INVESTIGATION OF THE BAILEY METHOD FOR THE DESIGN AND ANALYSIS OF DENSE-GRADED HMAC USING OREGON AGGREGATES

Final Report

SPR 304-311

by

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16. Abstract

Historically Oregon has specified gradations for dense-graded hot mix asphalt concrete (HMAC) using a combination of broadband limits and recommended "ideal" gradations. The recent adoption of SuperPave^{TM} and Stone Matrix Asphalt (SMA) technology has created new criteria for selecting gradations. This study evaluated a method of gradation design and analysis called the Bailey Method. The method uses specific ratios developed for aggregates in Illinois. The research involved using the Bailey Method to design and evaluate Oregon specific aggregate blends. Specimens were compacted and tested using the gradations developed under the Bailey Method. Finally, rut testing was performed on those mixture specimens.

The study recommended that a modified Bailey Method analysis should be used as an additional tool to develop and select trial blends for the design of dense-graded mixes. The study noted that the Bailey Method design process led to extremely fine mixes not common in Oregon. Additional sieves were recommended to be included to allow for the development of additional ratios.

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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
		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

NOTE: Volumes greater than 1000 L shall be shown in m^3.

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 PROBLEM STATEMENT

Historically Oregon has specified gradations for dense-graded Hot Mix Asphalt Concrete (HMAC) using a combination of broadband limits and recommended "ideal" or "golden" gradations. The recent adoption of SuperPave™ and Stone Matrix Asphalt (SMA) technology has created new criteria for selecting gradations.

In the case of SuperPave™ the new control points allow a wider range of gradations from which designers may choose. In some instances this has allowed designers to generate much finer mixes than historically used, and problems have occurred during construction of these dense-graded mixes.

In the case of SMA's the ability to achieve the recommended voids in coarse aggregate (VCA) has been a struggle.

Analysis of gradation in Oregon is generally limited to plotting the percent passing the sieves on a 0.45 power curve. Subsequent adjustments are based on moving this curve relative to the theoretical "maximum density" line. The desired end effect is to increase or decrease Voids in Mineral Aggregate (VMA). While this end is generally achieved, it does not address the quality of the mix created.

During the 2003 construction season the Oregon Department of Transportation (ODOT) Pavement Quality Engineer identified a number of problem mixes that were finer than those historically used by ODOT. With finer mixes it appeared that VMA was being created at the expense of the desirable "rock on rock" contact amongst the larger stone. Thus a more robust method of analyzing and designing asphalt concrete aggregate gradations for dense-grade mixtures was needed. Such a method would allow designers to accomplish the following:

1. Select design aggregate blends that provide the desired volumetric properties for long-lasting pavements;

2. Select design aggregate blends that provide the desired internal structure to resist permanent deformation during the design service life; and

3. Select field adjustments to aggregate blends that provide the desired design volumetric and performance characteristics for long-lasting pavements.

1.2 BACKGROUND

A Transportation Research Board publication recently reported on a method of gradation design and analysis called the Bailey Method (*Vavrik, et al. 2002*). The Bailey Method was originally developed by Mr. Robert Bailey (retired) of the Illinois Department of Transportation. It is a systematic approach to blending aggregates that provides aggregate interlock as the backbone of the structure and a balanced continuous gradation of particles to complete the blend.

The method uses dry rodded unit weights of the various materials to estimate the void space between the particles. This available space is then filled with the appropriate size and amount of material without disrupting the "rock on rock" contact of the larger stone.

The process is relatively simple and requires little additional analysis by the designer. The method uses specific ratios developed for aggregates in Illinois. While these ratios may apply in Oregon, it is probable that adjustments will be necessary if the process is to be used successfully with local aggregates.

This research involved designing and evaluating aggregate blends in Oregon using the Bailey Method. It also included compacting and testing mixture specimens using the gradations developed under the Bailey Method. The study also rut tested those mixture specimens.

1.3 OBJECTIVES AND METHODOLOGY

The objectives of this study were to sample, test, and analyze two aggregate sources (1 quarry and 1 gravel source) using the Bailey Method. The methodology used to accomplish these objectives consisted of the following tasks:

1. Determine the dry rodded unit weight and specific gravity properties of the individual fractionations per AASHTO T 19, T 84 and T 85 (*AASHTO 2004*).

2. Design a series of coarse aggregate ½ inch blends at the limits of the Bailey Criteria. Gradations were established by using the limits set by the SuperPave™ gradation control points on the No. 8 sieve. (10 blends per aggregate source)

3. Determine the dry rodded unit weight and specific gravity properties of the above blends.

4. Assess the Bailey Method design blend process using the above data.

5. Determine the asphalt cement content to attain 4.0% air voids for each blend.

6. Mix gyratory and rice samples with PG 70-22 asphalt using the above ½ inch blends. (Duplicate specimens per blend)

7. Compact the gyratory samples with 100 gyrations per ODOT TM 326 (*ODOT 2006b*).

8. Determine the volumetric properties of the mixes using the various blends per AASHTO T 166 and T 209 (*AASHTO 2004*).

9. Assess the relationship between the Bailey Criteria and the resultant volumetric properties of mixtures.

10. Fabricate specimens and test 10 blends (combination of sources) in the Asphalt Pavement Analyzer to determine their rut characteristics.

11. Assess the relationship between the Bailey Criteria and the rut characteristics of mixtures.

12. Make recommendations for implementation of the Bailey design blend process and Bailey Criteria.

2.0 SELECTION OF MATERIALS

Aggregates from two Oregon sources were used to evaluate a series of blends developed using the Bailey Method criteria. A design asphalt content was determined per the ODOT Contractor Mix Design Guidelines to provide mixtures with 4.0% air voids, Va (*ODOT 2006a*). The volumetric properties of these mixtures were determined and are reported below.

2.1 AGGREGATE BLENDS

The aggregate blends developed from the two aggregate sources in Oregon were from one gravel source and one quarry source:

- The LTM gravel source near White City.[1] This source is referred to as "Kirtland" and is ODOT Source No. 15-215-3.
- The Road and Driveway (R&D) quarry source near Lincoln City.[2] This source is referred to as "Fischer Quarry" and is ODOT Source No. 21-002-2.

The aggregate blends initially selected for this research were based on the upper and lower limits of the three Bailey Method criteria (*Vavrik, et al. 2002*). Four sieves are evaluated under the Bailey Method: the half sieve (Half S), the primary control sieve (PCS), the secondary control sieve (SCS), and the tertiary control sieve (TCS). This study was based on a ½ inch nominal maximum particle size (NMPS). Therefore, the half sieve was the ¼ inch sieve, the PCS was the No. 8 sieve, the SCS was the No. 30 sieve, and the TCS was the No. 100 sieve.

The Bailey Method uses three ratios of the various sieves above to control the final gradation. The ratios are as follows:

$$CA\ Ratio = \frac{(\%Pass\ Half\ Sieve - \%Pass\ PCS)}{(100\% - \%Pass\ Half\ Sieve)} \tag{2-1}$$

$$FA_c\ Ratio = \frac{\%Pass\ SCS}{\%Pass\ PCS} \tag{2-2}$$

$$FA_f\ Ratio = \frac{\%Pass\ TCS}{\%Pass\ SCS} \tag{2-3}$$

where

CA Ratio is the coarse aggregate ratio;

[1] LTM Incorporated, Medford, OR
[2] Road & Driveway Company, Newport, OR

FA_c Ratio is the fine aggregate coarse ratio; and
FA_f Ratio is the fine aggregate fine ratio.

The Bailey Method criteria for ½ inch mixes for each of the above ratios are shown in Table 2.1.

