Gradation	Difference
3/4"	0	0.0	0.0	100.0	100.0	0.0
1/2"	169.6	2.0	2.0	98.0	98.0	0.0
3/8"	1271.7	15.0	17.0	83.0	83.0	0.0
1/4"	1949.9	23.0	40.0	60.0	60.0	0.0
#4	932.6	11.0	51.0	49.0	49.0	0.0
#8	1526.0	18.0	69.0	31.0	31.0	0.0
#16	763.0	9.0	78.0	22.0	22.0	0.0
#30	508.7	6.0	84.0	16.0	16.0	0.0
#50	423.9	5.0	89.0	11.0	11.0	0.0
#100	254.3	3.0	92.0	8.0	8.0	0.0
#200	152.6	1.8	93.8	6.2	6.2	0.0
#200 -	525.6	6.2	100.0	0.0		
Total	**8478.0**	**100.0**				

Mixture: 15% RAP Binder / 15% RAS Binder

Target Mixture, RAP, and RAS Gradations

Sieve Size	Target %Pass	Batch RAP	RAS Grad.
3/4"	100	100	100
1/2"	98	98	100
3/8"	83	91	100
1/4"	60	78	98
#4	49	70	97
#8	31	56	96
#16	22	43	80
#30	16	32	60
#50	11	25	53
#100	8	20	46
#200	6.2	15.1	38.3
% Binder	**5.8**	**7.8**	**18.7**

Batch Percentages by Fraction

	Bin %	**11.15**	**4.65**			
		RAP	RAS	Virgin Aggr.		Combined
Fraction	Target (%)	Aggr. (%)	Aggr. (%)	BHF (%)	Aggr. (%)	Fraction
3/4" x 1/2"	2.0	0.2	0.0	0.0	1.8	2.0
1/2" x 3/8"	15.0	0.6	0.0	0.0	14.4	15.0
3/8" x 1/4"	23.0	1.2	0.093	0.0	21.7	23.0
1/4" x #4	11.0	0.7	0.0	0.0	10.3	11.0
#4 x #8	18.0	1.4	0.0	0.0	16.5	18.0
#8 x #16	9.0	1.2	0.7	0.0	7.0	9.0
#16 x #30	6.0	1.1	0.9	0.0	4.0	6.0
#30 x #50	5.0	0.8	0.3	0.0	3.9	5.0
#50 x #100	3.0	0.6	0.3	0.0	2.0	3.0
#100 x #200	1.8	1.1	0.4	0.0	0.4	1.8
#200 -	6.2	2.3	1.8	1.0	1.1	6.2
Total	100.0	11.2	4.7	1.0	83.2	100.0
% Binder Replacement		**14.99**	**14.99**			
% Binder	**5.8**	**0.87**	**0.87**	Virgin Binder, %		**4.06**

Batch Masses

Total batch mass, g	9000
Aggr. batch mass, g	8478

Fraction	Batch Mass, g RAP	RAS	BHF	Aggr.	Combined Aggregate
3/4" x 1/2"	25.1	0.0	0.0	146.4	169.6
1/2" x 3/8"	67.2	0.0	0.0	1209.7	1271.7
3/8" x 1/4"	129.5	8.4	0.0	1823.8	1949.9
1/4" x #4	75.3	4.2	0.0	859.8	932.6
#4 x #8	144.5	4.2	0.0	1389.4	1526.0
#8 x #16	133.5	67.0	0.0	585.5	763.0
#16 x #30	111.4	83.7	0.0	337.9	508.7
#30 x #50	66.2	29.3	0.0	339.0	423.9
#50 x #100	47.2	29.3	0.0	187.0	254.3
#100 x #200	52.2	32.2	0.0	78.3	152.6
#200 -	151.5	160.3	84.8	170.8	525.6
Aggr., g	925.2	340.2	84.8	7127.8	**8478.0**
Binder, g	78.3	78.3	365.5		**522.0**
Total, g	1003.5	418.5	7578.0		**9000.0**

Gradation Check

Sieve Size	Batch Mass, g	% Ret.	Cumul. % Ret.	% Passing	Target Gradation	Difference
3/4"	0	0.0	0.0	100.0	100.0	0.0
1/2"	169.6	2.0	2.0	98.0	98.0	0.0
3/8"	1271.7	15.0	17.0	83.0	83.0	0.0
1/4"	1949.9	23.0	40.0	60.0	60.0	0.0
#4	932.6	11.0	51.0	49.0	49.0	0.0
#8	1526.0	18.0	69.0	31.0	31.0	0.0
#16	763.0	9.0	78.0	22.0	22.0	0.0
#30	508.7	6.0	84.0	16.0	16.0	0.0
#50	423.9	5.0	89.0	11.0	11.0	0.0
#100	254.3	3.0	92.0	8.0	8.0	0.0
#200	152.6	1.8	93.8	6.2	6.2	0.0
#200 -	525.6	6.2	100.0	0.0		
Total	**8478.0**	**100.0**				

Mixture: 0% RAP Binder / 15% RAS Binder

Target Mixture, RAP, and RAS Gradations

Sieve Size	Target %Pass	Batch RAP	RAS Grad.
3/4"	100	100	100
1/2"	98	98	100
3/8"	83	91	100
1/4"	60	78	98
#4	49	70	97
#8	31	56	96
#16	22	43	80
#30	16	32	60
#50	11	25	53
#100	8	20	46
#200	6.2	15.1	38.3
% Binder	**5.8**	**7.8**	**18.7**

Batch Percentages by Fraction

		Bin %	**0.00**	**4.65**			
			RAP	RAS	Virgin Aggr.		Combined
Fraction	Target (%)		Aggr. (%)	Aggr. (%)	BHF (%)	Aggr. (%)	Fraction
3/4" x 1/2"	2.0		0.0	0.0	0.0	2.0	2.0
1/2" x 3/8"	15.0		0.0	0.0	0.0	15.0	15.0
3/8" x 1/4"	23.0		0.0	0.1	0.0	22.9	23.0
1/4" x #4	11.0		0.0	0.0	0.0	11.0	11.0
#4 x #8	18.0		0.0	0.0	0.0	18.0	18.0
#8 x #16	9.0		0.0	0.7	0.0	8.3	9.0
#16 x #30	6.0		0.0	0.9	0.0	5.1	6.0
#30 x #50	5.0		0.0	0.3	0.0	4.7	5.0
#50 x #100	3.0		0.0	0.3	0.0	2.7	3.0
#100 x #200	1.8		0.0	0.4	0.0	1.4	1.8
#200 -	6.2		0.0	1.8	1.0	3.4	6.2
Total	100.0		0.0	4.7	1.0	94.4	100.0
% Binder Replacement			**0.00**	**14.99**			
% Binder	**5.8**		**0.00**	**0.87**	Virgin Binder, %		**4.93**

Batch Masses

Total batch mass, g	9000
Aggr. batch mass, g	8478

Fraction	Batch Mass, g RAP	RAS	BHF	Aggr.	Combined Aggregate
3/4" x 1/2"	0.0	0.0	0.0	169.6	169.6
1/2" x 3/8"	0.0	0.0	0.0	1271.7	1271.7
3/8" x 1/4"	0.0	8.4	0.0	1943.1	1949.9
1/4" x #4	0.0	4.2	0.0	929.2	932.6
#4 x #8	0.0	4.2	0.0	1522.6	1526.0
#8 x #16	0.0	67.0	0.0	708.6	763.0
#16 x #30	0.0	83.7	0.0	440.6	508.7
#30 x #50	0.0	29.3	0.0	400.1	423.9
#50 x #100	0.0	29.3	0.0	230.5	254.3
#100 x #200	0.0	32.2	0.0	126.4	152.6
#200 -	0.0	160.3	84.8	310.5	525.6
Aggr., g	0.0	340.2	84.8	8053.0	**8478.0**
Binder, g	0.0	78.3	443.7		**522.0**
Total, g	0.0	418.5	8581.5		**9000.0**

Gradation Check

Sieve Size	Batch Mass, g	% Ret.	Cumul. % Ret.	% Passing	Target Gradation	Difference
3/4"	0	0.0	0.0	100.0	100.0	0.0
1/2"	169.6	2.0	2.0	98.0	98.0	0.0
3/8"	1271.7	15.0	17.0	83.0	83.0	0.0
1/4"	1949.9	23.0	40.0	60.0	60.0	0.0
#4	932.6	11.0	51.0	49.0	49.0	0.0
#8	1526.0	18.0	69.0	31.0	31.0	0.0
#16	763.0	9.0	78.0	22.0	22.0	0.0
#30	508.7	6.0	84.0	16.0	16.0	0.0
#50	423.9	5.0	89.0	11.0	11.0	0.0
#100	254.3	3.0	92.0	8.0	8.0	0.0
#200	152.6	1.8	93.8	6.2	6.2	0.0
#200 -	525.6	6.2	100.0	0.0		
Total	**8478.0**	**100.0**				

Mixture: 0% RAP Binder / 30% RAS Binder

Target Mixture, RAP, and RAS Gradations

Sieve Size	Target %Pass	Batch RAP	RAS Grad.
3/4"	100	100	100
1/2"	98	98	100
3/8"	83	91	100
1/4"	60	78	98
#4	49	70	97
#8	31	56	96
#16	22	43	80
#30	16	32	60
#50	11	25	53
#100	8	20	46
#200	6.2	15.1	38.3
% Binder	**5.8**	**7.8**	**18.7**

Batch Percentages by Fraction

		Bin %	**0.00**	**9.30**			
			RAP	RAS	Virgin Aggr.		Combined
Fraction	Target (%)		Aggr. (%)	Aggr. (%)	BHF (%)	Aggr. (%)	Fraction
3/4" x 1/2"	2.0		0.0	0.0	0.0	2.0	2.0
1/2" x 3/8"	15.0		0.0	0.0	0.0	15.0	15.0
3/8" x 1/4"	23.0		0.0	0.2	0.0	22.8	23.0
1/4" x #4	11.0		0.0	0.1	0.0	10.9	11.0
#4 x #8	18.0		0.0	0.1	0.0	17.9	18.0
#8 x #16	9.0		0.0	1.5	0.0	7.5	9.0
#16 x #30	6.0		0.0	1.9	0.0	4.1	6.0
#30 x #50	5.0		0.0	0.7	0.0	4.3	5.0
#50 x #100	3.0		0.0	0.7	0.0	2.3	3.0
#100 x #200	1.8		0.0	0.7	0.0	1.1	1.8
#200 -	6.2		0.0	3.6	1.0	1.6	6.2
Total	100.0		0.0	9.3	1.0	89.7	100.0
% Binder Replacement			**0.00**	**29.98**			
% Binder	**5.8**		**0.00**	**1.74**	Virgin Binder, %		**4.06**

Batch Masses

Total batch mass, g	9000
Aggr. batch mass, g	8478

Fraction	Batch Mass, g RAP	RAS	BHF	Aggr.	Combined Aggregate
3/4" x 1/2"	0.0	0.0	0.0	169.6	169.6
1/2" x 3/8"	0.0	0.0	0.0	1271.7	1271.7
3/8" x 1/4"	0.0	16.7	0.0	1936.3	1949.9
1/4" x #4	0.0	8.4	0.0	925.8	932.6
#4 x #8	0.0	8.4	0.0	1519.2	1526.0
#8 x #16	0.0	133.9	0.0	654.1	763.0
#16 x #30	0.0	167.4	0.0	372.6	508.7
#30 x #50	0.0	58.6	0.0	376.3	423.9
#50 x #100	0.0	58.6	0.0	206.7	254.3
#100 x #200	0.0	64.4	0.0	100.2	152.6
#200 -	0.0	320.6	84.8	180.2	525.6
Aggr., g	0.0	680.5	84.8	7712.7	**8478.0**
Binder, g	0.0	156.5	365.5		**522.0**
Total, g	0.0	837.0	8163.0		**9000.0**

Gradation Check

Sieve Size	Batch Mass, g	% Ret.	Cumul. % Ret.	% Passing	Target Gradation	Difference
3/4"	0	0.0	0.0	100.0	100.0	0.0
1/2"	169.6	2.0	2.0	98.0	98.0	0.0
3/8"	1271.7	15.0	17.0	83.0	83.0	0.0
1/4"	1949.9	23.0	40.0	60.0	60.0	0.0
#4	932.6	11.0	51.0	49.0	49.0	0.0
#8	1526.0	18.0	69.0	31.0	31.0	0.0
#16	763.0	9.0	78.0	22.0	22.0	0.0
#30	508.7	6.0	84.0	16.0	16.0	0.0
#50	423.9	5.0	89.0	11.0	11.0	0.0
#100	254.3	3.0	92.0	8.0	8.0	0.0
#200	152.6	1.8	93.8	6.2	6.2	0.0
#200 -	525.6	6.2	100.0	0.0		
Total	**8478.0**	**100.0**				

Mixture: 25% RAP Binder / 15% RAS Binder

Target Mixture, RAP, and RAS Gradations

Sieve Size	Target %Pass	Batch RAP	RAS Grad.
3/4"	100	100	100
1/2"	98	98	100
3/8"	83	91	100
1/4"	60	78	98
#4	49	70	97
#8	31	56	96
#16	22	43	80
#30	16	32	60
#50	11	25	53
#100	8	20	46
#200	6.2	15.1	38.3
% Binder	**5.8**	**7.8**	**18.7**

Batch Percentages by Fraction

		Bin %	**18.59**	**4.65**			
			RAP	RAS	Virgin Aggr.		Combined
Fraction	Target (%)		Aggr. (%)	Aggr. (%)	BHF (%)	Aggr. (%)	Fraction
3/4" x 1/2"	2.0		0.3	0.0	0.0	1.7	2.0
1/2" x 3/8"	15.0		1.0	0.0	0.0	14.0	15.0
3/8" x 1/4"	23.0		2.0	0.1	0.0	20.9	23.0
1/4" x #4	11.0		1.1	0.0	0.0	9.9	11.0
#4 x #8	18.0		2.4	0.0	0.0	15.6	18.0
#8 x #16	9.0		2.0	0.7	0.0	6.2	9.0
#16 x #30	6.0		1.8	0.9	0.0	3.3	6.0
#30 x #50	5.0		1.3	0.3	0.0	3.4	5.0
#50 x #100	3.0		1.1	0.3	0.0	1.6	3.0
#100 x #200	1.8		1.8	0.4	0.0	-0.3	1.8
#200 -	6.2		3.9	1.8	1.0	-0.5	6.2
Total	100.0		18.6	4.7	1.0	75.8	100.0
% Binder Replacement			**25.00**	**14.99**			
% Binder	**5.8**		**1.45**	**0.87**	Virgin Binder, %		**3.48**

Batch Masses

Total batch mass, g	9000
Aggr. batch mass, g	8478

	Batch Mass, g				Combined
Fraction	RAP	RAS	BHF	Aggr.	Aggregate
3/4" x 1/2"	41.8	0.0	0.0	131.0	169.6
1/2" x 3/8"	112.1	0.0	0.0	1168.3	1271.7
3/8" x 1/4"	215.8	8.4	0.0	1744.1	1949.9
1/4" x #4	125.5	4.2	0.0	813.5	932.6
#4 x #8	240.9	4.2	0.0	1300.5	1526.0
#8 x #16	222.5	67.0	0.0	503.4	763.0
#16 x #30	185.7	83.7	0.0	269.4	508.7
#30 x #50	110.4	29.3	0.0	298.3	423.9
#50 x #100	78.6	29.3	0.0	158.0	254.3
#100 x #200	87.0	32.2	0.0	46.2	152.6
#200 -	252.6	160.3	84.8	77.6	525.6
Aggr., g	1542.6	340.2	84.8	6510.4	**8478.0**
Binder, g	130.5	78.3	313.2		**522.0**
Total, g	1673.1	418.5	6908.4		**9000.0**

Gradation Check

Sieve Size	Batch Mass, g	% Ret.	Cumul. % Ret.	% Passing	Target Gradation	Difference
3/4"	0	0.0	0.0	100.0	100.0	0.0
1/2"	169.6	2.0	2.0	98.0	98.0	0.0
3/8"	1271.7	15.0	17.0	83.0	83.0	0.0
1/4"	1949.9	23.0	40.0	60.0	60.0	0.0
#4	932.6	11.0	51.0	49.0	49.0	0.0
#8	1526.0	18.0	69.0	31.0	31.0	0.0
#16	763.0	9.0	78.0	22.0	22.0	0.0
#30	508.7	6.0	84.0	16.0	16.0	0.0
#50	423.9	5.0	89.0	11.0	11.0	0.0
#100	254.3	3.0	92.0	8.0	8.0	0.0
#200	152.6	1.8	93.8	6.2	6.2	0.0
#200 -	525.6	6.2	100.0	0.0		
Total	**8478.0**	**100.0**				

Mixture: 15% RAP Binder / 30% RAS Binder

Target Mixture, RAP, and RAS Gradations

Sieve Size	Target %Pass	Batch RAP	RAS Grad.
3/4"	100	100	100
1/2"	98	98	100
3/8"	83	91	100
1/4"	60	78	98
#4	49	70	97
#8	31	56	96
#16	22	43	80
#30	16	32	60
#50	11	25	53
#100	8	20	46
#200	6.2	15.1	38.3
% Binder	**5.8**	**7.8**	**18.7**

Batch Percentages by Fraction

		Bin %	**11.15**	**9.30**			
			RAP	RAS	Virgin Aggr.		Combined
Fraction	Target (%)		Aggr. (%)	Aggr. (%)	BHF (%)	Aggr. (%)	Fraction
3/4" x 1/2"	2.0		0.2	0.0	0.0	1.8	2.0
1/2" x 3/8"	15.0		0.6	0.0	0.0	14.4	15.0
3/8" x 1/4"	23.0		1.2	0.2	0.0	21.6	23.0
1/4" x #4	11.0		0.7	0.1	0.0	10.2	11.0
#4 x #8	18.0		1.4	0.1	0.0	16.5	18.0
#8 x #16	9.0		1.2	1.5	0.0	6.3	9.0
#16 x #30	6.0		1.1	1.9	0.0	3.1	6.0
#30 x #50	5.0		0.8	0.7	0.0	3.6	5.0
#50 x #100	3.0		0.6	0.7	0.0	1.7	3.0
#100 x #200	1.8		1.1	0.7	0.0	0.0	1.8
#200 -	6.2		2.3	3.6	1.0	-0.7	6.2
Total	100.0		11.2	9.3	1.0	78.6	100.0
% Binder Replacement			**14.99**	**29.98**			
% Binder	**5.8**		**0.87**	**1.74**	Virgin Binder, %		**3.19**

Batch Masses

Total batch mass, g	9000
Aggr. batch mass, g	8478

	Batch Mass, g				Combined
Fraction	RAP	RAS	BHF	Aggr.	Aggregate
3/4" x 1/2"	25.1	0.0	0.0	146.4	169.6
1/2" x 3/8"	67.2	0.0	0.0	1209.7	1271.7
3/8" x 1/4"	129.5	16.7	0.0	1817.0	1949.9
1/4" x #4	75.3	8.4	0.0	856.4	932.6
#4 x #8	144.5	8.4	0.0	1386.0	1526.0
#8 x #16	133.5	133.9	0.0	531.1	763.0
#16 x #30	111.4	167.4	0.0	269.9	508.7
#30 x #50	66.2	58.6	0.0	315.2	423.9
#50 x #100	47.2	58.6	0.0	163.2	254.3
#100 x #200	52.2	64.4	0.0	52.1	152.6
#200 -	151.5	320.6	84.8	40.5	525.6
Aggr., g	925.2	680.5	84.8	6787.5	**8478.0**
Binder, g	78.3	156.5	287.2		**522.0**
Total, g	1003.5	837.0	7159.5		**9000.0**