Table 2.1: Bailey Method criteria for NMPS ½ inch

Ratio	Lower Limit	Upper Limit
CA Ratio	0.50	0.65
FA_c Ratio	0.35	0.50
FA_f Ratio	0.35	0.50

By selecting values for the percent passing on the PCS (No. 8), and selecting the desired Bailey Method criteria values, the percent passing on the other three sieves are controlled by these equations. The key to using this strategy is to select appropriate values for the PCS.

One element of this research was to interface with the SuperPave™ mix design process that dictates limits on the No. 8 sieve of 28% - 58%. Two other points of interest are the ODOT ideal gradation of 34% and the intersection of the maximum density line of the 0.45 power curve that is 39.0%. (ODOT mixes typically do not go above the maximum density line.)

With upper and lower limits on the three Bailey Method criteria and four possible targets on the No. 8 sieve, there are 2 x 2 x 2 x 4 = 32 possible blend combinations to consider. The complete list of blends is listed in the Appendix. For practical reasons this list was reduced to 10 blends for each material source. The methodology for selecting the blends was as follows:

1. Eliminate blends with high percentages passing No. 200
2. Eliminate blends with low percentages passing No. 200
3. Eliminate blends with percentages passing No. 8 above the maximum density line
4. Eliminate blends with unusual shaped 0.45 power curves

For the gravel pit material (LTM Kirtland) the ten blends that were selected are shown in Table 2.2.

Table 2.2: LTM Kirtland trial blends

Blend	CA Ratio	FA_c Ratio	FA_f Ratio	Half S ¼ in	PCS No. 8	SCS No. 30	TCS No. 100
1	0.65	0.50	0.50	56.4	28.0	14.0	7.0
2	0.65	0.50	0.35	56.4	28.0	14.0	4.9
3	0.65	0.35	0.50	63.0	39.0	13.6	6.8
4	0.65	0.35	0.50	56.4	28.0	9.8	4.9
5	0.65	0.35	0.35	63.0	39.0	13.6	4.8
6	0.50	0.50	0.50	52.0	28.0	14.0	7.0
7	0.50	0.50	0.35	52.0	28.0	14.0	4.9
8	0.50	0.35	0.50	59.3	39.0	13.7	6.9
9	0.50	0.35	0.50	52.0	28.0	9.8	4.9
10	0.50	0.35	0.35	59.3	39.0	13.7	4.8

After reviewing the volumetric data from the LTM Kirkland material, it was noted that significant increases in VMA could be achieved by manipulating the No. 30 sieve. The magnitude of the VMA change suggested that Oregon type ½ inch mixtures had the greatest sensitivity to particles in the vicinity of the No. 30 sieve in size. To better understand the impact of particles in the vicinity of the No. 30 sieve, it was decided to include the No. 16 and No. 50 sieves in analyzing the R&D Fischer Quarry material.

The Bailey Method ratios do not target the percent passing No. 200 (P200). The example given by Vavrik, et al. relies on mineral filler to independently control the P200 (*Vavrik, et al. 2002*). Oregon producers do not typically use mineral filler and rely on No. 8 – 0 or similar stockpiles to provide most of the P200 material. To model this concept the percent passing No. 200 for each LTM Kirtland blend was set at 80% of the percent passing No. 100 value. Having different P200 targets clouded the LTM Kirtland data, however; so a fixed P200 amount of 4.1% was used on the R&D Fischer Quarry material.

In addition, the Bailey Method does not specify the coarse sieves and leaves that to the discretion of the designer. Once they are selected, however, their loose bulk densities are the basis for the volume of fine aggregates.

The bulk densities of the coarse materials showed approximately 49% air voids in the coarse aggregate (+No. 8). This also roughly equates to 49% passing the No. 8 to fill the void space available.

For typical Oregon stockpiles, most of the No. 8 comes from the No. 8 – 0 pile. This is also where most of the percent passing No. 200 material resides. To increase the percent passing No. 8 sieve from the historical ODOT gradation of 34% to the 49% mark would also significantly increase the percent passing No. 200. Blends meeting a 49% passing the No. 8 target using typical Oregon stockpiles would be above the maximum density line and would have uncharacteristically high P200 values. For this reason it was decided to forgo the Bailey design process and use blends that were more representative of Oregon crushing and to focus on the Bailey analysis process.

SuperPave™ establishes maximum values of 100% passing on the ½ inch sieve and 90% passing on the ⅜ inch sieve for a ½ inch nominal maximum particle size (NMPS) mixture. These values were selected to go as "fine" as possible with the blend but still meet the SuperPave™ requirements. For this research, a value of 100% passing the ½ inch sieve and 90% passing the ⅜ inch sieve were chosen for all ten blends.

The LTM Kirtland material demonstrated an insensitivity of the volumetrics to the coarse sieves. Therefore it was decided to use a fixed coarse gradation for the R&D Fischer Quarry material.

Using a fixed coarse gradation, a fixed P200, and including the additional No. 16 and No. 50 sieves resulted in a set of Bailey ratios that in some instances either did not reach the limits or exceeded the limits of the criteria set in Table 2.1.

For the quarry material (R&D Fischer Quarry) the ten blends selected are shown in Table 2.3.

Table 2.3: R&D Fischer Quarry trial blends

Blend	CA Ratio	FA_c Ratio	FA_f Ratio	Half S ¼ inch	PCS No. 8	SCS No. 30	TCS No. 100
1	0.65	0.50	0.50	59.6	28.8	14.4	7.2
2	0.65	0.50	0.50	59.6	28.8	14.4	7.2
3	0.65	0.47	0.54	59.6	28.8	13.4	7.2
4	0.65	0.50	0.50	59.6	28.8	14.4	7.2
5	0.65	0.50	0.35	59.6	28.8	14.4	5.0
6	0.65	0.43	0.58	59.6	28.8	12.4	7.2
7	0.65	0.43	0.58	59.6	28.8	12.4	7.2
8	0.65	0.40	0.62	59.6	28.8	11.6	7.2
9	0.65	0.43	0.58	59.6	28.8	12.4	7.2
10	0.65	0.43	0.40	59.6	28.8	12.4	5.0

2.2 BULK DENSITY OF BLENDS

The bulk densities were measured in both the loose and rodded conditions per AASHTO T 19 (*AASHTO 2004*). The blends were batched and then screened on the No. 8 sieve (PCS). The bulk densities of the LTM Kirtland material blends are shown in Table 2.4.

Table 2.4: LTM Kirtland bulk densities (lbs/cu ft)

Blend	CA Ratio	FA_c Ratio	FA_f Ratio	+No. 8 DLC[a] Bulk Density	-No. 8 DLC[a] Bulk Density	+No. 8 DRC[b] Bulk Density	-No. 8 DRC[b] Bulk Density
1	0.65	0.50	0.50	86.81	102.06	96.86	115.27
2	0.65	0.50	0.35	86.08	97.82	96.50	109.46
3	0.65	0.35	0.50	87.27	96.51	96.65	107.98
4	0.65	0.35	0.50	86.08	95.56	96.50	107.32
5	0.65	0.35	0.35	87.27	94.79	96.65	104.90
6	0.50	0.50	0.50	86.33	98.84	97.18	111.08
7	0.50	0.50	0.35	86.33	96.17	97.18	106.92
8	0.50	0.35	0.50	87.08	95.52	97.05	107.28
9	0.50	0.35	0.50	86.33	95.56	97.18	106.76
10	0.50	0.35	0.35	87.08	93.23	97.05	103.62

[a] DLC = Dry Loose Condition
[b] DRC = Dry Rodded Condition

The bulk densities of the R&D Fischer Quarry material blends are shown in Table 2.5.