Gradation Check

Sieve Size	Batch Mass, g	% Ret.	Cumul. % Ret.	% Passing	Target Gradation	Difference
3/4"	0	0.0	0.0	100.0	100.0	0.0
1/2"	169.6	2.0	2.0	98.0	98.0	0.0
3/8"	1271.7	15.0	17.0	83.0	83.0	0.0
1/4"	1949.9	23.0	40.0	60.0	60.0	0.0
#4	932.6	11.0	51.0	49.0	49.0	0.0
#8	1526.0	18.0	69.0	31.0	31.0	0.0
#16	763.0	9.0	78.0	22.0	22.0	0.0
#30	508.7	6.0	84.0	16.0	16.0	0.0
#50	423.9	5.0	89.0	11.0	11.0	0.0
#100	254.3	3.0	92.0	8.0	8.0	0.0
#200	152.6	1.8	93.8	6.2	6.2	0.0
#200 -	525.6	6.2	100.0	0.0		
Total	**8478.0**	**100.0**				

Mixture: 25% RAP Binder / 30% RAS Binder

Target Mixture, RAP, and RAS Gradations

Sieve Size	Target %Pass	Batch RAP	RAS Grad.
3/4"	100	100	100
1/2"	98	98	100
3/8"	83	91	100
1/4"	60	78	98
#4	49	70	97
#8	31	56	96
#16	22	43	80
#30	16	32	60
#50	11	25	53
#100	8	20	46
#200	6.2	15.1	38.3
% Binder	**5.8**	**7.8**	**18.7**

Batch Percentages by Fraction

	Bin %	**18.59**	**9.30**			
		RAP	RAS	Virgin Aggr.		Combined
Fraction	Target (%)	Aggr. (%)	Aggr. (%)	BHF (%)	Aggr. (%)	Fraction
3/4" x 1/2"	2.0	0.3	0.0	0.0	1.7	2.0
1/2" x 3/8"	15.0	1.0	0.0	0.0	14.0	15.0
3/8" x 1/4"	23.0	2.0	0.2	0.0	20.9	23.0
1/4" x #4	11.0	1.1	0.1	0.0	9.8	11.0
#4 x #8	18.0	2.4	0.1	0.0	15.5	18.0
#8 x #16	9.0	2.0	1.5	0.0	5.5	9.0
#16 x #30	6.0	1.8	1.9	0.0	2.3	6.0
#30 x #50	5.0	1.3	0.7	0.0	3.0	5.0
#50 x #100	3.0	1.1	0.7	0.0	1.3	3.0
#100 x #200	1.8	1.8	0.7	0.0	-0.7	1.8
#200 -	6.2	3.9	3.6	1.0	-2.2	6.2
Total	100.0	18.6	9.3	1.0	71.1	100.0
% Binder Replacement		**25.00**	**29.98**			
% Binder	**5.8**	**1.45**	**1.74**	Virgin Binder, %		**2.61**

Batch Masses

Total batch mass, g	9000
Aggr. batch mass, g	8478

	Batch Mass, g				Combined
Fraction	RAP	RAS	BHF	Aggr.	Aggregate
3/4" x 1/2"	41.8	0.0	0.0	131.0	169.6
1/2" x 3/8"	112.1	0.0	0.0	1168.3	1271.7
3/8" x 1/4"	215.8	16.7	0.0	1737.3	1949.9
1/4" x #4	125.5	8.4	0.0	810.1	932.6
#4 x #8	240.9	8.4	0.0	1297.1	1526.0
#8 x #16	222.5	133.9	0.0	449.0	763.0
#16 x #30	185.7	167.4	0.0	201.4	508.7
#30 x #50	110.4	58.6	0.0	274.5	423.9
#50 x #100	78.6	58.6	0.0	134.2	254.3
#100 x #200	87.0	64.4	0.0	20.0	152.6
#200 -	252.6	320.6	84.8	-52.7	525.6
Aggr., g	1542.6	680.5	84.8	6170.1	**8478.0**
Binder, g	130.5	156.5	235.0		**522.0**
Total, g	1673.1	837.0	6489.9		**9000.0**

Gradation Check

Sieve Size	Batch Mass, g	% Ret.	Cumul. % Ret.	% Passing	Target Gradation	Difference
3/4"	0	0.0	0.0	100.0	100.0	0.0
1/2"	169.6	2.0	2.0	98.0	98.0	0.0
3/8"	1271.7	15.0	17.0	83.0	83.0	0.0
1/4"	1949.9	23.0	40.0	60.0	60.0	0.0
#4	932.6	11.0	51.0	49.0	49.0	0.0
#8	1526.0	18.0	69.0	31.0	31.0	0.0
#16	763.0	9.0	78.0	22.0	22.0	0.0
#30	508.7	6.0	84.0	16.0	16.0	0.0
#50	423.9	5.0	89.0	11.0	11.0	0.0
#100	254.3	3.0	92.0	8.0	8.0	0.0
#200	152.6	1.8	93.8	6.2	6.2	0.0
#200 -	525.6	6.2	100.0	0.0		
Total	**8478.0**	**100.0**				

APPENDIX D:
I-5 PROJECT CRACK SURVEY

Station	Photo ID	Pre-Grind Surface		Post-Grind Surface	
		A-Lane	B-lane	A-lane	B-lane
0+00	-	north end of gore, start grind	N/A	north end of gore, start of grind	N/A
0+34	1119, looking west	transverse crack; rutting/raveling		-	
2+14	-	-		probably transverse crack right edge	
2+65	-	-		f-mix left in center, but good bond	
2+88	-	-			
3+41	-	-		lots of f-mix left	
4+32	-	-	begin B-lane	-	begin B-lane
5+60	1120	-	transverse crack (per Dean, maybe CTB crack? Per Todd, doesn't look like thermal crack); longitudinal raveling	-	Tack seems a bit heavy; potential d-lam at midlane.
5+90	1122	-	transverse crack; longitudinal raveling in wheel paths	-	light crack right half
6+40	1123	-	2' long transverse crack, less raveling than previous stations	transverse crack across right half of lane	light crack right half
6+56	1124	transverse crack	-	transverse crack	-
6+82	1125	transverse crack, less raveling than previous stations, photo #1125	transverse crack, less raveling than previous stations, photo #1125	transverse crack	-
7+00	-	-	-	light transverse crack	deeper crack full width
7+18	-	-	-	light transverse crack	-
7+90	1126	light transverse crack	transverse crack, deeper than previous stations	transverse crack	-

Station	Photo ID	Pre-Grind Surface		Post-Grind Surface	
		A-Lane	B-lane	A-lane	B-lane
8+19	1127	light transverse crack	transverse crack, deeper than previous stations	-	full width crack; potential d-lam from this point back (5+60 to 8+10)
8+70	-	long joints open a bit from 8+70 to 10+08	-	-	-
9+10	-	-	-	-	crack starts left side of lane and extends across 3/4 of lane width
9+60	1128	-	transverse crack	transverse crack	-
10+08	1129	-	transverse crack	-	-
10+91	1130	-	very light transverse crack	-	moderately deep full width transverse crack; No tack from this point forward during observation (as such, cracks likely more visible)
11+13	1131	-	transverse crack	-	crack starts right side of lane and ends half way across lane width; 2.5 out of 5 rank for severity
11+37	1132	-	transverse crack deeper than previous stations	-	-
Stations previous to this were in a post-tack condition during survey. Later stations were in a pre-tack condition, meaning post-grind cracks were more visible.					
11+65	1133	-	Per Dean, looks like possible fatigue cracking, but not sure	-	-
11+75	-	-	-	one transverse crack coming from left edge; one transverse crack coming from rt edge	crack starts at right and continues across 3/4 of lane width, gets deeper as it heads towards right side of lane, 2 out of 5 rank for severity

Station	Photo ID	Pre-Grind Surface		Post-Grind Surface	
		A-Lane	B-lane	A-lane	B-lane
12+30	1134	-	transverse crack deeper than previous stations	transverse crack	-
12+52	-	-	-	-	full width crack, 2 out of 5 rank for severity
12+88	1135	-	faint transverse crack	transverse crack	-
13+36	1136	-	short transverse crack left side of lane		full width crack, 2.5 out of 5 rank for severity
14+01	-	-	-	potential d-lam area	full width crack, 2.5 out of 5 rank for severity; beginning of water-sprayed mill area (cracks in later stations might be more difficult to see)
14+39	1137	-	short transverse crack and rutting	-	-
14+56	1138	-	short/deep transverse crack; beginning of long joint that is opening	-	full width crack, 2.5 out of 5 rank for severity
14+80	1139	-	left half of lane has double transverse crack	-	-
14+88	-	-	-	per Dean, tack looks diluted	-
15+08	1140	longitudinal "drag" mark	deep transverse crack; really raveled	-	crack right half of lane, 2.5 out of 5 rank for severity; Milled surface looks good and sweeper is still working
15+63	-	-	transverse crack	transverse crack	-

Station	Photo ID	Pre-Grind Surface		Post-Grind Surface	
		A-Lane	B-lane	A-lane	B-lane
15+75	1141	transverse crack from B-lane continues a bit into A-lane	transverse crack; longitudinal crack left side of lane	-	full width crack, gets deeper as it heads right, 2 out of 5 rank for severity; longitudinal crack 6" from left edge of lane seems to start just before transverse crack and continues to next logged crack
15+98	1142	transverse crack right side of lane continues to B-lane	transverse crack left side of lane continues to A-lane; longitudinal crack left side of lane	transverse crack	crack left half of lane, 3 out of 5 rank for severity
16+16	1143	-	longitudinal crack along left side of lane at previous stations ends	-	-
16+24	1144	raveling	faint transverse crack	-	full width transverse crack, 2.5 out of 5 rank for severity
16+60	1145	fatiguing; several longitudinal and transverse cracks; see photo #1145	-	transverse crack	-
16+75	1146	big transverse crack	longitudinal crack along left side of lane	-	-
17+05	1147	big transverse crack	longitudinal crack along left side of lane	transverse crack	-
17+23	1148	transverse crack full width	transverse crack full width, still longitudinal crack	transverse crack	-

Station	Photo ID	Pre-Grind Surface		Post-Grind Surface	
		A-Lane	B-lane	A-lane	B-lane
17+48	1149	transverse crack full width, per Dean & Todd: looks like a reflective crack from concrete joint?	trans crack full width, per Dean & Todd: looks like reflective crack from concrete joint?; longit crack @ deepest part of transverse crack (left side of lane) - not joint (joint in A-lane)	transverse crack full width, per Dean & Todd: looks like a reflective crack from concrete joint?	-
17+67	1150	-	small transverse crack	-	full width crack, 2 out of 5 rank for severity
17+80	1151	-	deeper transverse crack than previous stations	-	-
18+06	1153	-	double transverse crack. Photo #1153; Longitudinal crack from 17+48 still visible and very deep with settling on its right side	-	-
18+19		-	-	transverse crack	-
18+24	1154	-	transverse crack left side	-	crack left half of lane
18+39	1155	transverse crack right side of lane continues to B-lane. Lots of raveling.	transverse crack left side of lane continues to A-lane. Lots of raveling	transverse crack	-
18+58	-	-	-	-	full width crack, 2 out of 5 rank for severity
19+16	-	-	-	-	crack mostly on left half w/ 6" wide shallow opening at left edge, 1.5 out of 5 rank for severity, longitudinal crack going to north ends 20' later 1' from left edge of lane

Station	Photo ID	Pre-Grind Surface		Post-Grind Surface	
		A-Lane	B-lane	A-lane	B-lane
19+47	-	transverse crack right side of lane continues to B-lane.	transverse crack left side of lane continues to A-lane.	-	-
19+88	-	-	-	2 grinding patterns?	
20+01	-	-	-	transverse crack	traffic barrier starts (for reference)
20+41	1157	-	longitudinal crack center of lane starts and heads north	-	-
20+69	1158	raveling starts and continues to north	longitudinal crack at center of lane ends	-	crack starts at left edge and continues 1/3 across lane width, 1 out of 5 rank for severity.
21+39	1159	-	longitudinal crack with transverse crack starting at its north end and heading east (running right half of lane)	-	Traffic barrier in way of pedestrian access - might have missed some cracks due to safety issues
22+20	1160	raveling. Joint has light but continuous opening.	-	-	-
22+60	-	-	-	potential d-lam area	-
22+87	-	longitudinal crack with intersecting transverse crack. Per Dean, looks like a 3-pull area - cracks are probably all from joints. Center pull at gore.	longitudinal crack on right side of lane with raveling along crack. Per Dean, looks like another joint.	cracks similar to those seen on surface	-
23+27	-	-	-	-	grinding and barrier ends (for reference)

Station	Photo ID	Pre-Grind Surface		Post-Grind Surface	
		A-Lane	B-lane	A-lane	B-lane
24+71	-	-	-	lots of f-mix. Definitely potential d-lam area.	didn't check this area due to safety hazards (lots of machinery with limited pedestrian access at sides)
25+59	-	raveling. Gore stops. Joint open a bit.	-	-	
26+28	-	-	-	d-lam potential not as bad as previous areas	
27+14	-	-	-	potential d-lam area	
28+76	-	-	-	pretty bad transverse crack	
29+96	-	-	-	potential d-lam area	
31+48	-	-	-	small transverse crack right side	
32+19	-	-	-	small transverse crack right side	
33+59	-	transverse joint		-	didn't check this area due to safety hazards (lots of machinery with limited pedestrian access at sides)
36+03	1161	Per Katie, deep raveling. Per Dean, looks like fatigue and stripping?	-	-	
36+45	1162	Per Katie, deep raveling. Per Dean, looks like fatigue and stripping?	-	-	
36+88	1163	Per Dean, looks really thin (thin lift?)	-	didn't check this area due to safety hazards (lots of machinery with limited pedestrian access at sides)	

Station	Photo ID	Pre-Grind Surface		Post-Grind Surface	
		A-Lane	B-lane	A-lane	B-lane
37+25	1164	trailer mark	-	didn't check this area due to safety hazards (lots of machinery with limited pedestrian access at sides)	didn't check this area due to safety hazards (lots of machinery with limited pedestrian access at sides)
38+00	1165	various surface damage. Photo #1165. Marks, dimples/divits. Under overpass.	-		
38+30	-	-	4 areas of surface damage - "dimples" approx 1" deep		
38+41	-	dimple (surface damage) mid lane	-		
38+60	-	patch left side begins. Roller mark further north on right side	dimple (surface damage further north, right side)		
39+03	-	patch left side ends. Surface damage areas with grass growing through. Roller mark begins mid lane	patch begins right side		
39+32	-	patch begins left side. Roller continues	-		
39+41	-	roller mark continues	patch ends right edge		
39+79	-	patch ends left side. Longitudinal and wandering roller crack begins further north. Roller mark continues. Long crack?	patch begins right side		

Station	Photo ID	Pre-Grind Surface		Post-Grind Surface	
		A-Lane	B-lane	A-lane	B-lane
40+32	-	long crack continues? Longitudinal roller mark continues.	patch ends right edge	didn't check this area due to safety hazards (lots of machinery with limited pedestrian access at sides)	didn't check this area due to safety hazards (lots of machinery with limited pedestrian access at sides)
40+42	-	roller mark longitudinal	roller mark		
40+51	-	surface damage approx 1" deep left side. Longitudinal roller mark.	-		
41+26	-	longitudinal roller mark ends	-		
42+87	-	surface damage left side	-		
43+11	-	-	three spots of surface damage right side		
44+50	-	-	raveling in wheel paths		
50+62	-	tree overhang			
55+65	-	-	raveling		
56+81	-	-	raveling continues to end of project		