Table 2.5: R&D Fischer Quarry bulk densities (lbs/cu ft)

Blend	CA Ratio	FA_c Ratio	FA_f Ratio	+No. 8 DLC[a] Bulk Density	-No. 8 DLC[a] Bulk Density	+No. 8 DRC[b] Bulk Density	-No. 8 DRC[b] Bulk Density
1	0.65	0.50	0.50	93.25	101.21	105.21	116.09
2	0.65	0.50	0.50	93.25	105.52	105.21	119.88
3	0.65	0.47	0.54	93.25	102.66	105.21	117.22
4	0.65	0.50	0.50	93.25	100.33	105.21	115.52
5	0.65	0.50	0.35	93.25	98.56	105.21	114.47
6	0.65	0.43	0.58	93.25	99.39	105.21	116.05
7	0.65	0.43	0.58	93.25	100.75	105.21	117.32
8	0.65	0.40	0.62	93.25	98.98	105.21	116.31
9	0.65	0.43	0.58	93.25	98.87	105.21	115.74
10	0.65	0.43	0.40	93.25	97.99	105.21	114.67

[a] DLC = Dry Loose Condition
[b] DRC = Dry Rodded Condition

To interpret the results in Tables 2.4 & 2.5, it is a useful reminder to understand the relationship between changing the various Bailey Method ratios and the effect on Voids in Mineral Aggregate (VMA). Table 2.6 shows this relationship.

Table 2.6: Effect of Bailey Method ratios on VMA

Bailey Method Ratio	Increase VMA	Decrease VMA
CA	⇧	⇩
FA_c	⇩	⇧
FA_f	⇩	⇧

⇧ = Increase in the Bailey Method Ratio
⇩ = Decrease in the Bailey Method Ratio

The relationship between the Bailey Method ratios and the dry bulk densities generally supports the contentions given in the Bailey Method regarding changes in VMA and the Bailey Method ratios. In general, reducing the CA Ratio should reduce VMA (increase bulk density). As shown in Table 2.4, the CA Ratio was adjusted in the LTM Kirtland blends. An increase in bulk density was not apparent in the + No. 8 DLC; however, the + No. 8 DRC did suggest a higher density for those blends at the minimum CA Ratio of 0.50, compared to the CA Ratio of 0.65. The change was not large, but it is generally accepted in Oregon that manipulating the coarse aggregate has a minimal effect on VMA.

The relationship between bulk density (VMA) and the – No 8 material was much more pronounced in the LTM Kirtland material (Table 2.4). Both the DLC and DRC results followed the same pattern.

The FA ratios are counter to the CA Ratio in that to increase VMA one must reduce the FA ratios. This should be seen as a reduction in bulk density with a reduction in the FA ratios. The LTM Kirtland data clearly supported this expectation. Moving either the FA_c or FA_f Ratios down did reduce bulk density. Moving them both down together gave the greatest reduction in bulk density.

In contrast, the R&D Fischer Quarry data (Table 2.5) seemed to defy the Bailey predictions. Blends 1, 2 and 4 had identical Bailey ratios, yet the DRC bulk densities varied from 115.52 to 119.88 lbs/cu ft. Blends 6, 7 and 9 also had identical Bailey ratios and showed a variation in DRC bulk densities from 115.74 to 117.32 lbs/cu ft. What was occurring here were changes in the No. 16 and No. 50 sieves, which are not reflected in the Bailey ratios. Recall that these sieves were added to the blend process for the R&D Fischer Quarry material to better define the large volumetric changes seen around the No. 30 sieve.

One anomaly was noted in the data when measuring the bulk densities on individual size materials (Table 2.7). The otherwise descending pattern of unit weights increased at the No. 100 sieve. The likely reason for this is that the sieves followed the pattern of decreasing in opening size by ½ except between the No. 30 and the No. 100. This result suggests that adding the No. 50 sieve would be appropriate to better model the descending pattern.

Table 2.7: Dry rodded bulk densities of separated size fine aggregates

	Dry Rodded Bulk Densities (lbs/cu ft)	
Sieve	**LTM Kirtland**	**R&D Fischer Quarry**
No. 4	89.54	95.12
No. 8	88.83	95.39
No. 16	88.11	93.68
No. 30	87.32	91.79
No. 100	90.61	93.86
No. 200	78.14	86.27

3.0 EVALUATION OF VOLUMETRIC PROPERTIES OF SELECTED BLENDS

To determine actual VMA's it was necessary to mix and compact specimens. To normalize the various blends, design asphalt contents were determined for each blend to produce 4.0% air voids.

3.1 LTM KIRTLAND MATERIAL

Table 3.1 provides a summary of the measured gravities and VMA for the ten asphalt blends developed using the LTM Kirtland materials:

Table 3.1: LTM Kirtland design volumetrics

Blend	CA Ratio	FA_c Ratio	FA_f Ratio	Design P_b[a]	Design G_{mm}[b]	Design G_{mb}[c]	Design VMA
1	0.65	0.50	0.50	6.9	2.417	2.320	16.93
2	0.65	0.50	0.35	6.7	2.425	2.328	16.47
3	0.65	0.35	0.50	6.5	2.435	2.334	15.99
4	0.65	0.35	0.50	8.0	2.378	2.283	19.22
5	0.65	0.35	0.35	7.0	2.419	2.321	16.91
6	0.50	0.50	0.50	6.4	2.435	2.338	15.87
7	0.50	0.50	0.35	6.7	2.420	2.323	16.68
8	0.50	0.35	0.50	6.3	2.440	2.342	15.56
9	0.50	0.35	0.50	7.6	2.380	2.285	18.84
10	0.50	0.35	0.35	6.6	2.426	2.329	16.29

[a] P_b = Asphalt Content, % by mass
[b] G_{mm} = Maximum Theoretical Specific Gravity of the Mixture
[c] G_{mb} = Bulk Specific Gravity of the Compacted Mixture

The design oil contents (P_b) and VMA's for several of the LTM Kirtland blends exceed typical Oregon dense-graded mixes. This suggests that the Bailey Method Criteria need to be shifted to better match Oregon's mixes.

3.1.1 Effect of CA Ratio on VMA (LTM Kirtland material)

Blends 1 through 5 were designed at the upper limit of 0.65. Blends 6 through 10 were designed at the lower limit of 0.50. In terms of - No. 8 (PCS) material, Blend 1 corresponds with Blend 6, Blend 2 with Blend 7, etc. Recall that VMA should decrease as the CA Ratio decreases. Table 3.2 shows the effect of changes in the CA Ratio on the LTM Kirtland material.

Table 3.2: Effect of CA Ratio on VMA (LTM Kirtland material)

Blend	**1**	**2**	**3**	**4**	**5**
CA Ratio	0.65	0.65	0.65	0.65	0.65
VMA	16.93	16.47	15.99	19.22	16.91
Corresponding Blend	**6**	**7**	**8**	**9**	**10**
CA Ratio	0.50	0.50	0.50	0.50	0.50
VMA	15.87	16.68	15.56	18.84	16.29
VMA Change with CA Ratio Decrease	⇩ - 1.06	⇧ + 0.21	⇩ - 0.43	⇩ - 0.38	⇩ - 0.62

Four out of the five blend combinations showed a measurable change in VMA in the predicted direction. The change in VMA between blends 2 and 7 was counter to what the Bailey Method predicted; however, the magnitude of the increase (0.21) could easily be attributed to the precision of the tests used to determine VMA.