Photo 1119

Photo 1120

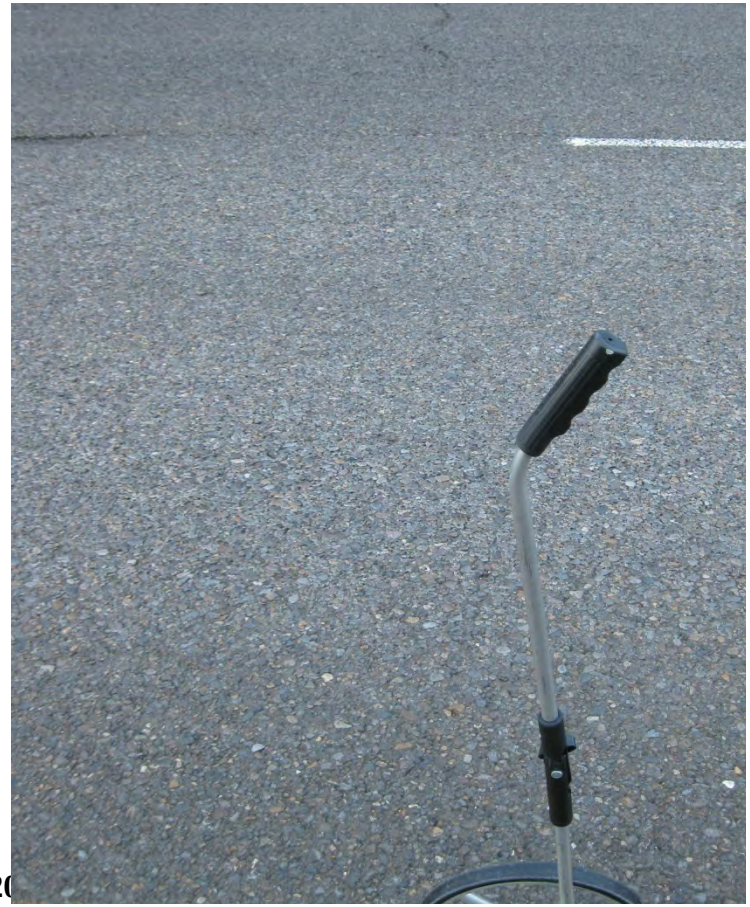


Photo 1122

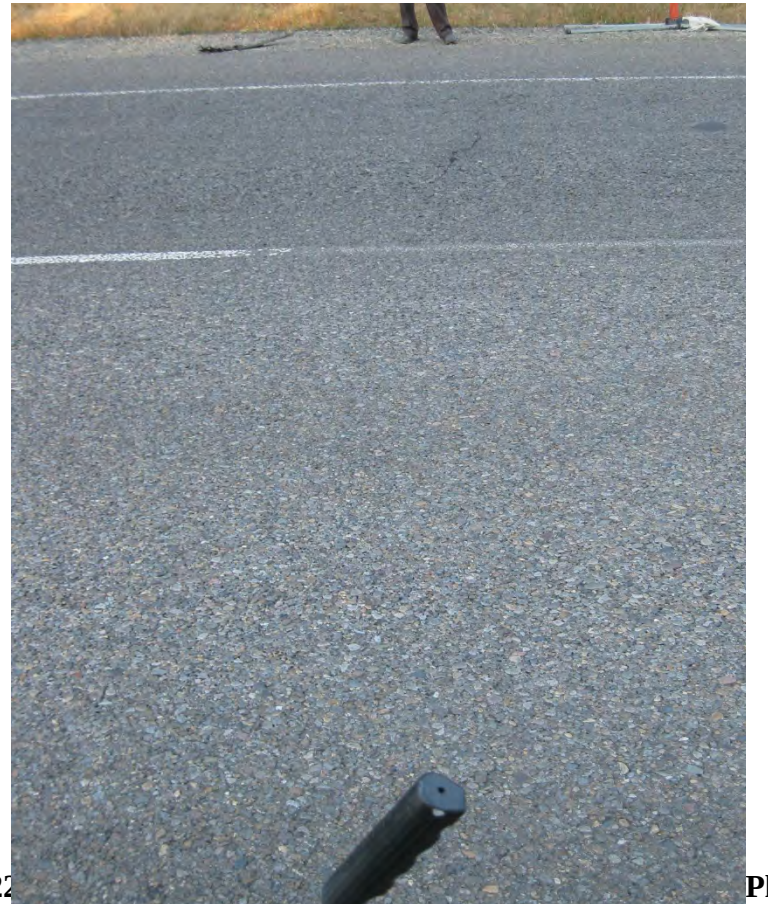


Photo 1123

Photo 1124

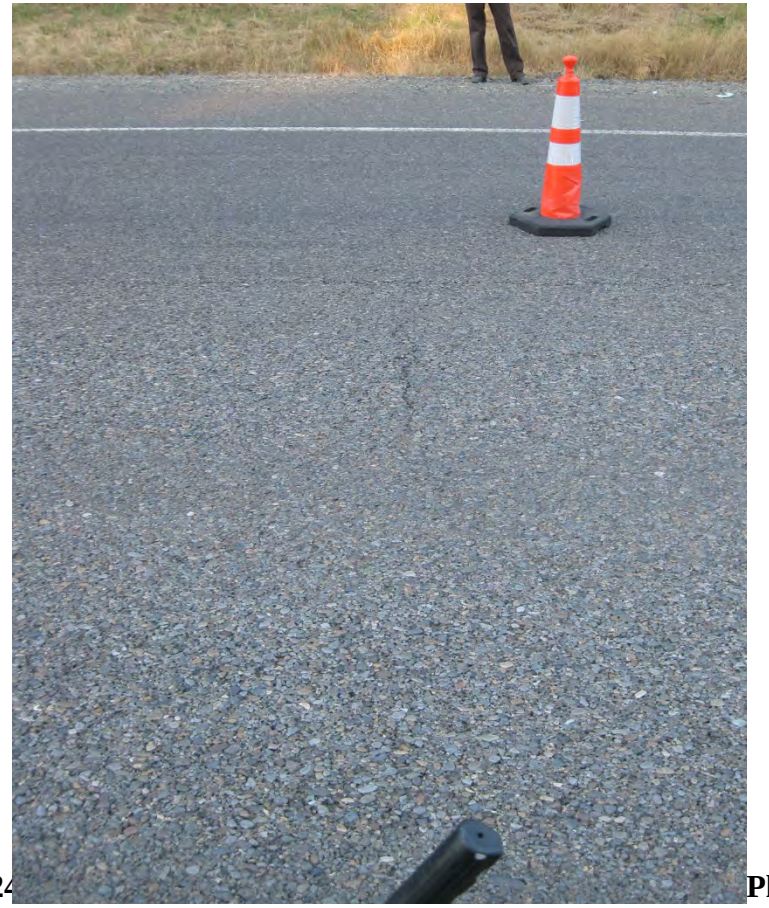


Photo 1125

Photo 1126

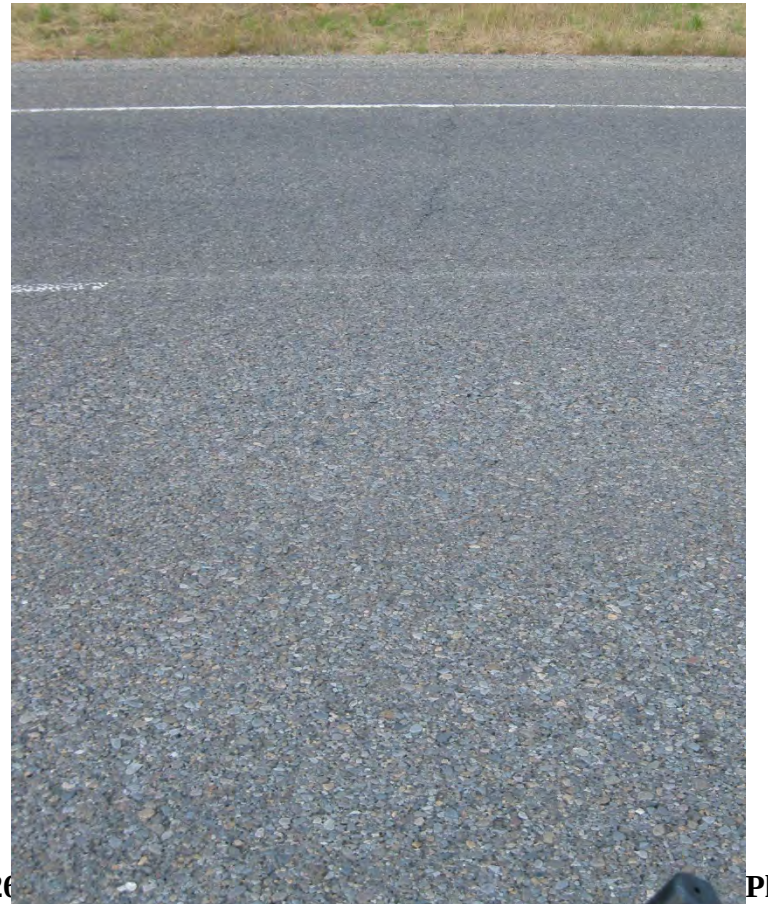


Photo 1127

Photo 1128

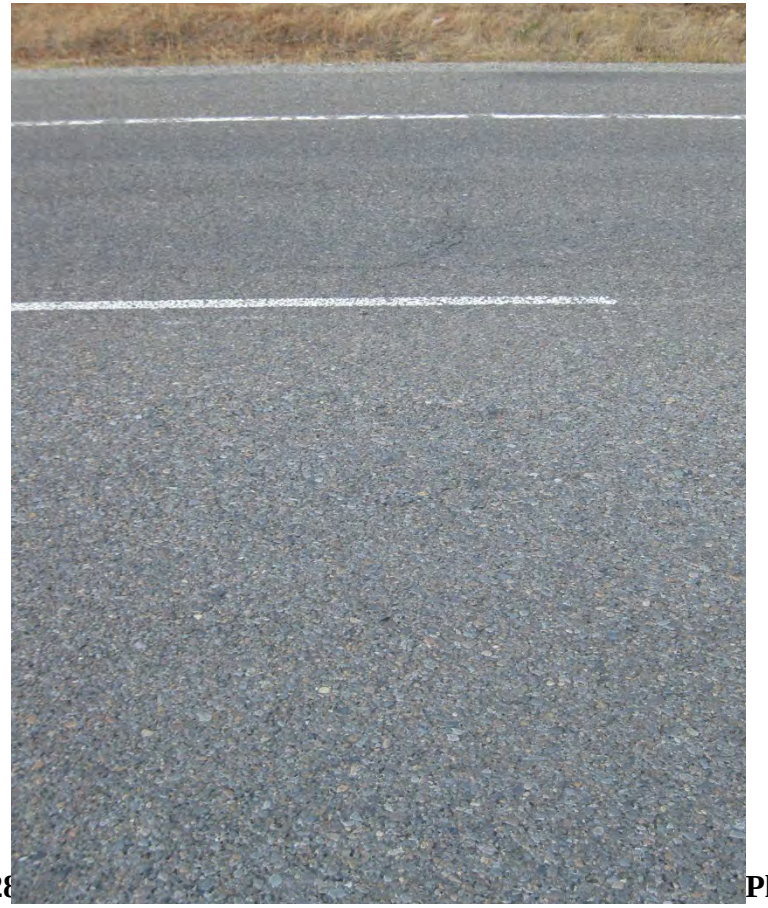


Photo 1129

Photo 1130

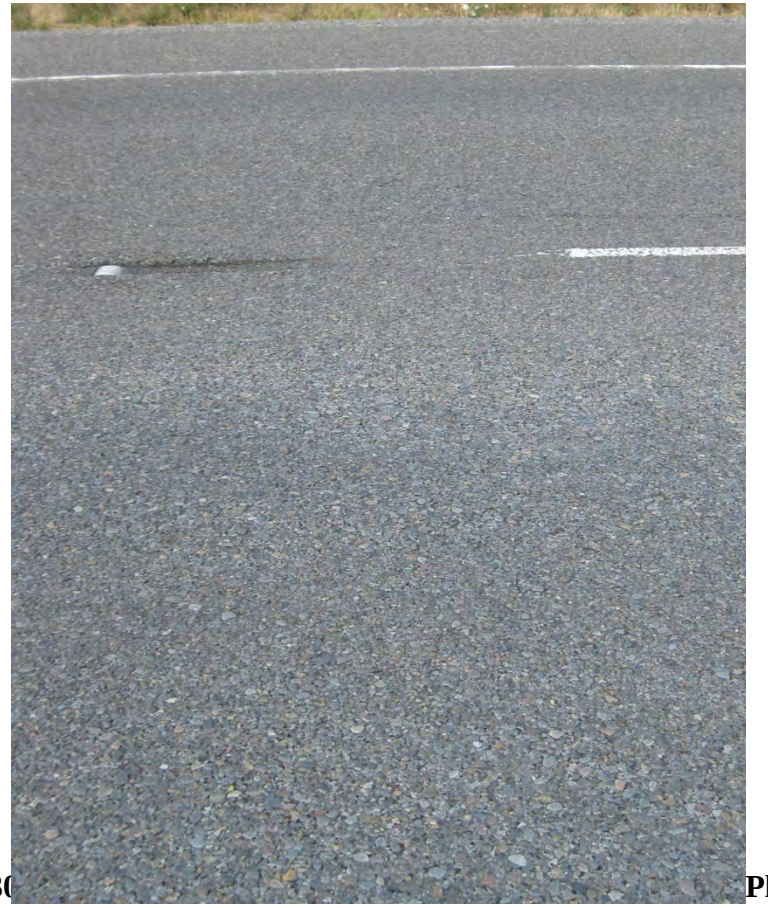


Photo 1131

Photo 1132

Photo 1133

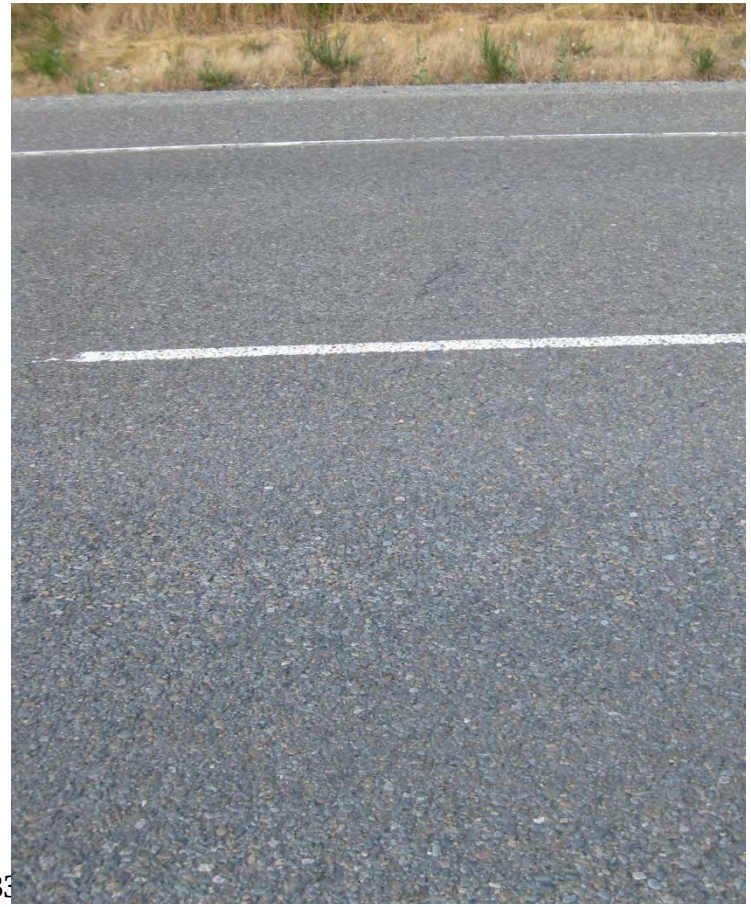


Photo 1134

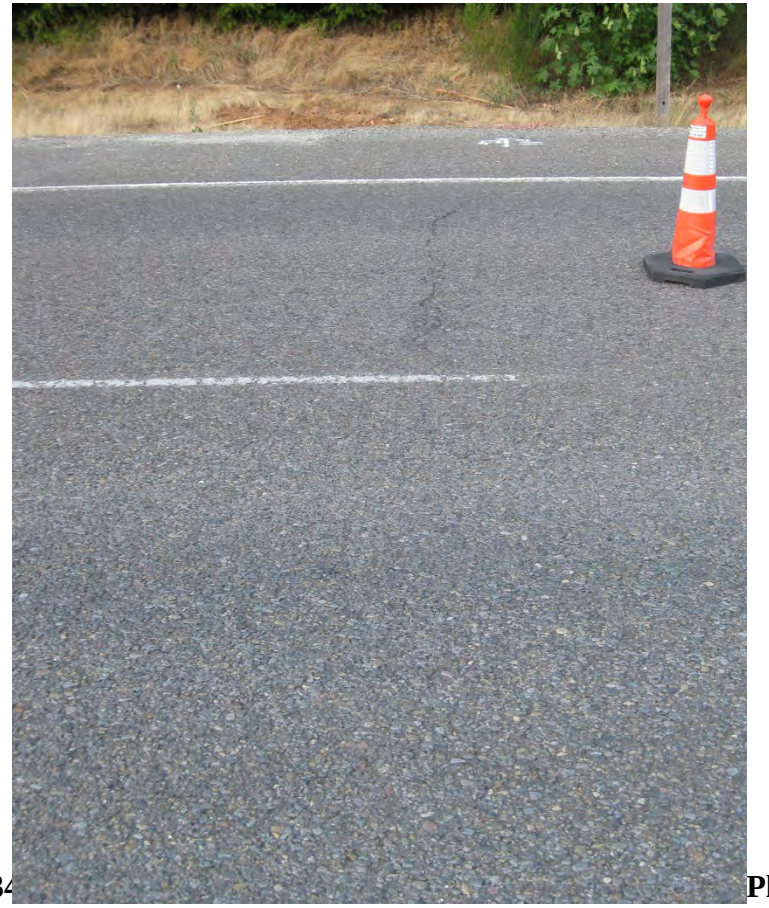


Photo 1135

Photo 1136

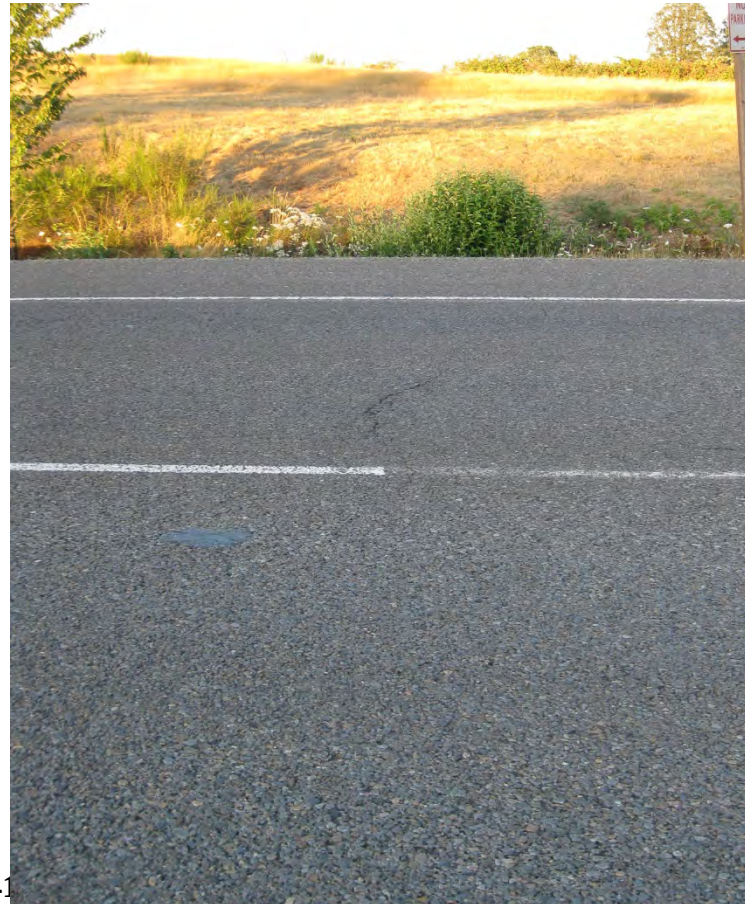
Photo 1137

Photo 1138

Photo 1139

Photo 1140

Photo 1141



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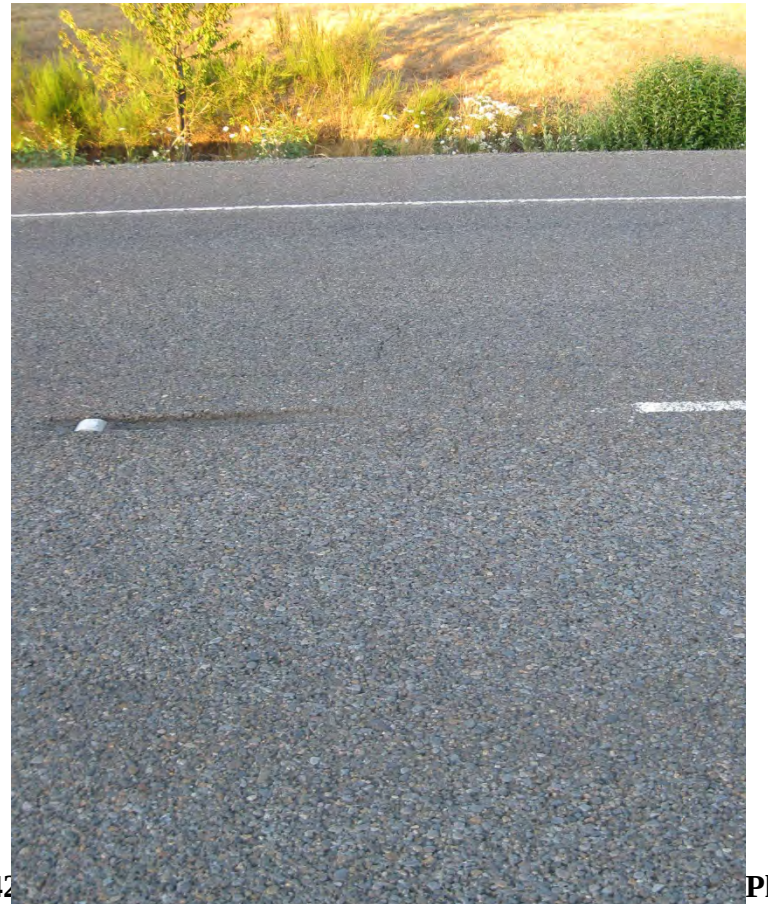