In all cases, the magnitude of the change achieved by spanning the full range of the Bailey Method criteria (0.50 to 0.65) supported what is already known in Oregon – that manipulating the coarse size materials is generally not a productive way to fix VMA problems.

3.1.2 Effect of FA_c Ratio on VMA (LTM Kirtland material)

To offset the effects of the CA Ratio, the FA_c Ratio was evaluated in two groups: the first five blends as one group (with a CA Ratio of 0.65) and the second five blends as a second group (with a CA Ratio of 0.50). Because a full factor matrix of blends was not tested, only two combinations of blends within these groups isolated the effects of the FA_c Ratio.

Recall that the FA_c Ratio is manipulated by changing the No. 8 (PCS) and the No. 30 (SCS) sieves. The Bailey Method predicts that the VMA should increase with a decrease in FA_c Ratio.

3.1.2.1 Group 1 (CA Ratio = 0.65)

Table 3.3 shows the effect of a change in the FA_c Ratio on VMA with two LTM Kirtland blends having a CA Ratio of 0.65.

Table 3.3: Effect of FA_c Ratio on VMA, CA Ratio of 0.65 (LTM Kirtland material)

Blend	**2**
FA_c Ratio	0.50
VMA	16.47
Corresponding Blend	**4**
FA_c Ratio	0.35
VMA	19.22
VMA Change with FA_c Ratio Decrease	⇧ + 2.75

Clearly the VMA behaved as predicted with the change in the FA_c Ratio. The only difference in these two blends was that Blend 2 had 14.0% passing on the No. 30 sieve, while Blend 4 had 9.8% passing No. 30. The percent passing on all other sieves remained the same.

Shifting the percent passing on the No. 30 sieve had the effect of increasing the Retained No. 30 size material and reducing the Retained No. 100 material (actually the Retained No. 50 and Retained No.100 material because a No. 50 sieve is not used in the Bailey Method).

As mentioned in Section 2.2, one of the anomalies in the data for the bulk density of for both the LTM Kirtland material and the R&D Fischer Quarry material was an increase in both the loose and rodded unit weights on the Retained No. 100 material in an otherwise descending pattern of lower bulk densities with decreasing sieve size (Table 2.7). This can be attributed to the sieve openings decreasing by approximately ½ except for the jump from the No. 30 to the No. 100 sieve. Adding a No. 50 sieve would be appropriate to better demonstrate the descending pattern in unit weights.

The increase in unit weight on the No. 100 sieve over the No. 30 sieve shows the ability of the combined No. 50 and No. 100 material to blend to a higher density than each individually. Removing this higher density material from a Blend 4 would give a very high return in terms of creating VMA.

3.1.2.2 Group 2 (CA Ratio = 0.50)

Table 3.4 shows the effect of a change in the FA_c Ratio on VMA with two LTM Kirtland blends having a CA Ratio of 0.50.

Table 3.4: Effect of FA_c Ratio on VMA, CA Ratio of 0.50 (LTM Kirtland material)

Blend	**7**
FA_c Ratio	0.50
VMA	16.68
Corresponding Blend	**9**
FA_c Ratio	0.35
VMA	18.84
VMA Change with FA_c Ratio Decrease	⇧ + 2.16

Again the VMA behaved as predicted with the change in the FA_c Ratio. As before, the only difference in these two blends was that Blend 7 had 14.0% passing on the No. 30 sieve, while Blend 9 had 9.8% passing No. 30. The percent passing on all other sieves remained the same.

3.1.3 Effect of FA_f Ratio on VMA (LTM Kirtland material)

As above, to offset the effects of the CA Ratio, the FA_f Ratio was evaluated in two groups: the first five blends as one group with a CA Ratio of 0.65 and the second five blends as a second group with a CA Ratio of 0.50. As before, because a full factor matrix of blends was not tested, only three combinations of blends within these two subsets isolated the effects of the FA_f Ratio.

Recall that the FA_f Ratio is manipulated by changing the No. 30 (SCS) and the No. 100 (TCS) sieves. The Bailey Method predicts that the VMA should increase with a decrease in FA_f Ratio.

3.1.3.1 Group 1 (CA Ratio = 0.65)

Table 3.5 shows the effect of a change the FA_f Ratio on VMA with two LTM Kirtland material blends having a CA Ratio of 0.65.

Table 3.5: Effect of FA_f Ratio on VMA, CA Ratio of 0.65 (LTM Kirtland material)

Blend	**3**
FA_f Ratio	0.50
VMA	15.99
Corresponding Blend	**5**
FA_f Ratio	0.35
VMA	16.91
VMA Change with FA_f Ratio Decrease	⇧ + 0.92

Clearly the VMA behaved as predicted with the change in the FA_f Ratio. There were, however, two differences in these two blends. Blend 3 had 2.0% more passing the No. 100 sieve and 1.6% more passing the No. 200 sieve than Blend 5. The change in VMA could be accounted for in the passing No. 200 alone.

3.1.3.2 Group 2 (CA Ratio = 0.50)

Table 3.6 shows the effect of a change in the FA_f Ratio on VMA with four LTM Kirtland material blends having a CA Ratio of 0.50.

Table 3.6: Effect of FA_f Ratio on VMA, CA Ratio of 0.50 (LTM Kirtland material)

Blend	**6**	**8**
FA_f Ratio	0.50	0.50
VMA	15.87	15.56
Corresponding Blend	**7**	**10**
FA_f Ratio	0.35	0.35
VMA	16.68	16.29
VMA Change with FA_f Ratio Decrease	⇧ + 0.81	⇧ + 0.73

Again the VMA behaved as predicted for the FA_f Ratio. As with Group 1, the only difference in the first two blends was that Blend 6 had 2.1% more passing the No. 100 sieve and 1.7% more passing the No. 200 sieve, compared to Blend 7. For the second set of blends, Blend 8 had 2.1% more passing the No. 100 sieve and 1.7% more passing the No. 200 sieve, compared to Blend 10. The change in VMA for both combinations of blends could be accounted for in the passing No. 200 alone.

3.2 R&D FISCHER QUARRY MATERIALS

Table 3.7 provides a summary of the measured gravities and VMA for the ten asphalt blends developed using the R&D Fischer Quarry materials:

Table 3.7: R&D Fischer Quarry design volumetrics

Blend	CA Ratio	FA_c Ratio	FA_f Ratio	Design P_b[a]	Design G_{mm}[b]	Design G_{mb}[c]	Design VMA
1	0.65	0.50	0.50	6.2	2.593	2.489	18.7
2	0.65	0.50	0.50	6.8	2.564	2.461	20.1
3	0.65	0.47	0.54	5.9	2.601	2.499	18.1
4	0.65	0.50	0.50	5.9	2.597	2.493	18.3
5	0.65	0.50	0.35	5.7	2.608	2.504	17.8
6	0.65	0.43	0.58	6.0	2.600	2.499	18.2
7	0.65	0.43	0.58	6.8	2.571	2.472	19.8
8	0.65	0.40	0.62	5.9	2.600	2.496	18.2
9	0.65	0.43	0.58	6.2	2.594	2.487	18.7
10	0.65	0.43	0.40	5.9	2.595	2.489	18.4

[a] P_b = Asphalt Content, % by mass
[b] G_{mm} = Maximum Theoretical Specific Gravity of the Mixture
[c] G_{mb} = Bulk Specific Gravity of the Compacted Mixture

3.2.1 Effect of CA Ratio on VMA (R&D Fischer Quarry material)

Based on the results with the LTM Kirtland material, it was decided to use a fixed CA blend for all ten blends and vary only the – No. 8 material to better understand the effects on VMA of the FA ratios. Therefore, the effect of changing the CA Ratio was not measured on the R&D Fischer Quarry material.