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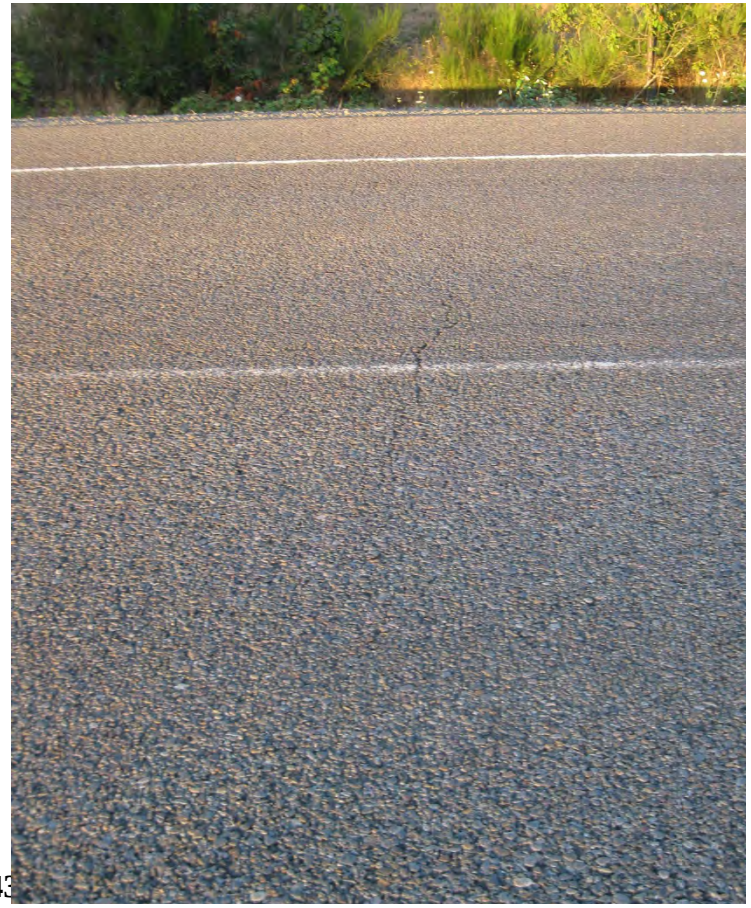

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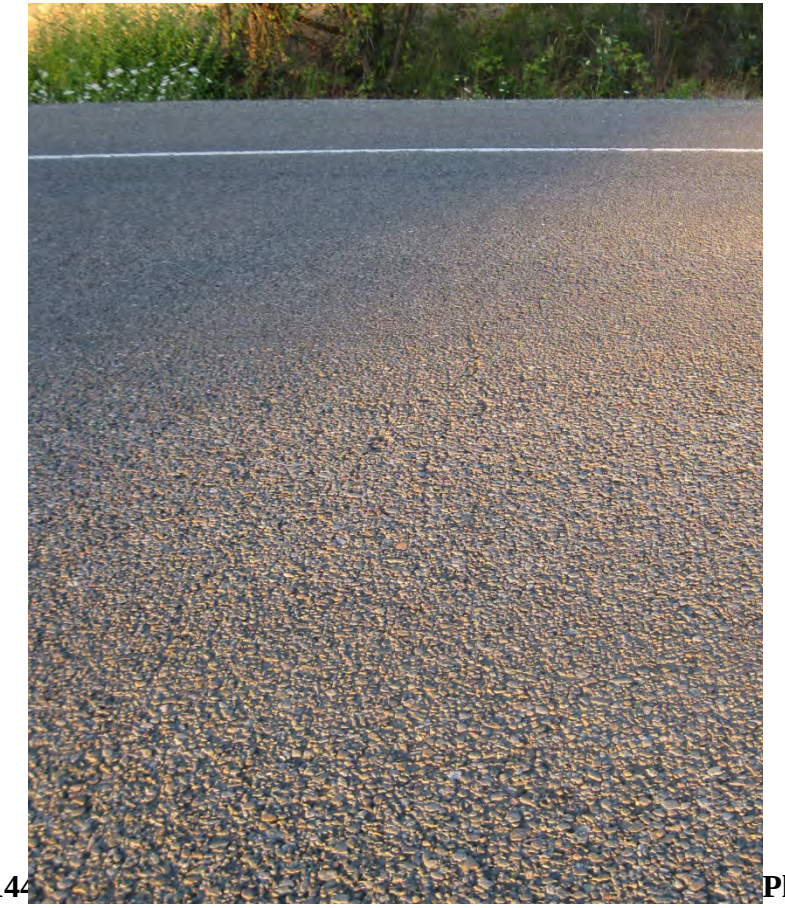


Photo 1145

Photo 1146

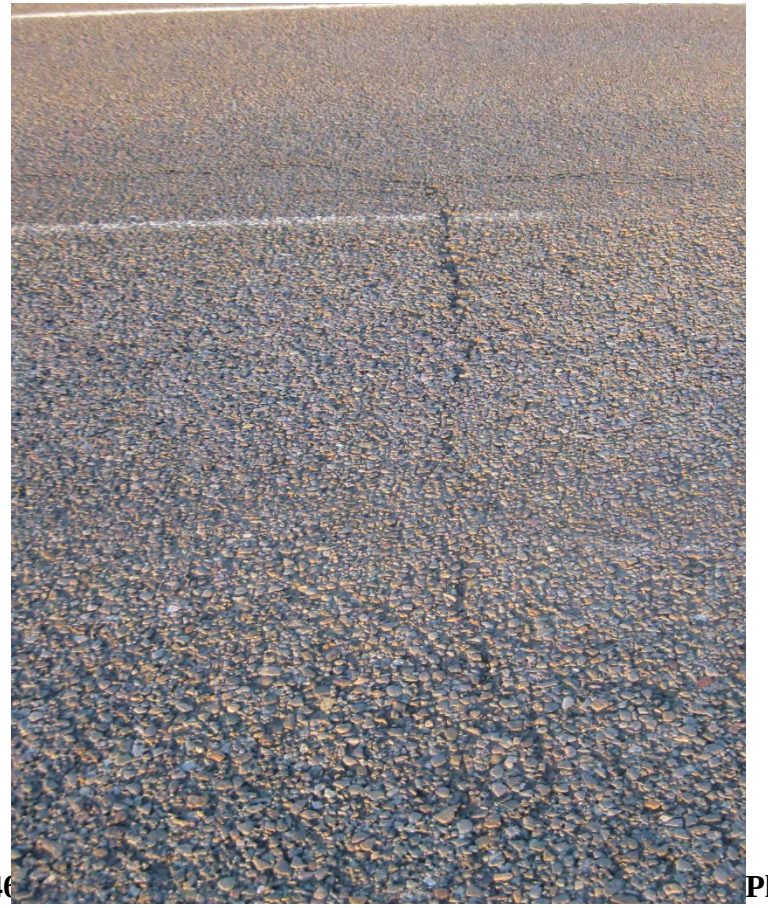


Photo 1147

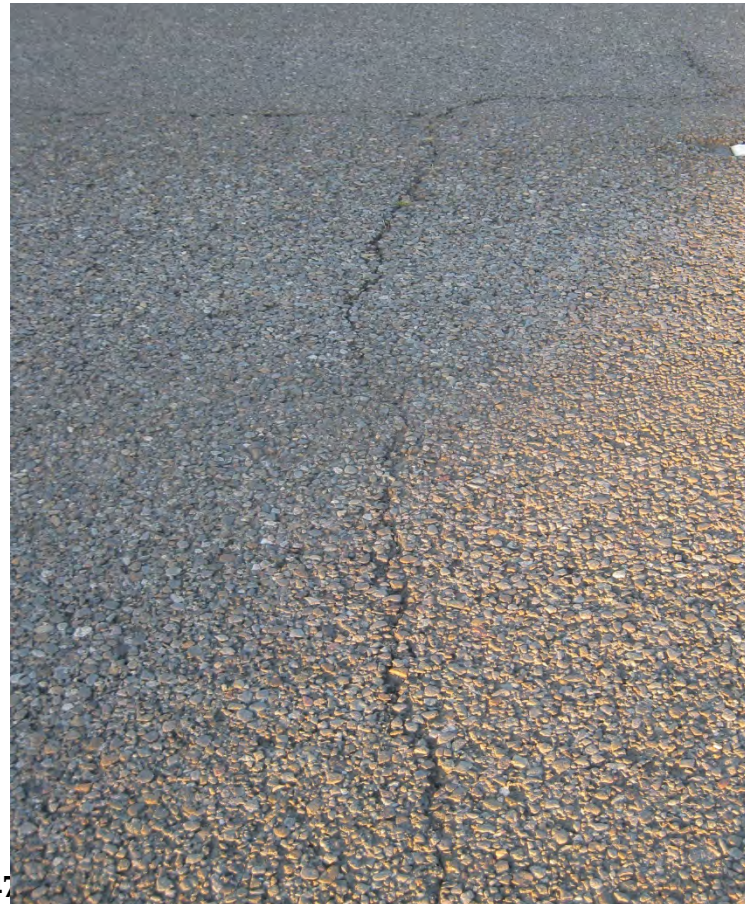


Photo 1148

Photo 1149

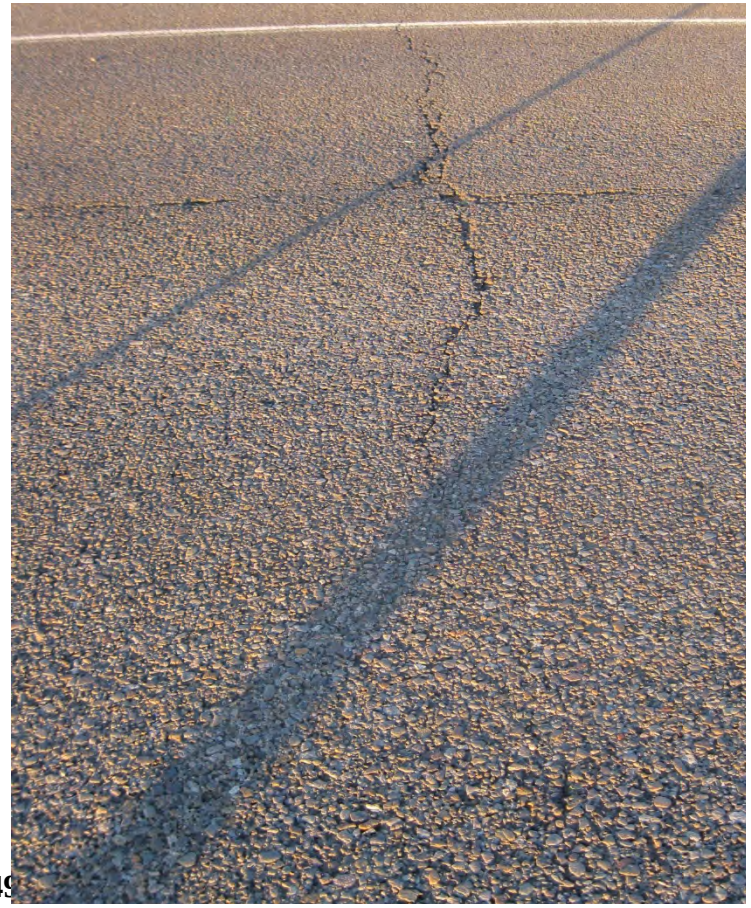


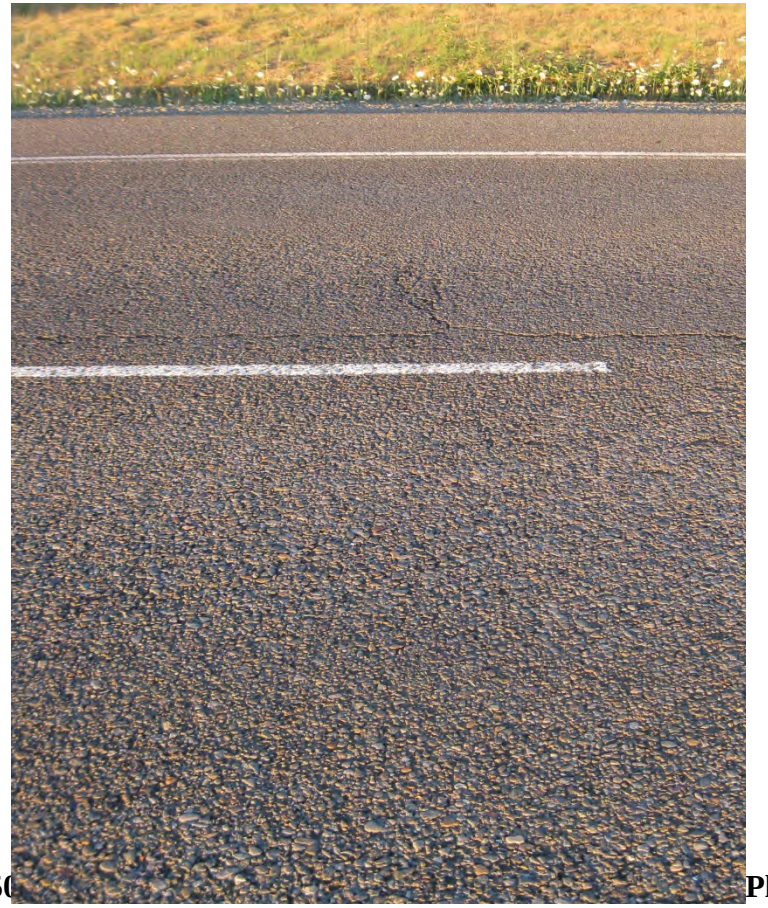
Photo 1150 

Photo 1151 

Photo 1153

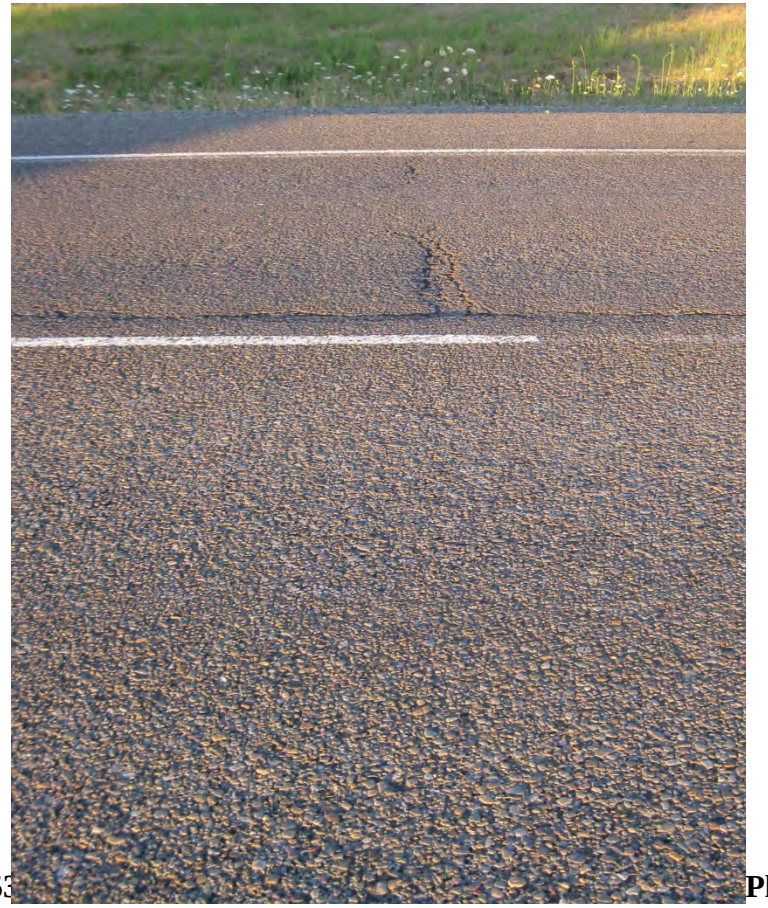
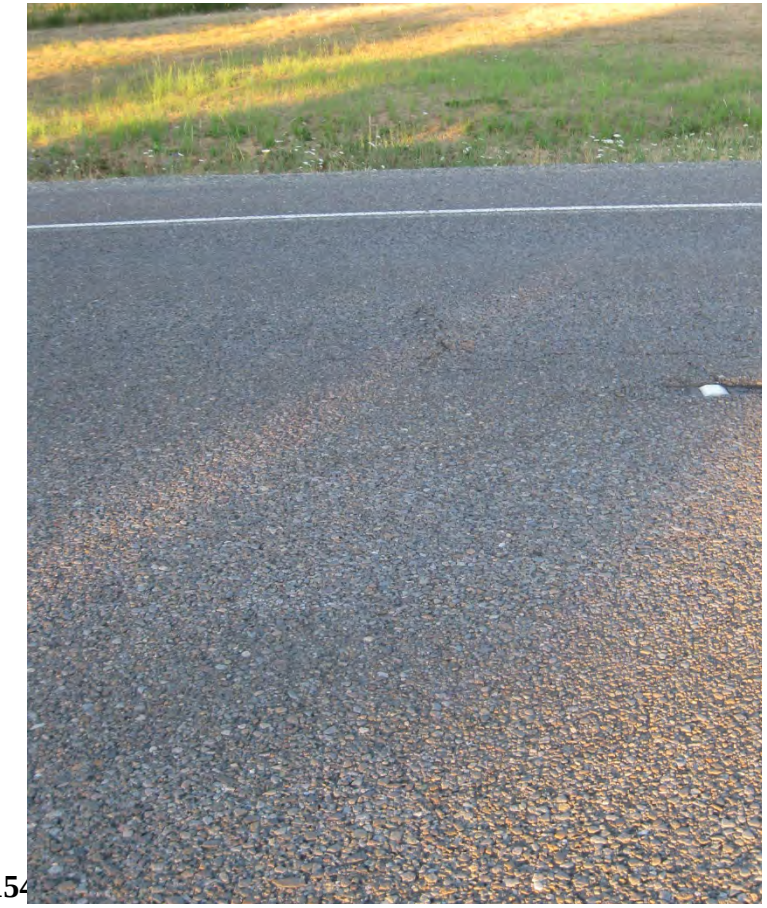


Photo 1154



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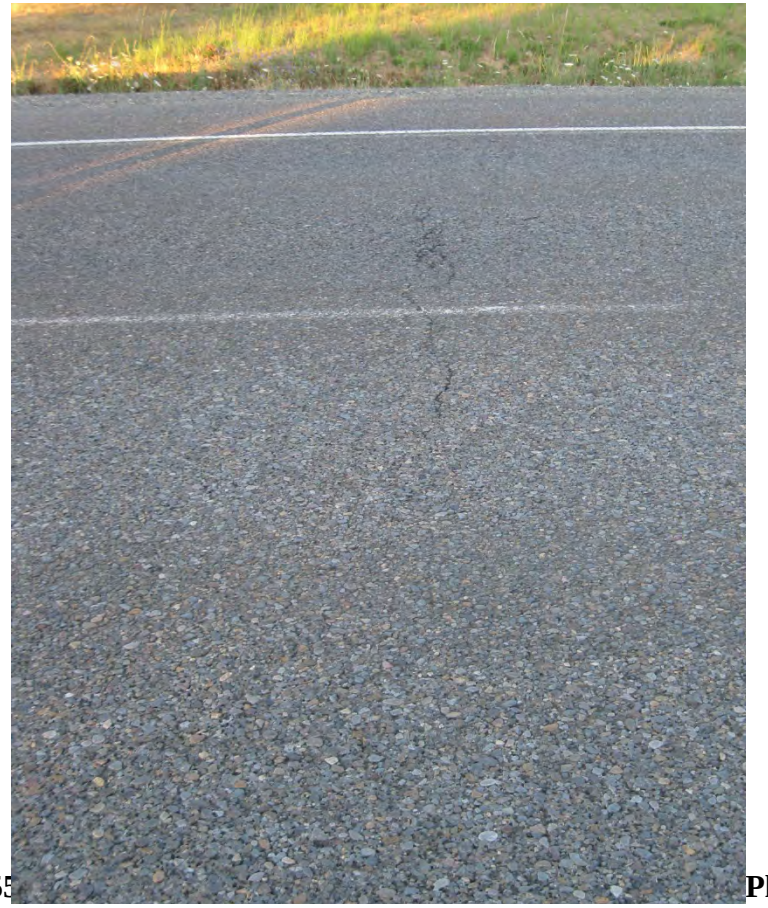

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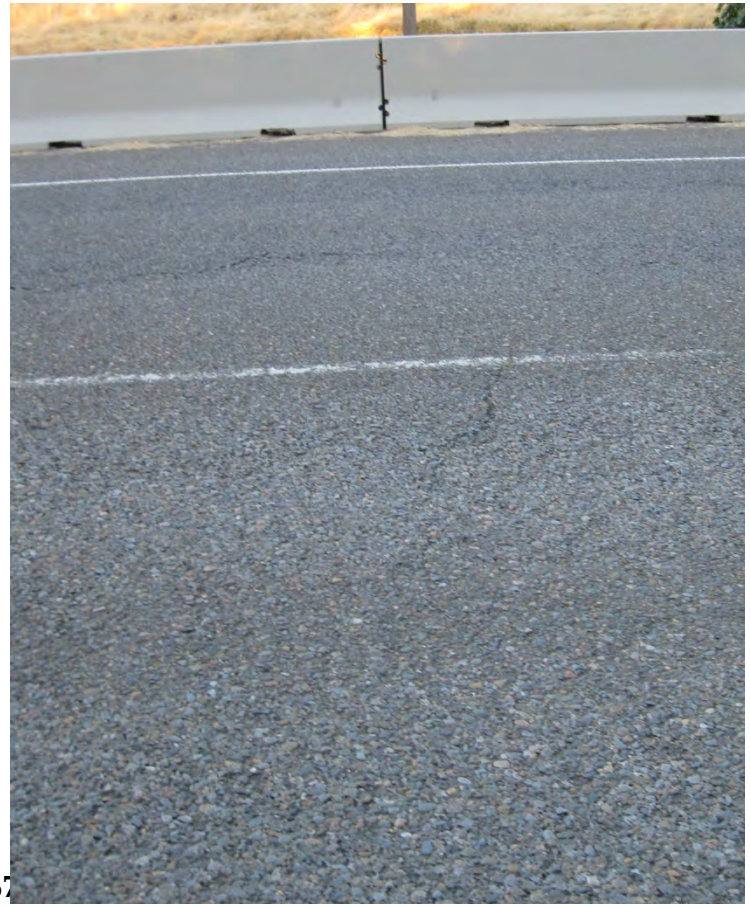


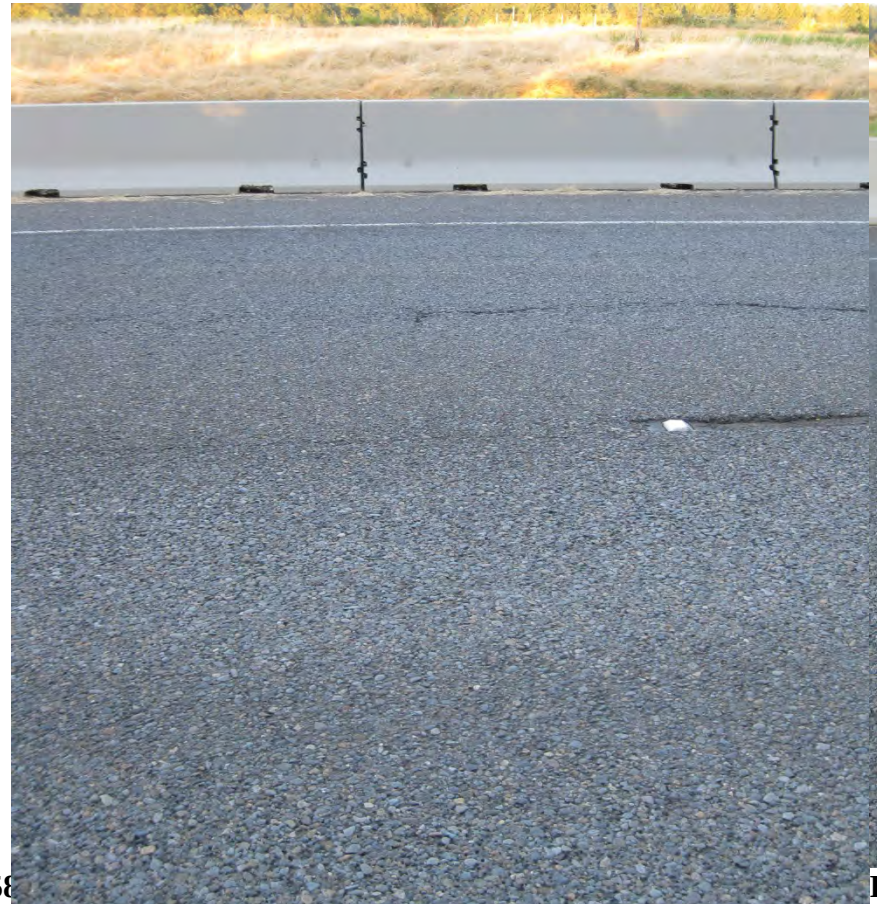


Photo 1158

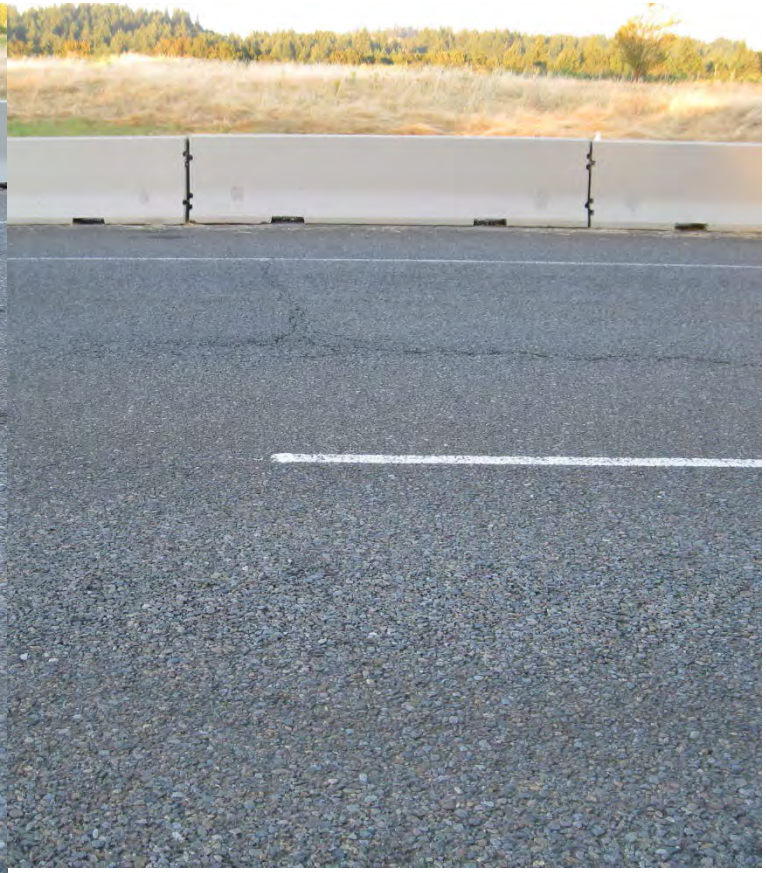


Photo 1159 (Station 21+39, looking east)

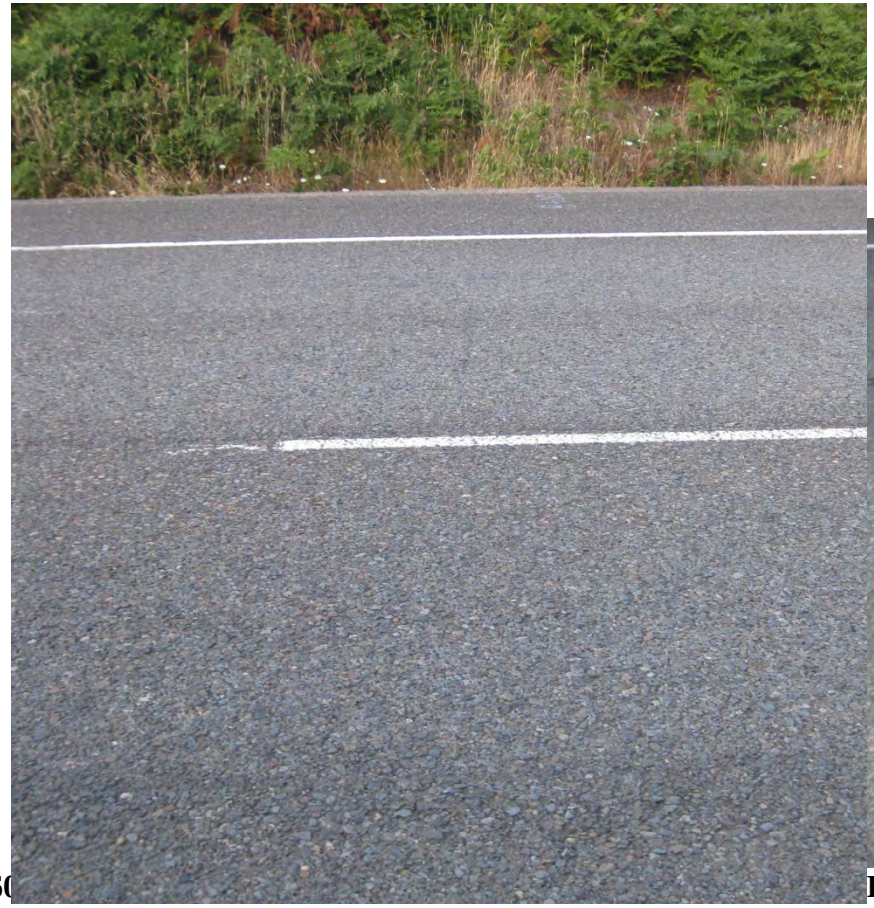


Photo 116(

Photo 1161 (Station 36+03, looking east)

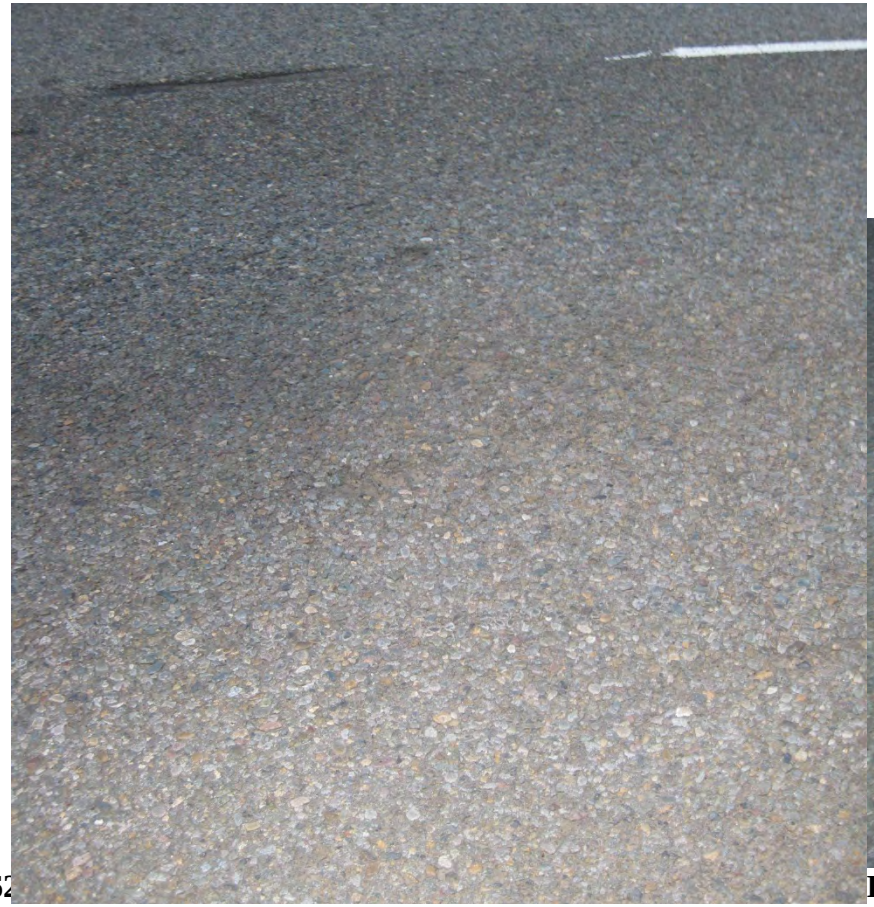


Photo 1162

Photo 1163 (Station 36+88, looking east)

Photo 1164 (Station 37+25, looking east)

Photo 1165 (Station 38+00, looking east)

APPENDIX E:
WESTERN RESEARCH INSTITUTE FINAL REPORT

Western Research
INSTITUTE

ANALYSIS SUMMARY and FINAL REPORT

Project Description:	Oregon State University/Prof. Todd Scholz
Sample IDs:	Shown below for each analytical method.
Date Received:	December 20, 2010
Authorized By:	Eric W. Kalberer

Executive Summary

Samples from two different paving projects, US-20 and I-5, were submitted for analysis to help determine the cause for softening in a RAP/RAS and virgin binder blend. Four samples were submitted for infrared spectroscopic (FTIR) analysis in search of residual solvent (toluene) from the extraction process. Residual solvent is known to have a softening effect on the rheological properties of asphalt binders. The data reported below indicate that there are trace amounts of toluene present but not in a sufficient amount to affect rheological measurements in any of the four samples. Some additional work was included to come to this conclusion and is described in detail below. In addition, extraction and Automated Flocculation Titrimetry (AFT), was requested on 6 different samples to determine whether the softening of the virgin binder, when blended with RAP/RAS, was a result of increased compatibility of the materials. This is an increasingly frequent phenomenon as more recycled binders are incorporated into the paving infrastructure. In fact, an increase in compatibility was found for both virgin binders when blended with both RAP and RAS, as is also shown below.

FTIR Analysis

Four samples were submitted for spectroscopic analysis to determine if residual toluene from the extraction process at ODOT was present and, thus, had an effect on rheological properties The samples were labeled:

- 10-4098 "A" (US-20): Extracted/Recovered binder from RAP/RAS mix.
- 10-134 "A" (US-20): Extracted/Recovered binder from RAP only mix.
- 10-4612 "C" (US-20): Virgin binder used on this project.
- 10-4969 (I-5): Extracted/Recovered binder from Rap only mix.

Absorbances at 693 cm^{-1} and 727 cm^{-1} can be used in an infrared spectrum to indicate the presence of toluene in an asphalt sample. Of course, there are other IR absorbances attributed to toluene, but the peak at 693 cm^{-1} is the only one in which there is no interference from the asphalt present. The peak at 727 cm^{-1} is typically sharper than at 693 cm^{-1}, however, there are asphalt related interferences there which make the peak at 693 cm^{-1} the only option for evaluating toluene clearly. None of the four samples analyzed indicated the presence of toluene as is shown in figure 1 below.

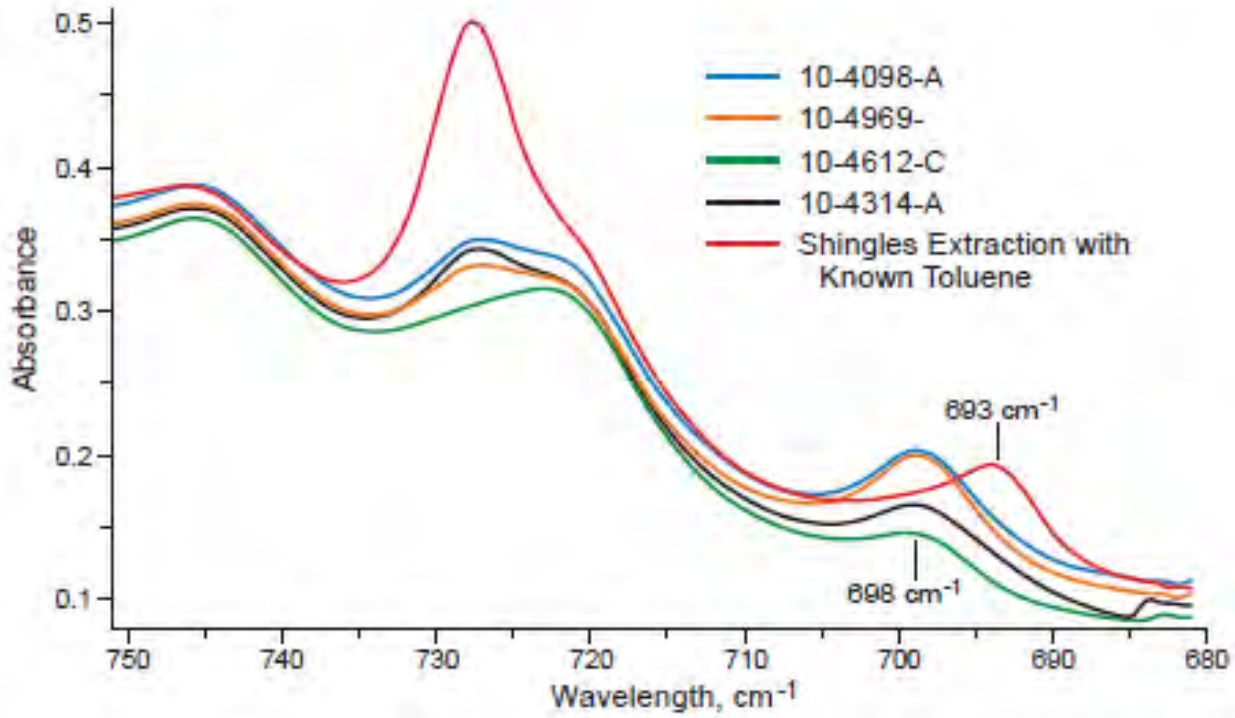


Figure 1. FTIR spectra for all four samples indicating lack of toluene in the material.

Upon closer inspection, there is a small bump in each spectrum at 698 cm^{-1} that could possibly be attributed to toluene if it is involved in hydrogen bonding with asphalt great enough to shift the absorbance up field. This has never actually been observed, but required some attention to insure certainty that our data is interpreted correctly. In addition, the peaks at 727 cm^{-1} do not correlate well with those at 698 cm^{-1} which means they are most likely not toluene-related. To test this possibility, one of the extracted samples was doped with toluene and a spectrum was obtained indicating a new, large peak at 693 cm^{-1} as expected and shown in pink in figure 1. This is another good indication that there is not residual toluene present in the extracted samples. GC/MS analysis of sample 10-4098-A was performed as well. This sample was selected because it has the largest absorbance at 698 cm^{-1} indicating the highest potential toluene content. GC/MS has a detection limit for low molecular weight organics like toluene in the 10ppm range, which is an order of magnitude or more greater sensitivity that FTIR. In the future, this approach may become the favored method for measuring solvent in asphalt. The GC/MS analysis did detect

toluene at a concentration of 0.05% by weight. This concentration is much too low to have a softening affect on the rheological properties of the asphalts. Therefore, the softening observed in the virgin binder blended with RAP is due to something else.

AFT Analysis

Automated Flocculation Titrimetry was performed on 6 samples extracted at WRI to determine if increased colloidal stability, or material compatibility, is responsible for the observed softening of the blended materials. The samples analyzed were:

I-5 project

- 70-22ER: Virgin Binder
- I5-RO-Mix: Extracted/Recovered RAP only mix
- I5-RR-Mix: Extracted/Recovered RAP/RAS mix

US-20 project

- 70-28ER: Virgin Binder
- US20-RO-Mix: Extracted/Recovered RAP only mix
- US20-RR-Mix: Extracted/Recovered RAP/RAS mix

An exhaustive listing of the data from the AFT analyses is included in Table 1 below. To help with understanding the data the results are broken into simplified terms. P_a is simply an indication of the extent of asphaltene content and also refers to how likely the asphaltenes may be dispersed in the system. As asphaltene content increases, in a blend or as asphalt ages, the P_a number actually decreases. P_o is an indication of what type of maltene fraction is present and how well they may help to disperse the asphaltenes. An increase in P_o value indicates an improvement in the solvent strength of the maltenes, or their ability to disperse the non-solvent asphaltenic material. P is most easily understood as the state of dispersion of the asphalt system. The higher the P value, the more disperse the system is and, in turn, the more compatible. δ_{floc} and δ_{oil} are values calculated from the P values. δ_{floc} is a solubility parameter corresponding to the start of flocculation of the asphaltenes and δ_{oil} is a solubility parameter directly related to the compatibility of the entire asphalt. A simple way to utilize these values deals with the ratio of the two parameters. Essentially, the greater the difference between δ_{floc} (low) and δ_{oil} (high) values, the more compatible the material under analysis is.