3.2.2 Supplemental sieve data for the R&D Fischer Quarry material

The blends for the R&D Fischer Quarry material were chosen to look at the effects of manipulating the particle size distribution around the No. 30 sieve. Table 3.8 shows the findings. The first 5 blends used Blend 1 as a baseline, with the subsequent four blends individually modifying one of the sieves adjacent to the No. 30 sieve. The last five blends used Blend 6 as the baseline with the same sieve changes on the subsequent four blends. Blends 1-5 align with blends 1-6 with only the No. 30 sieve changing approximately 2.0%.

Table 3.8: R&D Fischer Quarry trial blends (% passing)

Blend	Half S ¼ in	PCS No. 8	No. 16	SCS No. 30	No. 50	TCS No. 100	No. 200
1	59.6	28.8	23.2	14.4	11.6	7.2	4.1
2	59.6	28.8	16.2	14.4	11.6	7.2	4.1
3	59.6	28.8	23.2	13.4	11.6	7.2	4.1
4	59.6	28.8	23.2	14.4	8.1	7.2	4.1
5	59.6	28.8	23.2	14.4	11.6	5.0	4.1
6	59.6	28.8	23.2	12.4	11.6	7.2	4.1
7	59.6	28.8	16.2	12.4	11.6	7.2	4.1
8	59.6	28.8	23.2	11.6	11.6	7.2	4.1
9	59.6	28.8	23.2	12.4	8.1	7.2	4.1
10	59.6	28.8	23.2	12.4	11.6	5.0	4.1

3.2.3 Supplemental ratios using the No. 16 and No. 50 sieves

The R&D Fischer Quarry volumetric data (Table 3.7) mirrors the bulk density data (Table 2.5) in defying the Bailey predictions. Blends 1, 2 and 4 have identical Bailey ratios, yet the VMA's vary from 18.3% to 20.1%. Blends 6, 7 and 9 also have identical Bailey ratios and show a variation in VMA from 18.2% to 19.8%.

As stated above, what is occurring are changes in the No. 16 and No. 50 sieves that are not reflected in the Bailey ratios. Recall these sieves were added to the blend process for the R&D Fischer Quarry material to better define the large volumetric changes seen around the No. 30 sieve.

To understand what is occurring it is useful to look at sieve sizes and the 0.22 factor used by Bailey in selecting "control sieves." Table 3.9 lists the complete set of sieves used and their sieve openings.

Table 3.9: R&D Fischer Quarry trial blend sieves

Sieve	Nominal Sieve Opening (inches)	Bailey Designation
¾ in	0.750	
½ in	0.500	NMPS
⅜ in	0.375	
¼ in	0.250	Half Sieve
No. 4	0.187	
No. 8	0.0937	Primary
No. 16	0.0469	
No. 30	0.0234	Secondary
No. 50	0.0117	
No. 100	0.0059	Tertiary
No. 200	0.0029	
Pan	n/a	

The characteristic to note in this sieve series is that for the sieves No. 4 and smaller, the sieve openings are approximately decreasing by a factor of one half as the sieve sizes get smaller. Recall that the Bailey Method uses a factor of 0.22 to define the Primary, Secondary, and Tertiary sieves. The Bailey Method then "balances" the fines by keeping the percent passing the next lower "defined sieve" (i.e., Primary, Secondary, …) between 0.35 and 0.50 of the percent passing the upper "defined sieve."

The R&D Fischer Quarry data suggests that additional ratios can be defined between the No. 4 and No. 16, the No. 16 and No. 50 and the No. 50 and No. 200 which approximate this 0.22 factor. Because the fine sieves follow the "halving pattern," skipping a sieve gives a "quartering pattern," which is a factor of 0.25 ($\cong$ 0.22).

Define the following ratios:

$$FA_{No.4}\ Ratio = \frac{\%Pass\ No.16}{\%Pass\ No.4} \quad \textbf{(3-1)}$$

$$FA_{No.16}\ Ratio = \frac{\%Pass\ No.50}{\%Pass\ No.16} \quad \textbf{(3-2)}$$

$$FA_{No.50}\ Ratio = \frac{\%Pass\ No.200}{\%Pass\ No.50} \quad \textbf{(3-3)}$$

The R&D Fischer Quarry material can now be quantified with these additional FA ratios as shown in Table 3.10.

Table 3.10: R&D Fischer Quarry design FA ratios

Blend	$FA_{No.4}$ Ratio	FA_c Ratio	$FA_{No.16}$ Ratio	FA_f Ratio	$FA_{No.50}$ Ratio	Design VMA
1	0.50	0.50	0.50	0.50	0.35	18.7
2	0.35	0.50	0.72	0.50	0.35	20.1
3	0.50	0.47	0.50	0.54	0.35	18.1
4	0.50	0.50	0.35	0.50	0.51	18.3
5	0.50	0.50	0.50	0.35	0.35	17.8
6	0.50	0.43	0.50	0.58	0.35	18.2
7	0.35	0.43	0.72	0.58	0.35	19.8
8	0.50	0.40	0.50	0.62	0.35	18.2
9	0.50	0.43	0.35	0.58	0.51	18.7
10	0.50	0.43	0.50	0.40	0.35	18.4

3.2.4 Effect of No. 16 Sieve on FA ratios and VMA (R&D Fischer Quarry)

Recall that Blends 1 and 6 were considered baseline blends and that blends 2 and 7 were varied from the baseline on the No. 16 sieve by 7.0%. Table 3.11 shows the effect of changes in the percent passing the No. 16 sieve on FA ratios and VMA with four R&D Fischer Quarry blends.

Table 3.11: Effect of No. 16 Sieve on FA ratios and VMA (R&D Fischer Quarry material)

Blend	**1**	**6**
$FA_{No.4}$ Ratio	0.50	0.50
$FA_{No.16}$ Ratio	0.50	0.50
VMA	18.67	18.17
% Passing No. 16	23.2	23.2
Corresponding Blend	**2**	**7**
$FA_{No.4}$ Ratio	0.35	0.35
$FA_{No.16}$ Ratio	0.72	0.72
VMA	20.10	19.74
% Passing No. 16	16.2	16.2
VMA Change	⇧ + 1.43	⇧ + 1.57

In both cases the VMA increased with decreasing percent passing No. 16. The Bailey Method ratios were not impacted by this change (see Table 3.10). The decrease in the $FA_{No.4}$ Ratio stayed within the 0.35 to 0.50 range, and the VMA increase was consistent with this decrease.

The $FA_{No.16}$ Ratio however, increased and went above the 0.50 upper limit prescribed for the Bailey Method FA ratios. The increase in this ratio should have triggered a decrease in VMA. Two possibilities exist for why this did not occur:

1. The increase in VMA due to the $FA_{No.4}$ Ratio exceeded the decrease in VMA due to the $FA_{No.16}$ Ratio thus leaving a net gain in VMA.

2. The excess No. 16 size material may have acted as an "interceptor" rather than a filler of voids. This may have caused an increase in VMA even though the $FA_{No.16}$ Ratio increased.

3.2.5 Effect of No. 30 Sieve on FA ratios and VMA (R&D Fischer Quarry)

Again, recall that Blends 1 and 6 were considered baseline blends and that blends 3 and 8 were varied from the baseline on the No. 30 sieve by 1%. Table 3.12 shows the effect of changes in the percent passing the No. 30 sieve on FA ratios and VMA with four R&D Fischer Quarry blends.