For both the I-5 materials as well as the US-20 materials there is a marked increase in δ_{oil} from virgin binder to RAP modified as well as RAP/RAS binders while the δ_{floc} parameter remains essentially the same for all. This is a marked increase in material compatibility, or colloidal stability, and is expected to be the primary cause of softening of the neat, virgin binder when blended with the RAP and RAS. The stability of the δ_{floc} parameter from virgin to blended

binders is remarkable as there is certainly both an increase in asphaltene content as well as a change in the chemical characteristics in the blends.

Sample ID	AFT Parameter Data			Wiehe Blending Numbers	
	P_a	P_o	P	δ_{floc}	δ_{oil}
I-5					
70-22	0.70	0.75	2.5	7.5	8.4
70-22 RAP	0.64	1.2	3.3	7.6	9.3
70-22 RAP+RAS	0.62	1.5	3.9	7.6	9.3
US-20					
70-28	0.73	0.81	3.0	7.4	8.2
70-28 RAP	0.63	1.0	2.8	7.4	8.5
70-28 RAP+RAS	0.63	1.3	3.4	7.6	9.4

Table 1. AFT data for the six samples indicating increased compatibility.

The P values support the observation that the virgin binders became softer when blended with the recycled materials. The increase in P_o values from virgin to RAP to RAP/RAS modified binders is significant as this number is a direct indication of the solvent strength of the maltene fraction. The P values follow this same trend with the exception of the 70-28RAP sample, which shows a small decrease in P value. Interestingly, the P_a value decreases from the virgin binder to the modified systems in each case. It's expected that the amount of asphaltene should increase in a RAP or RAP/RAS modified binder. However, that increase should have a stiffening effect on the virgin binder. In this case, the dominant force at work is the increased solubility strength of the maltene fraction and the results are reflected in the AFT parameter data as well as the blending numbers. The question remains: what is happening inside of the blended asphalts that improves compatibility and lowers the resulting stiffness of the binder in comparison to the virgin binder.

Conclusions

As stated above, the FTIR analysis of the four samples extracted at ODOT do not contain a sufficient amount of residual toluene that would soften the blended binders. The more sensitive GC/MS analysis identified only trace amounts of toluene and helped to resolve some initial concern over an anomalous absorbance at 698 cm^{-1} in the FTIR. The peak at 698 cm^{-1} is exclusively asphalt related.

Results from AFT analysis indicate that there is indeed improved compatibility of the RAP only and RAP/RAS virgin binder blends over the neat, virgin binder. This improved compatibility is directly related to the softening of the blended materials. The improved compatibility is

dominated by the increased solubility strength of the maltene fraction of the blended asphalt and the resulting improvement of the dispersion of the asphaltenic material present. Additionally, these materials would be a good fit for inclusion in a federally funded study at WRI that requires additional analyses of the chemical composition of the materials in order to completely understand the phenomena that are affected when mixing recycled and virgin binders.

APPENDIX F:
EXAMPLE FOR DEVELOPMENT OF A BATCHING PLAN USING VIRGIN AGGREGATES AND RAP AND RAS

The following provides an example for developing a batch plan according to the proposed batching procedure provided in Section 3.3.1 for a mixture containing aggregates from three virgin aggregate stockpiles and two reclaimed material stockpiles (RAP and RAS). It includes instructions for manually adjusting the stockpile percentages to meet a target gradation (within acceptable tolerances) as well as a method for minimizing the deviation between the calculated combined aggregate gradation and the target gradation. Only the first seven steps are covered in this example since the remaining steps (8 through 13) are common practice.

1. Virgin aggregate gradations via AASHTO T 27 and T 11. Columns D, E, and F in Figure A.1 indicate the mixture will include aggregates from three virgin aggregate stockpiles (i.e., 1/2"-#4, #4-#8, and #8-0) as shown in Row 2, Columns D, E, and F. Rows 5 through 15 of these columns summarize the percentages passing the listed sieve sizes as obtained from the sieve analyses.

	Stockpile	1/2" - #4	#4 - #8	#8 - 0	RAP Aggr.	RAS Aggr.	Comparison: Combined vs. Target					
	Stockpile Percentage, P_{sj}	27.0	33.0	25.0	12.0	3.0						
	Check ΣP_{sj}	100.0					Combined Aggregate			Target		
	Sieve Size	Percent Passing					%Ret., P_i	Cum. %Ret.	%Pass	%Pass	Diff	Diff^2
	3/4"	100	100	100	100	100	0.0	0.0	100	100	0.0	0.0
	1/2"	97	100	100	98	99	1.1	1.1	98.9	99	0.1	0.0
	3/8"	61	99	100	91	99	10.9	12.0	88.0	86	-2.0	4.1
	1/4"	13	71	100	78	98	23.8	35.8	64.2	61	-3.2	10.5
	#4	4	44	99	70	97	12.6	48.3	51.7	50	-1.7	2.8
	#8	2	12	82	56	96	17.1	65.4	34.6	34	-0.6	0.4
	#16	2	7	57	43	81	9.9	75.3	24.7	24	-0.7	0.5
	#30	2	5	40	32	63	6.8	82.1	17.9	17	-0.9	0.8
	#50	2	4	24	25	56	5.4	87.5	12.5	12	-0.5	0.3
	#100	2	3	16	20	50	3.1	90.6	9.4	9	-0.4	0.2
	#200	1.1	2.2	7.8	15.1	41.2	3.4	94.0	6.0	6.0	0.0	0.0
	Pan	0	0	0	0	0	6.0	100	0.0	0	0.0	0.0
	Binder Content, %	---	---	---	5.0	20.0	1.3328	<--- Root Mean Square Error				

Figure A.1 – Spreadsheet for Determining Stockpile Percentages for a Given Target Gradation

2. Reclaimed material binder contents via AASHTO T 308. Columns G and H in Figure A.1 contain the data pertaining to the reclaimed material stockpiles. Row 17 indicates the binder contents of the RAP and RAS materials.

3. Reclaimed material residual aggregate gradations via AASHTO T 30. Rows 5 through 15 of Columns G and H show the percentages passing the listed sieve sizes as obtained from the sieve analyses on the residual aggregates obtained from the ignition oven tests (Step 2).

4. Trial target gradation (i.e., trial design aggregate structure) for the mixture. Rows 5 through 15 of Column L in Figure A.1 list the percentages passing the listed sieve sizes for the target gradation. In this case, the target gradation was obtained from an existing mix design that included 15 percent RAP, but no RAS.

5. Trial binder content (P_b) for the mixture. The existing mix design mentioned in Step 4 indicated a binder content of 6.0 percent for the job-mix formula. Since this was the optimum binder content of the mixture, it seems reasonable to start with this same binder content for the new mixture. Hence, for this example, a trial binder content (P_b) of 6.0 percent will be used.

6. Trial stockpile percentages of the reclaimed materials. The existing mix design mentioned in Step 4 included 15 percent RAP. For this example, the total reclaimed material content will be held to approximately the same percentage to avoid deviating significantly from the existing mix design. Based on experience, inclusion of approximately 3 percent RAS appears to be a reasonable starting point. Hence, for this example, the percentages of aggregate from the RAP and RAS stockpiles will be 12 and 3 percent, respectively.

   NOTE: These two trial percentages represent percentages of the total aggregate weight, not percentages of the total mixture weight.

7. Develop batch plan. The basic objective in this step is to determine the percentages of each stockpile that will result in a combined aggregate gradation that closely matches the target gradation (i.e., trial design aggregate structure). This can be done by manually adjusting the stockpile percentages, or in an automated fashion through use of the Solver data analysis tool in Microsoft Excel. Both methods are covered in this example. Once this is accomplished, batch quantities of the materials can be determined.

   Combined Aggregate Gradation

   Equation 3.1 can be used to determine the percentage of material in a given size fraction (e.g., 3/4"×1/2") due to the contribution of the same size material in all stockpiles containing this size. Equation 3.1 simply sums the percentages contributed by each stockpile (p_{ij}) for a given size fraction (i) taking into account the relative percentage of each stockpile in the mixture (P_{Sj}) to provide the total percentage (P_i) of the given size fraction. For example, the combined (total) percentage of the 3/4"×1/2" material shown in Figure A.1 can be determined as follows:

$$P_{\frac{3}{4}\times\frac{1}{2}} = (100-97)\frac{27}{100} + (100-98)\frac{12}{100} + (100-99)\frac{3}{100} = \mathbf{1.1}$$

   Note that the differences in the parentheses are simply the percentages of the 3/4"×1/2" material in each stockpile that contains this size material (i.e., only the 1/2"-#4, RAP, and RAS stockpiles). Note also that the result listed in Row 6 of Column I in Figure A.1 is the same as listed above since this cell contains Equation 3.1. In like fashion, the percentages of the remaining size fractions can be determined using Equation 3.1 as shown in Rows 7 through 16 of Column I in Figure A.1 (i.e., each of these cells contains Equation 3.1).

Once the percentages of the size fractions are determined, the remaining calculations for cumulative percent retained and percent passing are the same as in an ordinary sieve analysis. That is, cumulative percent retained is calculated by summing the values in the percent retained column (i.e., Column J in Figure A.1 is the summation of Column I). Likewise, percent passing is 100 minus cumulative percent retained for each size fraction (e.g., percent passing the #4 sieve—Row 10 of Column K—is 100 minus the value in Row 10 of Column J).

Note that Figure A.1 contains two columns (M and N) with headings Diff and Diff^2. Diff is the difference between Columns L and K (i.e., L – K) for each size fraction, and Diff^2 is the square of the differences; that is, $(L - K)^2$. The values listed in Column M (i.e., Diff) can be used when employing the manual method for adjusting the stockpile percentages to assist in minimizing differences between the combined gradation and target gradation, whereas the values listed in both columns (Diff and Diff^2) are utilized in the automated method.

Finally, Figure A.1 includes a cell (Row 18, Column I) containing the root mean square error. This value provides a measure of the difference (error) between the combined gradation and the target gradation and is calculated as follows:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}\left([\![(P]\!]_{Target})_i - [\![(P]\!]_{CombAggr})_i\right)^2}{n}}$$

Where:

RMSE = root mean square error

$(P_{Target})_i$ = percent passing the i^{th} sieve size for the target gradation

$(P_{CombAggr})_i$ = percent passing the i^{th} sieve size for the combined aggregate gradation

n = number of size fractions in the target gradation with percentages greater than zero (i.e., number of rows in Column I of Figure A.1 where the value in the row is greater than zero)

Minimizing this value (whether using the manual method or the automated method) when adjusting the stockpile percentages minimizes the difference between the combined aggregate gradation and the target gradation.

Stockpile Percentages via Manual Method

Equation 3.1 relies on the stockpile percentages for determining the combined aggregate gradation. Hence, changing any of the stockpile percentages changes the combined aggregate gradation. In a spreadsheet set up as shown in Figure A.1 and discussed in the preceding paragraphs, these values can be iteratively manipulated to minimize the difference

between the combined aggregate gradation and the target gradation. For example, Figure A.2 shows modified (adjusted) percentages of the virgin aggregate stockpiles (Row 3, Columns D through F) relative to those shown in Figure A.1. Note the magnitudes of the differences for each size fraction listed in Column M of Figure A.2 relative to those listed in Figure A.1. Some increased while others decreased. Note also the magnitude of the root mean square error (RSME) shown in Row 18, Column I. The adjusted stockpile percentages shown in Figure A.2 resulted in an RMSE of less than half the RMSE shown in Figure A.1 indicating significantly lower difference (error) between the combined aggregate gradation and target gradation. The stockpile percentages can be adjusted manually in this manner until the difference between the two gradations is minimized to one's satisfaction.

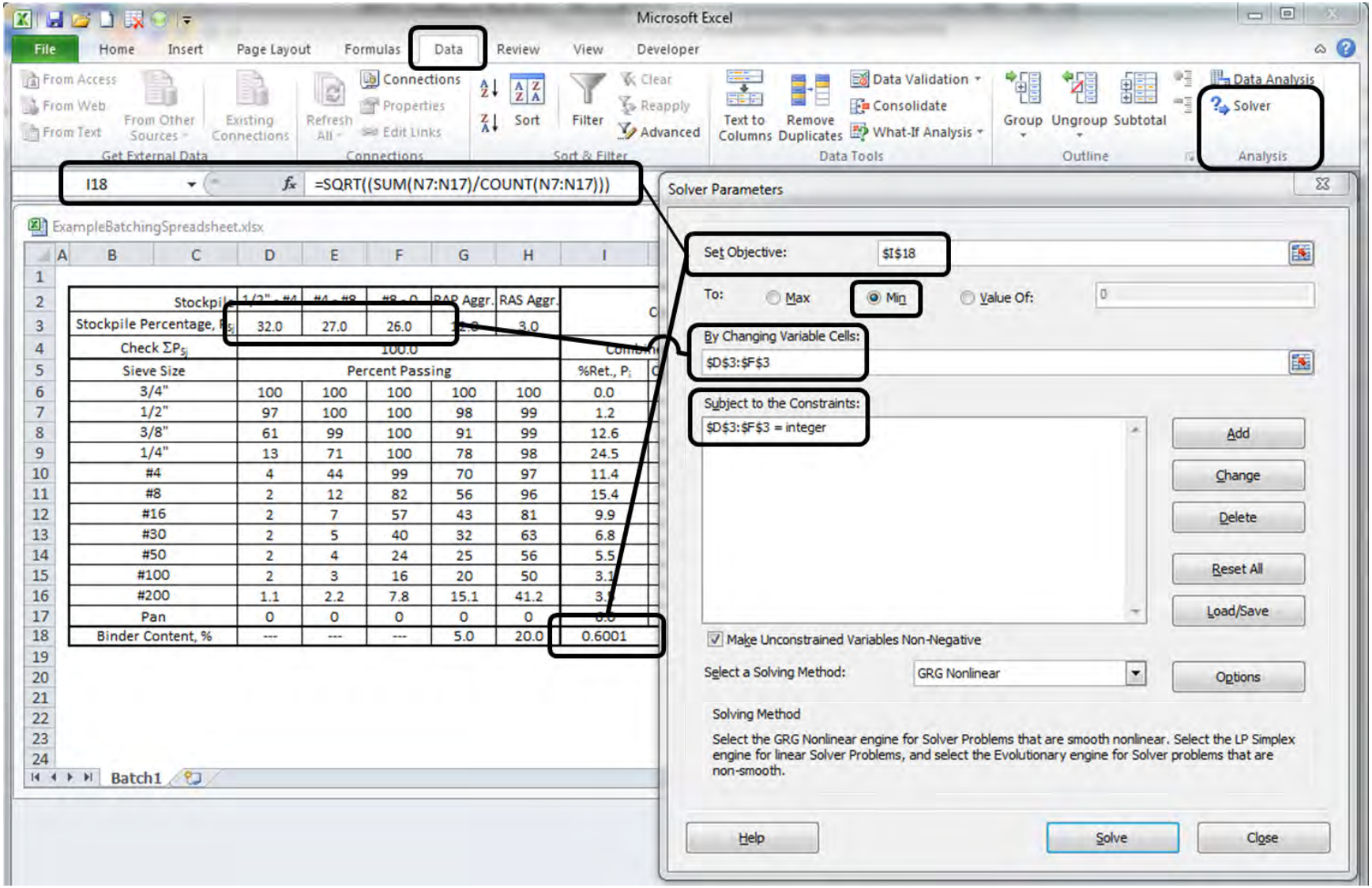
	A	B	C	D	E	F	G	H	I	J	K	L	M	N
1														
2		Stockpile		1/2" - #4	#4 - #8	#8 - 0	RAP Aggr.	RAS Aggr.	Comparison: Combined vs. Target					
3		Stockpile Percentage, P_{sj}		32.0	27.0	26.0	12.0	3.0						
4		Check ΣP_{sj}		100.0					Combined Aggregate			Target		
5		Sieve Size		Percent Passing					%Ret., P_i	Cum. %Ret.	%Pass	%Pass	Diff	Diff^2
6		3/4"		100	100	100	100	100	0.0	0.0	100	100	0.0	0.0
7		1/2"		97	100	100	98	99	1.2	1.2	98.8	99	0.2	0.1
8		3/8"		61	99	100	91	99	12.6	13.9	86.1	86	-0.1	0.0
9		1/4"		13	71	100	78	98	24.5	38.4	61.6	61	-0.6	0.4
10		#4		4	44	99	70	97	11.4	49.8	50.2	50	-0.2	0.0
11		#8		2	12	82	56	96	15.4	65.2	34.8	34	-0.8	0.6
12		#16		2	7	57	43	81	9.9	75.1	24.9	24	-0.9	0.9
13		#30		2	5	40	32	63	6.8	81.9	18.1	17	-1.1	1.3
14		#50		2	4	24	25	56	5.5	87.4	12.6	12	-0.6	0.4
15		#100		2	3	16	20	50	3.1	90.5	9.5	9	-0.5	0.3
16		#200		1.1	2.2	7.8	15.1	41.2	3.5	94.0	6.0	6.0	0.0	0.0
17		Pan		0	0	0	0	0	6.0	100	0.0	0	0.0	0.0
18		Binder Content, %		---	---	---	5.0	20.0	0.6001	<--- Root Mean Square Error				
19														

Figure A.2 – Spreadsheet with Adjusted Stockpile Percentages

Stockpile Percentages via Automated Method

The Solver data analysis tool in Microsoft Excel can be used to find an optimal (maximum or minimum) value of an equation—called the objective function—in a cell within the spreadsheet. Hence, the Solver tool can be used to minimize the RMSE formula in the example spreadsheet, thereby minimizing the difference between the combined aggregate gradation and the target gradation. Figure A.3 shows how to set up the Solver tool to accomplish this. Note that the Solver tool can be found in the Analysis group under the Data tab.

Figure A.3 indicates that the Solver tool will optimize the formula in cell I18 (i.e., Row 18, Column I), which contains the equation for the root mean square error. It also indicates that the Solver tool has been set to minimize the formula (i.e., the radio button next to Min has been selected). Finally, the figure indicates that the RMSE is to be minimized by changing the variables in cells D3 through F3 (i.e., the stockpile percentages for the virgin aggregates).



	B	C	D	E	F	G	H	I
2	Stockpile		1/2" - #4	#4 - #8	#8 - 0	RAP Aggr.	RAS Aggr.	C
3	Stockpile Percentage, P_{Si}		32.0	27.0	26.0	[illegible]	3.0	
4	Check ΣP_{Si}		100.0					Combin
5	Sieve Size		Percent Passing					%Ret., P_i
6	3/4"		100	100	100	100	100	0.0
7	1/2"		97	100	100	98	99	1.2
8	3/8"		61	99	100	91	99	12.6
9	1/4"		13	71	100	78	98	24.5
10	#4		4	44	99	70	97	11.4
11	#8		2	12	82	56	96	15.4
12	#16		2	7	57	43	81	9.9
13	#30		2	5	40	32	63	6.8
14	#50		2	4	24	25	56	5.5
15	#100		2	3	16	20	50	3.1
16	#200		1.1	2.2	7.8	15.1	41.2	3.[illegible]
17	Pan		0	0	0	0	0	0.0
18	Binder Content, %		---	---	---	5.0	20.0	0.6001

Figure A.3 – Establishing Parameters in the Solver Tool

Note that constraints can be placed on the variables used to minimize the objective function by clicking on the Add button next to the Subject to the Constraints list box. Figure A.3 indicates that constraints have been placed on the stockpile percentages to hold them to integer values during the optimization process. These constraints can be removed if it is desired to minimize the RMSE using non-integer stockpile percentages.