Table 3.12: Effect of No. 30 Sieve on FA ratios and VMA (R&D Fischer Quarry material)

Blend	1	6
FA_c Ratio	0.50	0.50
FA_f Ratio	0.50	0.50
VMA	18.67	18.17
% Passing No. 30	14.4	12.4
Corresponding Blend	**3**	**8**
FA_c Ratio	0.47	0.40
FA_f Ratio	0.54	0.62
VMA	18.08	18.18
% Passing No. 30	13.4	11.6
VMA Change	⇩ - 0.59	⇧ + 0.01

In this case the VMA decreased slightly or remained essentially unchanged with decreasing percent passing No. 30. The Bailey Method ratios went in opposite directions. The decrease in the FA_c Ratio stayed within the 0.35 to 0.50 range while the increase in FA_f Ratio went above the 0.50 upper limit.

All four blends in Table 3.12 vary only on the No. 30 sieve, with Blend 1 having the highest percent passing at 14.4% and Blend 8 having the lowest at 11.6%. Conventional thinking is that moving the No. 30 away from the maximum density line (i.e. decreasing the percent passing No. 30) should increase VMA.

Blends 3, 6, and 8 marginally follow this pattern; however, Blend 1, having the most passing the No. 30, should have the lowest VMA, not the highest. The precision in measuring VMA may be a factor; the No. 30 may also be acting as an "interceptor."

Table 3.13 shows the effect of changes in the percent passing the No. 30 sieve on VMA with another set of R&D Fischer Quarry blends.

Table 3.13: Effect of No. 30 Sieve on VMA (R&D Fischer Quarry material)

Blend	1	2	3	4	5
FA_c Ratio	0.50	0.50	0.47	0.50	0.50
FA_f Ratio	0.50	0.50	0.54	0.50	0.35
VMA	18.67	20.10	18.08	18.28	17.74
% Passing No. 30	14.4	14.4	13.4	14.4	14.4
Corresponding Blend	**6**	**7**	**8**	**9**	**10**
FA_c Ratio	0.43	0.43	0.40	0.43	0.43
FA_f Ratio	0.58	0.58	0.62	0.58	0.40
VMA	18.17	19.74	18.18	18.74	18.41
% Passing No. 30	12.4	12.4	11.6	12.4	12.4
VMA Change with No. 30 Decrease	⇩ - 0.50	⇩ - 0.36	⇧ + 0.10	⇧ + 0.46	⇧ + 0.67

This series of blends suggests that there is a complex interaction between gradation and VMA. The magnitude and the direction of change in the No. 30 sieve is approximately the same for all five pairs of blends. The impact on VMA is, however, dependent on other changes in the blend.

Of particular interest is the somewhat linear appearance of the VMA change across the five pairs of data. If we use the Blend 1 and Blend 6 comparison as a new baseline, a review of Table 3.8 indicates that three of the remaining pairs, in addition to changing the percent passing the No. 30 sieve, had one other sieve adjusted (Note: Blends 1, 3, 6, & 8 only differ on the No. 30 sieve). These changes are shown in Table 3.14.

Table 3.14: Combined effect of the No. 30 Sieve and other sieves on VMA (R&D Fischer Quarry material)

Blends Compared	Change in No. 30 Sieve	Other Sieve Decreased	VMA Change
1 & 6	-2.0	n/a	- 0.50
2 & 7	-2.0	No. 16 (-7.0%)	- 0.36
3 & 8	-1.8	n/a	+ 0.10
4 & 9	-2.0	No. 50 (-3.5%)	+ 0.46
5 & 10	-2.0	No. 100 (-2.2%)	+ 0.67

The relationship appears to be that the change in VMA due to a decrease in the percent passing the No. 30 can be magnified by also decreasing the percent passing on additional sieves *at or below the No. 30.*

3.2.6 Effect of No. 50 Sieve on FA ratios and VMA (R&D Fischer Quarry)

Blends 1 and 6 were the baseline blends and Blends 4 and 9 were decreased on the No. 50 sieve by 2.5%. Table 3.15 shows the effect of changes in the percent passing the No. 50 sieve on VMA with four R&D Fischer Quarry blends.

Table 3.15: Effect of No. 50 Sieve on VMA (R&D Fischer Quarry material)

Blend	**1**	**6**
$FA_{No.4}$ Ratio	0.50	0.50
$FA_{No.16}$ Ratio	0.50	0.50
VMA	18.67	18.17
% Passing No. 50	11.6	11.6
Corresponding Blend	**4**	**9**
$FA_{No.4}$ Ratio	0.50	0.50
$FA_{No.16}$ Ratio	0.35	0.35
VMA	18.28	18.74
% Passing No. 50	8.1	8.1
VMA Change	⇩ - 0.39	⇧ + 0.57

Blends 6 and 9 behaved as predicted by the Bailey Method with an increase in VMA when the $FA_{No.16}$ Ratio dropped. Blend 1 and 4, however, decreased; again this may be a result of a lack of precision in measuring VMA.

3.2.7 Effect of No. 100 Sieve on FA ratios and VMA (R&D Fischer Quarry)

Blends 1 and 6 were the baseline blends and Blends 5 and 10 were decreased on the No. 100 sieve by 2.2%. Table 3.16 shows the effect of changes the percent passing the No. 100 sieve on VMA with four R&D Fischer Quarry blends.

Table 3.16: Effect of No. 100 Sieve on VMA (R&D Fischer Quarry material)

Blend	**1**	**6**
FA_c Ratio	0.50	0.43
FA_f Ratio	0.50	0.58
VMA	18.67	18.17
% Passing No. 100	7.2	7.2
Corresponding Blend	**5**	**10**
FA_c Ratio	0.50	0.43
FA_f Ratio	0.35	0.40
VMA	17.74	18.41
% Passing No. 100	5.0	5.0
VMA Change	⇩ - 0.93	⇧ + 0.24

As with the other changes, Blends 6 and 10 behaved as predicted by the Bailey Method with an increase in VMA when the FA_f Ratio dropped. The opposite effect with Blends 1 and 5, however, again suggests that the Blend 1 data may be an outlier due to a lack of precision in measuring VMA.

4.0 RUT TESTING OF SELECTED BLENDS

4.1 SELECTION OF BLENDS FOR RUT TESTING

Selected asphalt blends containing the LTM Kirtland material and the R&D Fischer Quarry material were rut tested per ODOT TM 320-01 in the Asphalt Pavement Analyzer. The blends selected were as follows:

LTM Kirtland (Gravel):

Blend 1 – Baseline
Blend 2 – Measures the effect of the FA_f Ratio
Blend 4 – Measures the effect of the FA_c Ratio
Blend 5 – Measures the effect of combined FA_c and FA_f Ratios
Blend 6 – Measures the effect of the CA Ratio
Blend 10 – Measures the effect of the combined CA, FA_c, and FA_f Ratios

R&D Fischer (Quarry):

Blend 1 – Baseline
Blend 2 – Measures the effect of the No. 16 sieve
Blend 8 – Measures the effect of the No. 30 sieve
Blend 9 – Measures the effect of the No. 50 sieve

4.2 RUT TESTING RESULTS – LTM KIRTLAND MATERIAL

Table 4.1 shows the results of rut testing on the asphalt blends containing LTM Kirtland material:

Table 4.1: Rut results of the LTM Kirtland material

Blend	P_b	VMA	VFA	$P200/P_{be}$	CA Ratio	FA_c Ratio	FA_f Ratio	Rut Depth (mm)
1	6.9	16.9	76	0.97	0.65	0.50	0.50	2.9
2	6.7	16.5	76	0.71	0.65	0.50	0.35	3.3
4	8.0	19.2	79	0.57	0.65	0.35	0.50	4.0
5	7.0	16.9	76	0.66	0.65	0.35	0.35	3.5
6	6.4	15.9	75	1.07	0.50	0.50	0.50	3.1
10	6.6	16.3	75	0.70	0.50	0.35	0.35	3.6

The narrow range of rut depths (2.9 to 4.0 mm) compared to the changes at the extreme limits of the Bailey ratios for this material suggests that the ratios are not strong predictors of the rutting potential of mixtures.

4.2.1 Effect of CA Ratio on rut depth (LTM Kirtland material)

Decreasing the CA Ratio should decrease the VMA which in turn would reduce the effective asphalt content. This reduction in effective asphalt should be reflected in a reduction in rut depth. Table 4.2 shows the effect of a change in the CA Ratio on rut depth with two blends using LTM Kirtland material.

Table 4.2: Effect of CA Ratio on rut depth (LTM Kirtland material)

Blend	**1**
CA Ratio	0.65
VMA	16.93
Rut Depth	2.9
Corresponding Blend	**6**
CA Ratio	0.50
VMA	15.87
Rut Depth	3.1
Rut Depth Change with CA Ratio Decrease	⇧ + 0.2

In fact the approximate 1% decrease in VMA resulted in a slight increase in rut depth. This suggests that the Bailey CA Ratio is not an indicator of rut susceptibility.

4.2.2 Effect of FA_c Ratio on rut depth (LTM Kirtland material)

Bailey predicts that a decrease in the FA_c Ratio should result in an increase in the VMA and therefore a possible increase in effective binder content. This increase in available asphalt cement should increase the rut susceptibility. Table 4.3 shows the effect of changes in the FA_c Ratio on VMA and rut depth with four LTM Kirtland material blends.

Table 4.3: Effect of FA_c Ratio on rut depth (LTM Kirtland material)

Blend	**1**	**2**
FA_c Ratio	0.50	0.50
VMA	16.93	16.47
Rut Depth	2.9	3.3
Corresponding Blend	**4**	**5**
FA_c Ratio	0.35	0.35
VMA	19.22	16.91
Rut Depth	4.0	3.5
Rut Depth Change with FA_c Ratio Decrease	⇧ + 1.1	⇧ + 0.2

Both sets of corresponding blends show an increase in rut depth, supporting an inverse relationship between rut depth and the FA_c Ratio.

4.2.3 Effect of FA_f Ratio on rut depth (LTM Kirtland material)

Similar to the FA_c Ratio, Bailey predicts that a decrease in the FA_f Ratio should result in an increase in the VMA and therefore a possible increase in effective binder content. This increase in available asphalt cement should increase the rut susceptibility. Table 4.4 shows the effect of changes in the FA_f Ratio on VMA and rut depth with four LTM Kirtland material blends.

Table 4.4: Effect of FA_f Ratio on rut depth (LTM Kirtland material)

Blend	**1**	**4**
FA_f Ratio	0.50	0.50
VMA	16.93	19.22
Rut Depth	2.9	4.0
Corresponding Blend	**2**	**5**
FA_f Ratio	0.35	0.35
VMA	16.47	16.91
Rut Depth	3.3	3.5
Rut Depth Change with FA_f Ratio Decrease	⇧ + 0.4	⇩ - 0.5

The VMA's between the corresponding blends did not behave as predicted by the Bailey Method and hence the rut results were inconsistent as well.

4.3 RUT TESTING RESULTS – R&D FISCHER QUARRY MATERIAL

The Bailey Method does not identify the No. 16, and No. 50 sieves as key sieves, yet they had a clear impact on the volumetrics, even when the Bailey Method ratios remained unchanged. A series of blends were selected from the R&D Fischer Quarry material to evaluate rut susceptibility to these sieves. Table 4.5 shows the effects of changes in the percent passing the No. 16, No. 30, and No. 50 sieves on rutting with four asphalt blends using the R&D Fischer Quarry material.

Table 4.5: Rut results of the R&D Fischer Quarry material

Blend	P_b	VMA	VFA	$P200/P_{be}$	No. 16	No. 30	No. 50	Rut Depth (mm)
1	6.2	18.7	79	0.67	23.2	14.4	11.6	4.1
2	6.8	20.1	80	0.61	16.2	14.4	11.6	6.5
8	5.9	18.2	78	0.70	23.2	11.6	11.6	4.4
9	6.2	18.7	78	0.68	23.2	12.4	8.1	3.6

4.3.1 Effect of the No. 16 Sieve on rut depth (R&D Fischer Quarry material)

Decreasing the percent passing the No. 16 sieve should increase the VMA, which in turn would increase the effective asphalt content. This increase in effective asphalt should be reflected in an increase in rut depth. Table 4.6 shows the effect of a change in the percent passing the No. 16 sieve on VMA and rut depth.

Table 4.6: Effect of No. 16 Sieve on rut depth (R&D Fischer Quarry material)

Blend	**1**
% Passing No. 16	23.2
VMA	18.7
Rut Depth	4.1
Corresponding Blend	**2**
% Passing No. 16	16.2
VMA	20.1
Rut Depth	6.5
Rut Depth Change with No. 16 Decrease	⇧ + 2.4

The decreasing No. 16 did in fact increase VMA by 1.4%, and the predicted rut depth went up.

4.3.2 Effect of the No. 30 Sieve on rut depth (R&D Fischer Quarry material)

Decreasing the percent passing the No. 30 sieve should increase the VMA, which in turn would increase the effective asphalt content. This increase in effective asphalt should be reflected in an increase in rut depth. Table 4.7 shows the effect of a change in the percent passing the No. 30 sieve on VMA and rut depth.

Table 4.7: Effect of No. 30 Sieve on rut depth (R&D Fischer Quarry material)

Blend	**1**
Passing No. 30	14.4
VMA	18.7
Rut Depth	4.1
Corresponding Blend	**8**
Passing No. 30	11.6
VMA	18.2
Rut Depth	4.4
Rut Depth Change with No. 30 Increase	⇧ + 0.3

An increase in the percent passing the No. 30 sieve did actually decrease VMA by about 0.5%, and the predicted rut depth went up slightly.

4.3.3 Effect of the No. 50 Sieve on rut depth (R&D Fischer Quarry material)

Decreasing the passing No. 50 Sieve should increase the VMA which in turn would increase the effective asphalt content. This increase in effective asphalt should be reflected in an increase in rut depth. Table 4.8 shows the effect of a change in the percent passing the No. 50 sieve on VMA and rut depth.

Table 4.8: Effect of No. 50 Sieve on rut depth (R&D Fischer Quarry material)

Blend	**8**
% Passing No. 50	11.6
VMA	18.2
Rut Depth	4.4
Corresponding Blend	**9**
% Passing No. 50	8.1
VMA	18.7
Rut Depth	3.6
Rut Depth Change with No. 50 Decrease	⇩ - 0.8

The decreasing No. 50 did cause the VMA to increase by approximately 0.5%, and the predicted rut depth actually went down by 0.8mm. The thing to note here is that the percent passing the No. 30 sieve also increased by 0.8% between these two blends, and the change in No. 30 and the change in No. 50 appear to be offsetting each other to some extent.

5.0 CONCLUSIONS

5.1 BAILEY METHOD DESIGN PROCESS

Preliminary attempts to adapt the Bailey Method *Design Process* led to extremely fine asphalt mixes which are not common in Oregon. The use of bulk density did show promise as a relatively simple way to provide a rapid comparison between trial blends. To produce traditional "S – shaped" gradations, it will be necessary to modify the Bailey Method Design Process.