One can also select the method for optimization using the Select a Solving Method drop-down list. Figure A.3 indicates that GRG Nonlinear has been selected. Note that the frame beneath the drop-down list provides descriptions for the solving methods.

Once the parameters are established, the objective function (i.e., RMSE equation) can be minimized by clicking on the Solve button. Figure A.4 shows the optimized solution for stockpile percentages constrained as integers. Note that the RMSE value in Row 18, Column I is much lower than that shown in Figure A.2. This was due to the adjustments made to the percentages for the #4-#8 and #8-0 stockpiles.

Stockpile	1/2" - #4	#4 - #8	#8 - 0	RAP Aggr.	RAS Aggr.	Comparison: Combined vs. Target					
Stockpile Percentage, P_{Sj}	32.0	28.0	25.0	12.0	3.0						
Check ΣP_{Sj}	100.0					Combined Aggregate			Target		
Sieve Size	Percent Passing					%Ret., P_i	Cum. %Ret.	%Pass	%Pass	Diff	Diff^2
3/4"	100	100	100	100	100	0.0	0.0	100	100	0.0	0.0
1/2"	97	100	100	98	99	1.2	1.2	98.8	99	0.2	0.1
3/8"	61	99	100	91	99	12.6	13.9	86.1	86	-0.1	0.0
1/4"	13	71	100	78	98	24.8	38.7	61.3	61	-0.3	0.1
#4	4	44	99	70	97	11.7	50.3	49.7	50	0.3	0.1
#8	2	12	82	56	96	15.6	65.9	34.1	34	-0.1	0.0
#16	2	7	57	43	81	9.7	75.6	24.4	24	-0.4	0.2
#30	2	5	40	32	63	6.7	82.2	17.8	17	-0.8	0.6
#50	2	4	24	25	56	5.3	87.6	12.4	12	-0.4	0.2
#100	2	3	16	20	50	3.1	90.6	9.4	9	-0.4	0.1
#200	1.1	2.2	7.8	15.1	41.2	3.4	94.0	6.0	6.0	0.0	0.0
Pan	0	0	0	0	0	6.0	100	0.0	0	0.0	0.0
Binder Content, %	---	---	---	5.0	20.0	0.3614	<--- Root Mean Square Error				

Figure A.4 – Optimization Results for Stockpile Percentages Constrained as Integers

Figure A.5 shows the optimized results for stockpile percentages not constrained to integer values. Although the RSME value is lower than as shown in Figure A.4, note that the stockpile percentages no longer sum to 100 percent (i.e., the cell to the right of Check ΣP_{Sj} indicates the stockpile percentages sum to 100.3 percent) due to the percentage for the #4-#8 stockpile being 28.3. Obviously, this value would need to be rounded down to 28.0 so that the summation of stockpile percentages equals 100 (which was found by constraining the stockpile percentages to integers as shown in Figure A.4). Solver can be set to constrain the summation of stockpile percentages to 100 percent as discussed next.

Stockpile	1/2" - #4	#4 - #8	#8 - 0	RAP Aggr.	RAS Aggr.	Comparison: Combined vs. Target					
Stockpile Percentage, P_{Si}	32.0	28.3	25.0	12.0	3.0						
Check ΣP_{Si}	100.3					Combined Aggregate			Target		
Sieve Size	Percent Passing					%Ret., P_i	Cum. %Ret.	%Pass	%Pass	Diff	Diff^2
3/4"	100	100	100	100	100	0.0	0.0	100	100	0.0	0.0
1/2"	97	100	100	98	99	1.2	1.2	98.8	99	0.2	0.1
3/8"	61	99	100	91	99	12.6	13.9	86.1	86	-0.1	0.0
1/4"	13	71	100	78	98	24.9	38.7	61.3	61	-0.3	0.1
#4	4	44	99	70	97	11.8	50.5	49.5	50	0.5	0.2
#8	2	12	82	56	96	15.6	66.1	33.9	34	0.1	0.0
#16	2	7	57	43	81	9.7	75.8	24.2	24	-0.2	0.0
#30	2	5	40	32	63	6.7	82.5	17.5	17	-0.5	0.3
#50	2	4	24	25	56	5.3	87.8	12.2	12	-0.2	0.0
#100	2	3	16	20	50	3.1	90.9	9.1	9	-0.1	0.0
#200	1.1	2.2	7.8	15.1	41.2	3.4	94.3	5.7	6.0	0.3	0.1
Pan	0	0	0	0	0	6.0	100	-0.3	0	0.3	0.1
Binder Content, %	---	---	---	5.0	20.0	0.2868	<--- Root Mean Square Error				

Figure A.5 – Optimization Results for Unconstrained Stockpile Percentages

If desired, the Solver tool can be setup to adjust all stockpile percentages during the optimization process. In addition, the summation of stockpile percentages can be constrained to 100 percent. Figure A.6 illustrates the settings for the Solver tool to accomplish both and Figure A.7 displays the optimized results. Note that the constraint for the stockpile percentages being integers was removed (Figure A.6) providing the best overall set of stockpile percentages (i.e., lowest RMSE value and, hence, least difference between gradations).

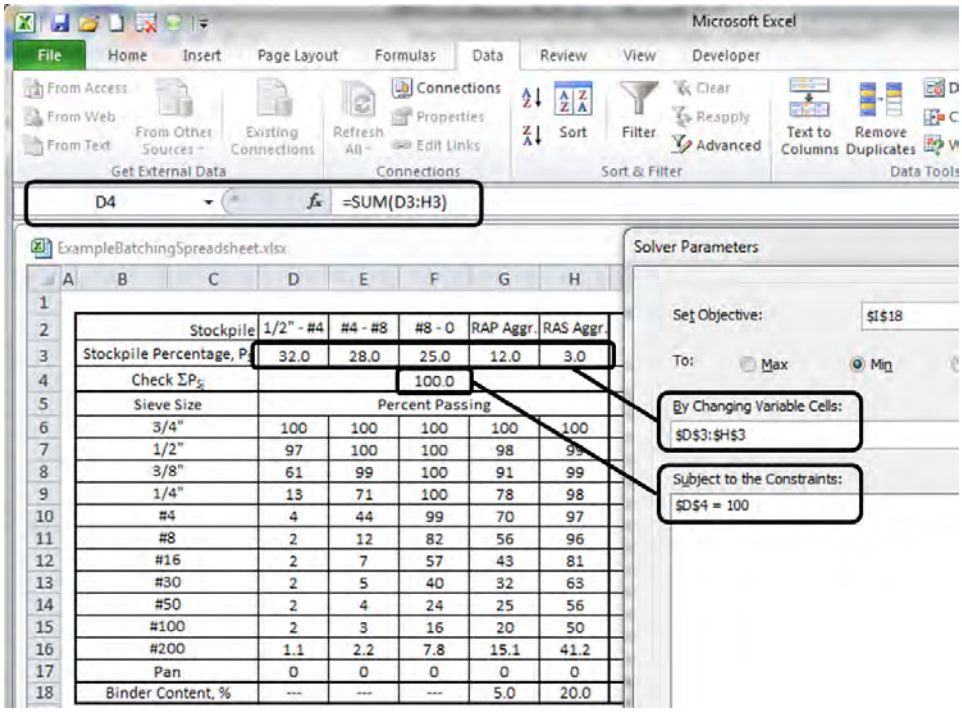


Figure A.6 – Settings to Adjust all Stockpile Percentages and Constrain these to 100 Percent

	A	B	C	D	E	F	G	H	I	J	K	L	M	N
1														
2		Stockpile		1/2" - #4	#4 - #8	#8 - 0	RAP Aggr.	RAS Aggr.	Comparison: Combined vs. Target					
3		Stockpile Percentage, P_{sj}		32.0	27.5	25.7	13.3	1.5						
4		Check ΣP_{sj}		100.0					Combined Aggregate			Target		
5		Sieve Size		Percent Passing					%Ret., P_i	Cum. %Ret.	%Pass	%Pass	Diff	Diff^2
6		3/4"		100	100	100	100	100	0.0	0.0	100	100	0.0	0.0
7		1/2"		97	100	100	98	99	1.2	1.2	98.8	99	0.2	0.1
8		3/8"		61	99	100	91	99	12.7	14.0	86.0	86	0.0	0.0
9		1/4"		13	71	100	78	98	24.8	38.8	61.2	61	-0.2	0.1
10		#4		4	44	99	70	97	11.6	50.4	49.6	50	0.4	0.2
11		#8		2	12	82	56	96	15.7	66.1	33.9	34	0.1	0.0
12		#16		2	7	57	43	81	9.8	75.9	24.1	24	-0.1	0.0
13		#30		2	5	40	32	63	6.7	82.5	17.5	17	-0.5	0.2
14		#50		2	4	24	25	56	5.4	87.9	12.1	12	-0.1	0.0
15		#100		2	3	16	20	50	3.1	91.0	9.0	9	0.0	0.0
16		#200		1.1	2.2	7.8	15.1	41.2	3.4	94.4	5.6	6.0	0.4	0.2
17		Pan		0	0	0	0	0	5.6	100	0.0	0	0.0	0.0
18		Binder Content, %		---	---	---	5.0	20.0	0.2581	<--- Root Mean Square Error				
19														

Figure A.7 – Best Overall Set of Stockpile Percentages

Note also that constraints can also be placed on individual stockpile percentages during the optimization process. For example, either reclaimed material stockpile can be constrained to be less than a specified percentage, or another cell formula can be added to sum the two reclaimed material stockpile percentages and constrain the summation of the two stockpiles to be less than a specified percentage.

Determine Batch Masses

Batch masses can be determined once the stockpile percentages have been adjusted. Perhaps the easiest way to accomplish this is to first convert the gradations for the stockpiles from percent passing to percent retained. Figure A.8 shows the values from Figure A.7 (in percent passing) converted to percentages retained. The values for a given sieve size were determined by subtracting the percentage passing the given sieve size from the percentage passing the next larger sieve size. For example, the percentage retained on the 1/2” sieve from the 1/2”-#4 stockpile (3, as shown in Figure A.8) was determined by subtracting 97 (percentage passing the 1/2” sieve) from 100 (percentage passing the 3/4” sieve). Note that Figure A.8 also includes a section that provides a check to ensure the conversion process was done correctly.

Once converted, Equation 3.2a or 3.2b can be used to calculate the batch masses for the virgin aggregate stockpiles and for the *aggregates* from the reclaimed material stockpiles. It is important to note that these equations assume use of residual aggregate gradations for the reclaimed materials (not gradations of the reclaimed materials with coated aggregates). As such, the batch masses determined using Equation 3.2a or 3.2b need to be adjusted to account for the mass of binder coating the aggregate particles. This is accomplished using Equations 3.3a or 3.3b. Hence, a two-stage process is employed, with the first stage being determination of the batch masses for uncoated aggregates.

Stockpile	1/2" - #4	#4 - #8	#8 - 0	RAP Aggr.	RAS Aggr.	Check			
Stockpile Percentage, P_{sj}	32.0	27.5	25.7	13.3	1.5				
100	100.0					Combined Aggregate			Target
Sieve Size, i	Percent Retained, p_{ij}					%Ret., P_i	Cum. %Ret.	%Pass	%Pass
3/4"	0	0	0	0	0	0.0	0.0	100	100
1/2"	3	0	0	2	1	1.2	1.2	98.8	99
3/8"	36	1	0	7	0	12.7	14.0	86.0	86
1/4"	48	28	0	13	1	24.8	38.8	61.2	61
#4	9	27	1	8	1	11.6	50.4	49.6	50
#8	2	32	17	14	1	15.7	66.1	33.9	34
#16	0	5	25	13	15	9.8	75.9	24.1	24
#30	0	2	17	11	18	6.7	82.5	17.5	17
#50	0	1	16	7	7	5.4	87.9	12.1	12
#100	0	1	8	5	6	3.1	91.0	9.0	9
#200	0.9	0.8	8.2	4.9	8.8	3.4	94.4	5.6	6.0
Pan	1.1	2.2	7.8	15.1	41.2	5.6	100.0	0.0	---

Figure A.8 – Stockpile Gradations Converted to Percentages Retained

Use of Equation 3.2a requires the total mass of aggregate in a given batch, whereas Equation 3.2b requires the total mass of mixture in a given batch. The choice of which equation is a matter of convenience, and both will provide the same result provided that the relationship between the mass of aggregate (M_A), total mass of mixture (M_T), and binder content of the mixture (P_b) is upheld; that is,

$$M_A = M_T\left(1 - {}^{P_b}/_{100}\right)$$

Figure A.9 shows the batch masses for the virgin aggregates and for the residual aggregates from the reclaimed materials. It indicates a mixture binder content of 6.0 percent (from Step 5), a mixture batch mass of 6,500 grams, and an aggregate batch mass of 6,110 grams determined from the above equation; that is, 6500 × (1 - 6.0 / 100) = 6110. It should be noted that a mixture batch mass of 6,500 grams was chosen arbitrarily for this example, but one that provides approximately enough material to compact the mixture to a cylinder 6 inches in diameter by 6 inches in height to a density of approximately 146 lb/ft^3. In practice, one should determine the mixture batch mass based on the ultimate disposition of the compacted test specimen. For example, if a certain density (air void content) is desired such as for mix design purposes, the mixture batch mass should be determined such that it provides a given density (air void content) for a specified volume.

Mixture Binder Content, P_b, %	6.0
Mixture Batch Mass, M_T, grams	6500
Aggregate Batch Mass, grams	6110

Stockpile	1/2" - #4	#4 - #8	#8 - 0	RAP Aggr.	RAS Aggr.
Stockpile Percentage, P_{Sj}	32.0	27.5	25.7	13.3	1.5
Sieve Size, i	Batch Mass*, m_{ij}, grams				
3/4"	0.0	0.0	0.0	0.0	0.0
1/2"	58.7	0.0	0.0	16.3	0.9
3/8"	703.9	16.8	0.0	56.9	0.0
1/4"	938.5	470.5	0.0	105.6	0.9
#4	176.0	453.7	15.7	65.0	0.9
#8	39.1	537.7	266.9	113.8	0.9
#16	0.0	84.0	392.6	105.6	13.7
#30	0.0	33.6	266.9	89.4	16.5
#50	0.0	16.8	251.2	56.9	6.4
#100	0.0	16.8	125.6	40.6	5.5
#200	17.6	13.4	128.8	39.8	8.1
Pan	21.5	37.0	122.5	122.7	37.8
Check Mass, g	1955.3	1680.3	1570.2	812.6	91.6
Check Percent	32.0	27.5	25.7	13.3	1.5
Check Total Mass	6110.0				

*Excludes mass of binder on the reclaimed materials

Figure A.9 – Virgin and Residual Aggregate Batch Weights

The following examples illustrate the use of Equations 3.2a and 3.2b to calculate the batch mass of the 1/2"×3/8" size fraction from the 1/2"-#4 virgin aggregate stockpile. Figure A.8 indicates 36 percent retained on the 3/8" sieve (Row 27, Column D) while Figure A.9 indicates a stockpile percentage of 32.0 percent (Row 44, Column D).

- Using Equation 3.2a with an aggregate batch mass of 6,110 grams gives:

$$m_{i_j} = {}^{p_{i_j}}/_{100} \times {}^{P_{S_j}}/_{100} \times M_A = {}^{36}/_{100} \times {}^{32}/_{100} \times 6110 = 703.9\ grams$$

- Using Equation 3.2b with a mixture batch mass of 6,500 grams and a mixture binder content of 6.0 percent gives:

$$m_{i_j} = {}^{p_{i_j}}/_{100} \times {}^{P_{S_j}}/_{100} \times \left[1 - {}^{P_b}/_{100}\right] \times M_T$$

$$= {}^{36}/_{100} \times {}^{32}/_{100} \times \left[1 - {}^{6.0}/_{100}\right] \times 6500 = 703.9\ grams$$

Note that both equations give the same result. Note also that Figure A.9 includes checks at the bottom of the table (i.e., in Rows 58 through 60). Row 58 displays the summation of batch masses for each stockpile. The sum of the columns in Row 58 is displayed in Row 60, which provides a means for checking that this value is equal to the total aggregate batch mass. That is, this value can be checked against the value shown in Row 41, Column E to ensure they are the same; if not, the equations in the spreadsheet should be checked for

errors. Row 59 displays the stockpile percentages based on the values in Row 58 and the value in Row 60. These values can be checked against the values listed in Row 44 to ensure they are the same for each stockpile; if not, the equations in the spreadsheet should be checked for errors.

Once the batch masses for the virgin and residual aggregates have been determined, those for the reclaimed materials need to be adjusted using Equation 3.3a or 3.3b to account for the mass of binder coating the aggregate particles. Figure A.10 shows the adjusted batch masses while the following examples illustrate the use of Equations 3.3a and 3.3b to make these adjustments.

64	RAP Binder Content, $(P_b)_{RAP}$			5.0			
65	RAS Binder Content, $(P_b)_{RAS}$			20.0			
66							
67	Stockpile	1/2" - #4	#4 - #8	#8 - 0	RAP	RAS	
68	Stockpile Percentage, P_{Si}	32.0	27.5	25.7	13.3	1.5	
69	Sieve Size, i	Batch Mass*, m_{ij}, grams					
70	3/4"	0.0	0.0	0.0	0.0	0.0	
71	1/2"	58.7	0.0	0.0	17.2	1.1	
72	3/8"	703.9	16.8	0.0	59.9	0.0	
73	1/4"	938.5	470.5	0.0	111.2	1.1	
74	#4	176.0	453.7	15.7	68.4	1.1	
75	#8	39.1	537.7	266.9	119.8	1.1	
76	#16	0.0	84.0	392.6	111.2	17.1	
77	#30	0.0	33.6	266.9	94.1	20.6	
78	#50	0.0	16.8	251.2	59.9	8.0	
79	#100	0.0	16.8	125.6	42.7	6.9	
80	#200	17.6	13.4	128.8	41.9	10.1	
81	Pan	21.5	37.0	122.5	129.2	47.3	
82	Totals	1955.3	1680.3	1570.2	855.4	114.5	
83		6175.7					
84	RAP Binder	Mass (grams) =		42.8	$(P_{br})_{RAP}$ =	0.66	
85	RAS Binder	Mass (grams) =		22.9	$(P_{br})_{RAS}$ =	0.35	
86	Total Reclaimed Binder	Mass (grams) =		65.7	P_{br} =	1.01	
87	Virgin Binder	Mass (grams) =		324.3	P_{virgin} =	5.0	
88	Mixture	Mass (grams) =		6500.0	P_b =	6.0	
89	Percent of virgin binder replaced by RAP binder					11.0	
90	Percent of virgin binder replaced by RAS binder					5.8	
91	Percent of virgin binder replaced by RAM binder					16.8	
92	*Includes mass of binder on the reclaimed materials						

Figure A.10 – Batch Masses Including Mass of Binder on Reclaimed Materials

The following examples illustrate the use of Equations 3.3a and 3.3b to calculate the batch mass of the 1/2”×3/8” size fraction from the RAP residual aggregate stockpile. Figure A.10 indicates a RAP binder content of 5.0 percent (Row 64, Column E), Figure A.8 indicates 7 percent retained on the 3/8” sieve (Row 27, Column G), and Figure A.10 indicates a stockpile percentage of 13.3 percent (Row 68, Column G).