The use of bulk densities does show promise as a rapid tool to rank blends without the additional work of mixing and compacting specimens.

5.2 BAILEY METHOD ANALYSIS PROCESS

The Bailey Method *Analysis Process*, which uses three ratios to control the gradation for dense-graded mixtures, has proven to be a useful tool. The simple analysis process allows the mix designer to make rational decisions regarding adjustments to gradation to enhance the volumetric properties of mixes.

The three ratios under the Bailey Method may not be sufficient in all cases. The data from the R&D Fischer Quarry blends showed that changes on the No. 50, No. 100, and No.200 sieves can also have significant impacts on VMA that are not measured by the Bailey Method ratios. Additional ratios were defined in this research to cover these sieves.

Even with additional ratios, the interaction between VMA and gradation is complex and may not be modeled by simple "two-dimensional" tools such as the 0.45 power curve.

The FA ratio criteria of 0.35 to 0.50 appear to be appropriate for use with Oregon mixtures. A look at a cut-face on a typical Oregon dense-graded asphalt mix shows that the coarse aggregate is generally afloat in a matrix of finer aggregate particles.

In most cases, the key to improving mix performance will probably lie with making the appropriate choices about the fine aggregates. The "packing" concepts of the Bailey Method are probably at play in the fine aggregates in Oregon mixes.

5.3 RUT SUSCEPTIBILITY AND THE BAILEY RATIOS

The narrow range of rut results for the LTM Kirtland blends limited the ability to make strong conclusions regarding the use of the Bailey ratios as predictors of rut susceptibility. In general, increasing VMA tended to increase rutting.

The R&D Fischer quarry blends showed a larger range of rut depths. However, in order to make the desired Bailey ratios, the resultant blends had higher than normal VMA's. These mixes would normally show more rut susceptibility than blends better matching conventional ODOT designs.

In a broad sense, the data did indicate that rut susceptibility is impacted by the fine aggregate blend. However, the data did not suggest that the Bailey ratios provided an improved prediction of rut susceptibility beyond the currently recognized relationships with volumetric properties of mixes.

5.4 RECOMMENDATIONS

The following recommendations are made, based on the findings of this research:

- A modified Bailey Method analysis process should be incorporated into the mix design process as an additional tool to develop and select trial blends for the design of dense-graded mixes.
- Additional sieves should be included (No.16, No.50, No.100) during aggregate quality control testing and included in the Quality Level analysis.
- Standard spreadsheets should be developed for rapidly computing the ratios.
- Ratio criteria should be provided for information initially and eventually adopted as design criteria.
- Contractor Mix Design Training (CMDT) should incorporate some form of Bailey Method analysis for the coming training season.

6.0 REFERENCES

American Association of State Highway and Transportation Officials (AASHTO). *Standard Specifications for Transportation Materials and Methods of Sampling and Testing, Part 2 – Tests*. Washington, DC. 2004.

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APPENDIX

CANDIDATE BLENDS USING THE BAILEY METHOD CRITERIA AND THE SUPERPAVE™ CRITERIA

ODOT Bailey Method Candidate Blends

Criteria	CA Ratio	FA_f Ratio	FA_c Ratio
1	0.65	0.50	0.50
2	0.65	0.50	0.35
3	0.65	0.35	0.50
4	0.65	0.35	0.35
5	0.50	0.50	0.50
6	0.50	0.50	0.35
7	0.50	0.35	0.50
8	0.50	0.35	0.35

12.5 mm Mixture:	%Pass No. 8
SuperPave Upper CP	58.0
0.45 Power Curve	39.0
ODOT Golden Grad.	34.0
SuperPave Lower CP	28.0

Criteria 1

Control	¼ in	No. 8	No. 30	No. 100	CA Ratio	FA_f Ratio	FA_c Ratio
PCS 58.0	74.6	58.0	29.0	14.5	0.65	0.50	0.50
PCS 39.0	63.0	39.0	19.5	9.8	0.65	0.50	0.50
PCS 34.0	60.0	34.0	17.0	8.5	0.65	0.50	0.50
PCS 28.0	56.4	28.0	14.0	7.0	0.65	0.50	0.50

Criteria 2

Control	¼ in	No. 8	No. 30	No. 100	CA Ratio	FA_f Ratio	FA_c Ratio
PCS 58.0	74.6	58.0	29.0	10.2	0.65	0.50	0.35
PCS 39.0	63.0	39.0	19.5	6.9	0.65	0.50	0.35
PCS 34.0	60.0	34.0	17.0	6.0	0.65	0.50	0.35
PCS 28.0	56.4	28.0	14.0	4.9	0.65	0.50	0.35

Criteria 3

Control	¼ in	No. 8	No. 30	No. 100	CA Ratio	FA_f Ratio	FA_c Ratio
PCS 58.0	74.6	58.0	20.3	10.2	0.65	0.35	0.50
PCS 39.0	63.0	39.0	13.6	6.8	0.65	0.35	0.50
PCS 34.0	60.0	34.0	11.9	6.0	0.65	0.35	0.50
PCS 28.0	56.4	28.0	9.8	4.9	0.65	0.35	0.50

Criteria 4

Control	¼ in	No. 8	No. 30	No. 100	CA Ratio	FA_f Ratio	FA_c Ratio
PCS 58.0	74.6	58.0	20.3	7.1	0.65	0.35	0.35
PCS 39.0	63.0	39.0	13.6	4.8	0.65	0.35	0.35
PCS 34.0	60.0	34.0	11.9	4.2	0.65	0.35	0.35
PCS 28.0	56.4	28.0	9.8	3.4	0.65	0.35	0.35

Criteria 5

Control	¼ in	No. 8	No. 30	No. 100	CA Ratio	FA_f Ratio	FA_c Ratio
PCS 58.0	72.0	58.0	29.0	14.5	0.50	0.50	0.50
PCS 39.0	59.3	39.0	19.5	9.8	0.50	0.50	0.50
PCS 34.0	56.0	34.0	17.0	8.5	0.50	0.50	0.50
PCS 28.0	52.0	28.0	14.0	7.0	0.50	0.50	0.50

Criteria 6

Control	¼ in	No. 8	No. 30	No. 100	CA Ratio	FA_f Ratio	FA_c Ratio
PCS 58.0	72.0	58.0	29.0	10.2	0.50	0.50	0.35
PCS 39.0	59.3	39.0	19.5	6.8	0.50	0.50	0.35
PCS 34.0	56.0	34.0	17.0	6.0	0.50	0.50	0.35
PCS 28.0	52.0	28.0	14.0	4.9	0.50	0.50	0.35

Criteria 7

Control	¼ in	No. 8	No. 30	No. 100	CA Ratio	FA_f Ratio	FA_c Ratio
PCS 58.0	72.0	58.0	20.3	10.2	0.50	0.35	0.50
PCS 39.0	59.3	39.0	13.7	6.9	0.50	0.35	0.50
PCS 34.0	56.0	34.0	11.9	6.0	0.50	0.35	0.50
PCS 28.0	52.0	28.0	9.8	4.9	0.50	0.35	0.50

Criteria 8

Control	¼ in	No. 8	No. 30	No. 100	CA Ratio	FA_f Ratio	FA_c Ratio
PCS 58.0	72.0	58.0	20.3	7.1	0.50	0.35	0.35
PCS 39.0	59.3	39.0	13.7	4.8	0.50	0.35	0.35
PCS 34.0	56.0	34.0	11.9	4.2	0.50	0.35	0.35
PCS 28.0	52.0	28.0	9.8	3.4	0.50	0.35	0.35