- Using Equation 3.3a with an aggregate batch mass of 6,110 grams gives:

$$m_{i_j} = \frac{\left[{}^{p_{i_j}}/_{100}\right] \times \left[{}^{P_{S_j}}/_{100}\right] \times M_A}{100 - [(P]_{br})_{RAM_j}} \times 100$$

$$= \frac{\left[{}^{7}/_{100}\right] \times \left[{}^{13.3}/_{100}\right] \times 6110}{100 - 5.0} \times 100 = 59.9\ grams$$

- Using Equation 3.2b with a mixture batch mass of 6,500 grams and a mixture binder content of 6.0 percent gives:

$$m_{i_j} = \frac{\left[{}^{p_{i_j}}/_{100}\right] \times \left[{}^{P_{S_j}}/_{100}\right] \times \left[1 - {}^{P_b}/_{100}\right] \times M_T}{100 - [(P]_{br})_{RAM_j}} \times 100$$

$$= \frac{\left[{}^{7}/_{100}\right] \times \left[{}^{13.3}/_{100}\right] \times \left[1 - {}^{6.0}/_{100}\right] \times 6500}{100 - 5.0} \times 100 = 59.9\ grams$$

Note that both equations give the same result. Note also that Figure A.10 includes other values at the bottom of the table. In particular, it includes the following:

- The total batch mass for each stockpile as displayed in Row 82. These are the quantities to be used for batching purposes.
- The total batch mass less virgin binder as displayed in Row 83. This is the summation of values in Row 82.
- The mass of RAP binder and the percent of RAP binder in the mixture, $(P_{br})_{RAP}$, are listed in Row 84. The mass of RAP binder can be determined as the difference between the total batch mass of RAP (Row 82, Column G in Figure A.10) and the total RAP residual aggregate batch mass (Row 58, Column G in Figure A.9); that is, 855.4 – 812.6 = 42.8 grams. The percent of RAP binder in the mixture can be determined by dividing the mass of RAP binder by the mixture batch mass and multiplying by 100; that is, (42.8 / 6500) × 100 = 0.66 percent.
- The mass of RAS binder and the percent of RAS binder in the mixture, $(P_{br})_{RAS}$, are listed in Row 85. The mass of RAS binder can be determined as the difference between the total batch mass of RAS (Row 82, Column H in Figure A.10) and the total RAS residual aggregate batch mass (Row 58, Column H in Figure A.9); that is, 114.5 – 91.6 = 22.9 grams. The percent of RAS binder in the mixture can be determined by dividing the mass of RAS binder by the mixture batch mass and multiplying by 100; that is, (22.9 / 6500) × 100 = 0.35 percent.

- The total mass of reclaimed binder and percent of RAM (i.e., RAP and RAS) binder in the mixture, P_{br}, are listed in Row 86. The mass of RAM binder can be determined by summing the masses of the RAP and RAS binders; that is, 42.8 + 22.9 = 65.7 grams. It can also be determined by subtracting the total aggregate batch mass (Row 60 in Figure A.9) from the total batch mass of virgin aggregates and reclaimed materials (Row 83 in Figure A.10); that is, 6175.7 – 6110.0 = 65.7 grams. The percent of RAM binder in the mixture can be determined by dividing the mass of RAM binder by the mixture batch mass and multiplying by 100; that is, (65.7 / 6500) × 100 = 1.01 percent. It can also be determined by summing the individual contributions from the RAP and RAS; that is, 0.66 + 0.35 = 1.01 percent.
- The mass of virgin binder and percent virgin binder in the mixture, P_{virgin}, are listed in Row 87. The mass of virgin binder can be determined by multiplying the total batch mass by the mixture binder content divided by 100 and subtracting from this result the mass of RAM; that is, 6500 × (6.0 / 100) – 65.7 = 324.3 grams. The percent of virgin binder can be determined by dividing the mass of virgin binder by the mixture batch mass and multiplying by 100; that is, (324.3 / 6500) × 100 = 5.0 percent. It can also be determined by subtracting the RAM binder content from the mixture binder content; that is, 6.0 – 1.0 = 5.0 percent.
- As a check Row 88 lists the mixture batch mass and mixture binder content, P_b. The mixture batch mass can be determined by adding the value listed in Row 83 to the mass of virgin binder listed in Row 87; that is, 6175.7 + 324.3 = 6500.0 grams. The mixture binder content can be determined by summing the virgin and reclaimed binder masses, dividing this value by the mixture batch mass, and multiplying the result by 100; that is, (65.7 + 324.3) / 6500 × 100 = 6.0 percent.
- Finally, the percentages of virgin binder replaced by the reclaimed materials are listed in Rows 89 to 90. The percentage of virgin binder replaced by the RAP binder can be determined by dividing the percent of RAP binder in the mixture, $(P_{br})_{RAP}$, by the mixture binder content, $P_{b,}$ and multiplying the result by 100; that is, (0.66 / 6.0) × 100 = 11.0 percent. Similarly, the percentage of virgin binder replaced by the RAS binder can be determined by dividing the percent of RAS binder in the mixture, $(P_{br})_{RAS}$, by the mixture binder content, $P_{b,}$ and multiplying the result by 100; that is, (0.35 / 6.0) × 100 = 5.8 percent. The total percentage of virgin binder replaced by the reclaimed materials can be determined by summing the individual contributions of the RAP and RAS binders; that is, 11.0 + 5.8 = 16.8 percent.

Figure A.11 summarizes the quantities to be used for batching purposes. Note that the quantities for the RAP and RAS include both the mass of aggregate and the mass of binder in the reclaimed materials.

	A	B	C	D	E	F	G	H
94								
95		Stockpile		1/2" - #4	#4 - #8	#8 - 0	RAP	RAS
96		Batch Mass, grams		1955.3	1680.3	1570.2	855.4	114.5
97		Virgin Binder, grams				324.3		
98								

Figure A.11 – Final Batch Plan

APPENDIX G:
RECOMMENDED MODIFICATIONS TO ODOT TM 323

ODOT TM 323
DETERMINATION OF CALIBRATION FACTORS
For
DETERMINING THE ASPHALT BINDER CONTENT OF HOT MIX ASPHALT
BY THE
IGNITION METHOD

1. SCOPE

1.1 This test method covers the determination of a Calibration Factor (CF) used in determining asphalt binder content of HMAC paving mixtures with or without reclaimed materials (RAP or RAS) by the ignition method according to AASHTO T308. This test method also includes determination of gradation correction factors.

1.2 The values stated in metric units are to be regarded as the standard.

1.3 This method may involve hazardous materials, operations, and equipment. This method does not purport to address all of the safety problems associated with its use. It is the responsibility of whoever uses this method to consult and establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.

2. REFERENCED DOCUMENTS

AASHTO T308 Determining the Asphalt Binder Content of Hot Mix Asphalt (HMA) by the Ignition Method. If using the Infra-Red oven see T 308 for details on temperature.

AASHTO T30 Mechanical Analysis of Extracted Aggregate

ODOT Contractor Mix Design Guidelines for Asphalt Concrete

3. SUMMARY OF TEST METHOD

Four samples of HMAC with a known asphalt content and gradation are batched. The asphalt binder in two, possibly four of the samples is incinerated according to AASHTO T308 and the asphalt binder content is calculated. The difference between the known (batched) asphalt binder content and calculated asphalt binder content (from incineration results) is determined for each sample. The average of the difference is the Calibration Factor (CF) applied to production tests according to AASHTO T308. The gradations of the incinerated samples are determined and compared with a "blank" sample that has not been incinerated.

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Establish a Calibration Factor (C_F) for each JMF. This procedure must be performed for every ignition furnace on a project for each JMF before any acceptance or verification testing is completed.

The CMDT, who develops the JMF for a project will provide properly batched samples to each of the field QC and QA laboratories and to the ODOT Central Laboratory for the CAT1 to use in calculating a Calibration Factor (C_F) and gradation correction factors. An alternate CMDT may provide the required calibration samples if approved by the Engineer.

A new calibration factor is required if the source or grade of the asphalt cement changes, if the source of RAP changes, if a different ignition furnace is used, or for a new JMF. A new calibration factor shall be determined for each JMF prior to its first use every calendar year. Calibration factors for a JMF shall be "transferred" from project to project during a calendar year, unless one of the above conditions applies.

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4. APPARATUS

Supply apparatus as required by AASHTO T308. Use the same ignition furnace for the calibration that will be used for production testing.

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5. CALIBRATION SAMPLE PREPARATION – MIXTURES WITHOUT RECLAIMED MATERIALS

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5.1 Sample the aggregate, mineral filler, lime, fibers, and other appropriate additives to be used for the calibration specimens from material designated for use on the project. Use the brand and grade of asphalt cement designated for the JMF.

5.2 Prepare six calibration mixture samples at the JMF asphalt binder content and gradation and with the appropriate proportions of mineral filler, lime, fibers or any other additive.

Batch the specimens according to standard industry procedures, modified as follows:

- Batch each sample separately and according to the tolerances in Section 5.4.
- Before adding asphalt randomly select one sample and set it aside as the "blank" sample. See Section 5.3.
- Provide sample sizes meeting the requirements of AASHTO T308
- Mix and discard one of the remaining five samples. The purpose of this sample is to "butter" the mixing bowl.
- For the remaining four (or more) samples, tare the mixing bowl and weigh the mixing bowl again after the mixture is removed from the bowl. The empty bowl must be within ±1 gram of the previous tare weight.
- Individually identify each calibration sample and supply documentation showing the actual weights of aggregate, asphalt cement, mineral filler, lime, fibers or any other additive for each sample and resultant actual calculated asphalt

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binder content for each sample. Also provide documentation for each sample verifying that the empty bowl weight after mixing is within ±1 gram of the empty bowl weight prior to mixing. An example batch form (2327CB) is available under Section 3 of the MFTP.

NOTE: Errors in batching or failure to take great care in ensuring that all sample material is removed from the mixing bowl can result in significant errors in the Calibration Factor.

These errors can affect the statistical pay factor for the Contractor and the quantity of asphalt binder the Agency pays for. Every effort should be taken to ensure that batching and mixing errors are minimized. The amount of lime in a calibration sample can substantially affect the calibration factor, so extra care shall be taken to ensure the proper amount is batched.

5.3 The "blank" sample as selected in 5.2 shall have the same gradation, but no asphalt shall be added. This "blank" sample will be used to establish correction factors for the aggregate gradations. The "blank" sample is not burned.

5.4 Batch each sample according to the JMF target values or the virgin aggregate portion of a RAP JMF and within the following tolerances:

Batching Tolerances "Virgin Aggregate and Add Oil"

Sieve Size	Allowable Difference
Larger than 2.36 mm (No. 8)	±3.0%
Size 2.36 mm (No. 8)	±2.0%
Larger than 75 µm (No. 200) and smaller than 2.36 mm (No. 8)	±1.0%
Size 75 µm (No. 200) and smaller	±0.5%
Asphalt	±0.10%

6. CALIBRATION SAMPLE PREPARATION - MIXTURES WITH RECLAIMED MATERIALS

If allowed by the Engineer, the percentage of asphalt binder in reclaimed materials **(Pbr)** and the gradation of the residual aggregate from the reclaimed materials may be determined by an alternative method. If an alternative method is allowed, skip to Section 6.7.

6.1 Sample the aggregate, reclaimed material (RAP and/or RAS), mineral filler, lime, fibers, and other appropriate additives to be used for the calibration specimens from material designated for use on the project. Use the brand and grade of virgin asphalt cement designated for the JMF.

6.2 Batch a minimum of five samples of each reclaimed material, as appropriate, according to the gradation of the reclaimed material in the JMF. Batch each sample so that it consists of 100% reclaimed material. If the mixture contains only RAP, batch five 100% RAP samples. If the mixture contains a RAP/RAS blend from a combined stockpile (bin), batch five 100% RAP/RAS samples. If the mixture contains a RAP/RAS blend from separate stockpiles (bins), batch five

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100% RAP samples and five 100% RAS samples. If the mixture contains only RAS, batch 100% RAS samples. Batch the samples according to standard industry practices with a sample size appropriate for AASHTO T308. Note that for infrared furnaces, the higher set temperature "burn profile" may be necessary to provide complete combustion of the sample.

6.3 Test each sample of 100% reclaimed material according to AASHTO T308 Method A or Method B (with a 60 minute burn time) to determine the binder content of each.

6.4 Determine the average total percent loss of the five samples. Subtract 0.5% from the average total percent loss. By definition, a Calibration Factor of 0.5% shall be the standard for 100% reclaimed materials, since it is difficult and time consuming to determine the Calibration Factor for mixtures comprised of 100% reclaimed materials. ***See Section 8 for example calculations.***

6.5 The value(s) determined in Section 6.4 will be considered the percentage of asphalt binder in the reclaimed material(s) **(Pbr)**.

6.6 Perform sieve analysis on the recovered (residual) aggregate from each incinerated sample of reclaimed material according to AASHTO T30. Average the five gradations for each material. The average gradation for each reclaimed material will be considered the stockpile (bin) gradation for the reclaimed material. The gradation for each reclaimed material shall be provided with the calibration samples.

6.7 Prepare six calibration mixture samples at the JMF asphalt binder content and gradation with the appropriate proportions of reclaimed material, mineral filler, lime, fibers or any other additive. Batch the specimens according to standard industry procedures, modified as given below. The actual asphalt binder content used to calculate the Calibration Factor will be a combination of **Pbr** for each reclaimed material and the virgin asphalt binder added.

- Batch each sample separately. The batching of the virgin aggregate shall meet the tolerances outlined in Section 5.4.
- Provide sample sizes meeting the requirements of AASHTO T308.
- Before adding reclaimed materials or asphalt binder randomly select one sample and set it aside as the "blank" sample. See Section 6.8.
- Mix and discard one of the remaining five samples. The purpose of this sample is to "butter" the mixing bowl.

  NOTE: For each sample, combine and thoroughly dry-mix the virgin aggregate and reclaimed material(s) before adding virgin asphalt cement.
- For the remaining four (or more) samples, tare the mixing bowl and weigh the mixing bowl again after the mixture is removed from the bowl. The empty bowl must be within ±1 gram of the previous tare weight.
- Individually identify each calibration sample and supply documentation showing the actual weights of aggregate, reclaimed material(s), virgin asphalt cement,

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mineral filler, lime, fibers or any other additive for each sample and resultant actual (calculated) asphalt binder content for each sample. Also provide documentation for each sample verifying that the empty bowl weight after mixing was within ±1 gram of the empty bowl weight prior to mixing. An example batch form (2327CB) is available under Section 3 of the MFTP.

NOTE: Errors in batching or failure to take great care in ensuring that all sample material is removed from the mixing bowl can result in significant errors in the Calibration Factor. These errors can affect the statistical pay factor for the Contractor and the quantity of asphalt binder the Agency pays for. Every effort should be taken to ensure that batching and mixing errors are minimized. The amount of lime in a calibration sample can substantially affect the calibration factor, so extra care shall be taken to ensure the proper amount is batched.

6.8 For the "blank" sample, virgin aggregate (including mineral filler, lime, fibers or any other additive) and reclaimed material(s) in the proper proportions will be provided separately. The virgin aggregate shall be batched within the tolerances of section 5.4. Incinerate the reclaimed material(s) provided for the "blank" sample according to AASHTO T308 Method A or Method B (with a 60-minute burn time). Gradations for the residual aggregate from the reclaimed material(s) and the virgin aggregate (including mineral filler, lime, fibers or any other additive) shall be determined separately according to AASHTO T 30 and AASHTO T27/11.

Mathematically combine the results of the residual aggregate from the reclaimed material(s) and the virgin aggregate (including mineral filler, lime, fibers or any other additive) to determine the overall gradation result. Provide separate sieve analysis results for the residual aggregate from the reclaimed material(s), the virgin aggregate component, and the overall computed gradation.

NOTE: Reporting of the separate gradations provides a check of the batching process and ensures the virgin aggregate component, in a JMF containing RAP, has been accurately accounted for according to the JMF percentages.

7. CALIBRATION PROCEDURE (MIXTURES WITH OR WITHOUT RECLAIMED MATERIALS)

7.1 Freshly mixed samples may be tested immediately. Cooled calibration samples must be preheated to 171±5°C (340±9°F) for 120±5 minutes to remove moisture.

7.2 Test two of the samples according to AASHTO T308 Method A or Method B (with a 60 minute burn time) to determine the binder content of each. **The method used for calibration must be used for production testing**. The incinerator shall be kept at 538°C even if the correction factor exceeds 0.5%.

7.3 If the difference between the binder contents of the two samples exceeds 0.15 percent, perform two additional tests and, from the four tests, discard the high and low result. Determine the Calibration Factor from the two original or remaining

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results, as appropriate. Calculate the difference between the actual and measured binder contents for each sample.

The Calibration Factor (C_F) is the average of the differences expressed in percent by mass of the HMAC mix. ***See Section 8 for example calculations***

7.4 Perform sieve analysis on the residual aggregates from the incinerated samples used to calculate the Calibration Factor according to AASHTO T30. Average the two results. Perform sieve analysis on the "blank" sample according to AASHTO T30.

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7.5 Determine the difference in gradation between the "blank" sample and the average of the two incinerated calibration samples. The gradation correction factor for each sieve size is the difference between the result from the "blank" sample and the average of the two incinerated calibration samples to the nearest 0.1%. ***See Section 8 for example calculations.***

If the correction factor for any single sieve size exceeds the allowable difference for that sieve established in the following table, contact the Engineer. The Engineer will determine whether or not to apply the gradation correction factors for all sieves.

Gradation Difference Tolerances

Sieve	Allowable Difference
Sizes larger than 2.36 mm (No. 8)	±5.0%
Size 2.36 mm (No. 8)	±4.0%
Sizes larger than 75 µm (No. 200) and smaller than 2.36 mm (No. 8)	±2.0%
Size 75 µm (No. 200) and smaller	±1.0%

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8. CALCULATIONS

CALIBRATION FACTOR *(Section 7.3)*

$$C_F = \frac{[\,(D1 - P1) + (D2 - P2)\,]}{2}$$

D1, D2 = Total sample loss in percent in calibration samples 1 and 2.
P1, P2 = Actual asphalt binder (%) added in calibration samples 1 and 2.
C_F = Calibration Factor

IF: D1 = 6.52 %
D2 = 6.62 %
P1 and P2 = 6.20 %

THEN: C_F = 0.37 %

GRADATION CORRECTION FACTORS *(Section 7.5)*

Sieve Size	Blank Gradation %	Average of two Incinerated samples %	Correction Factor %
19 mm (3/4")	97.0	94.0	+3.0
12.5mm (1/2")	86.3	85.9	+0.4
9.5mm (3/8")	77.3	75.8	+1.5
4.75mm (No. 4)	46.5	47.3	-0.8
2.36mm (No. 8)	31.2	32.0	-0.8
600µm (No. 30)	12.4	14.2	-1.8
75µm (No. 200)	6.0	7.2	-1.2

FINAL GRADATION CALCULATION *(Section 7.5)*

Sieve Size	Incinerated Washed Gradation %	Correction Factor %	Final Gradation
19mm (3/4")	94.6	+3.0	98
12.5mm (1/2")	86.9	+0.4	87
9.5mm (3/8")	54.3	+1.5	56
4.75mm (No. 4)	47.8	-0.8	47
2.36mm (No. 8)	32.5	-0.8	32
600µm (No. 30)	15.3	-1.8	14
75µm (No. 200)	8.6	-1.2	7.4

PERCENT ASPHALT BINDER IN 100% RECLAIMED MATERIAL *(Section 6.4)*

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Pbr = (D1 + D2 + D3 + D4) / 4 - 0.5%

D1, D2, D3, D4 = Total loss in the ignition furnace (from Section 6.3)

0.5% = standard mix calibration factor for all reclaimed materials

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Pbr = [(6.6 + 6.1 + 5.9 + 6.2) / 4] - 0.5%

Pbr = 5.7%