AGGREGATE GRADING ANALYSIS USING THE BAILEY METHOD OF GRADATION SELECTION

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CERTIFICATION OF APPROVAL

Aggregate Grading Analysis Using the Bailey Method of Gradation Selection

by

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CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

THABISO FRANS MATOME

ABSTRACT

In the design of Hot Mix Asphalt (HMA) the aggregate gradation is one of the important factors that have to be considered in pavement design and ultimately, in the construction, because it accounts for the overall strength of asphalt in terms of resisting permanent deformation such as rutting. The purpose of this project is to implement the aggregate gradation analysis to a mix, which follows the standard of Malaysia in accordance with the Jabatan Kerja Raya (JKR) standard specification for road works of Malaysia, using the Bailey method of gradation which follows a design and analysis procedure that includes an examination of aggregate packing and aggregate interlock, blending aggregates by volume, a new understanding of coarse and fine aggregate, and analysis of the resulting gradation.

The idea was to analyze and compare, based on the Marshall Mix design factors and the Hamburg Wheel track test, a hot-mix asphalt (HMA) constructed using aggregates with a gradation limit that is in accordance with JKR and an HMA constructed using aggregates that are optimized by the Bailey method which uses aggregate packing concepts to analyze the combined gradation and relate the packing characteristics to the mixture volumetric properties and compaction characteristics. During the course of the research, the findings gave us a basis in which to analyze whether this method can be adopted and also if it will be useful and/or beneficial to the Malaysian pavement design industry.

What the findings yielded was that the HMA designed following the JKR standards i.e. ACW 20 wearing course, according to the bailey method, is as follows:

- The mix was susceptible to segregation
- Has a possibility of tenderizing
- May be difficult to compact

So the bailey method was able to yield a new and better performing HMA blend.

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CHAPTER 1

INTRODUCTION

1.1 Background

The Bailey method, based on experience, is a practical tool successfully utilized for developing and analyzing hot mix asphalt in the laboratory and in the field. It also provides a good starting point for mix design and is an invaluable aid when making adjustments at the plant to improve air voids, Voids in mineral aggregates (VMA) and the overall workability of the mix, whether using Marshall or Superpave (Pine 2005).

This method, The Bailey method, mainly focuses on aggregate packing. The determination of which particles/aggregates form the coarse fraction of the aggregate structure, meaning which particles/aggregates form the voids, and which ones fit into the voids created by the coarse fraction within the overall structure. This has to be known in order to understand the aggregate packing characteristics of the structure.

An evaluation of the individual aggregates and the combined aggregate blend by volume as well as by weight is also included in the method. The latter is done in order to better understand which fraction, whether coarse or fine, is controlling the overall aggregate structure.

1.2 Problem Statement

From the beginning of asphalt mixture design it was desired to understand the interaction of aggregates, asphalt, and the voids created during their compaction. In asphalt mixture design, guidance is lacking in the selection of the design aggregate structure and understanding the interaction of that aggregate structure and mixture volumetric properties.

Furthermore, Fatigue cracking and rutting of flexible pavements are major issues and are closely related to packing characteristics of the mix, volumetric aspects of the mix and also aggregate characteristics. When designing hot mix asphalt, the performance of the HMA has to resist permanent deformation which deteriorates the safety, aesthetics and performance of the pavement structure.

In order to combat this problem the bailey method, using its asphalt mixture concepts of aggregate interlock and aggregate packing, will be used to improve the air voids, VMA, strengthen the aggregate skeleton and the overall workability of the mix by developing aggregate blend that meets volumetric criteria and provides adequate compaction characteristics.

1.3 Objective and Scope of Study

The objectives of this study are to:

- Incorporate an analytical gradation design and evaluation method into the Marshal mix design procedure
- Analyze, theoretically, the compaction and performance characteristics of the resulting hot mix asphalt mixture(s).
- Design a new blend and compare the latter mix (Bailey method) to the JKR standard HMA.

The Bailey method of aggregate gradation and evaluation will be used to design and evaluate the aggregate structures for the mixture(s) in the study. The compaction characteristics of the mixtures will be analyzed and the performance of the designed mixtures will be evaluated using both simulative and fundamental laboratory tests. Gradation parameters will be used to analyze the effect of gradation on compaction and performance properties of asphalt mixtures. The aggregate types that will be used will be the ones commonly used in Malaysia i.e. granite and, three aggregate structures (coarse, medium, and fine) will be designed using the Bailey method of aggregate gradation evaluation. The asphalt mixtures will have a certain NMPS mixtures and will be designed for particular volume of traffic. A certain performance grade, based on the JKR, binder will be used for the mixtures. Laboratory tests, namely sieve analysis, Marshall Tests, etc will be conducted, including the Hamburg wheel tracking test.

CHAPTER 2

LITERATURE REVIEW and/or THEORY

2.1 Literature Review

2.1.1 Factors that contribute to variability in VMA according to Chadbourn et al. (2000)

VMA is the volume of inter-granular void space between the aggregate particles of a compacted paving mixture. It includes the air voids and the volume of the asphalt not absorbed into the aggregate. In other words, VMA describes the portion of space in a compacted asphalt pavement or specimen which is not occupied by the aggregate. VMA is expressed as a percentage of the total volume of the mix. When aggregate particles are coated with asphalt binder, a portion of the asphalt binder is absorbed into the aggregate, whereas the remainder of the asphalt binder forms a film on the outside of the individual aggregate particles. Since the aggregate particles do not consolidate to form a solid mass, air pockets also appear within the asphalt-aggregate mixture. Therefore, as Figure 2.1.1 illustrates, the four general components of HMA are: aggregate, absorbed asphalt, asphalt not absorbed into the aggregate (effective asphalt), and air. Air and effective asphalt, when combined, are defined as VMA.

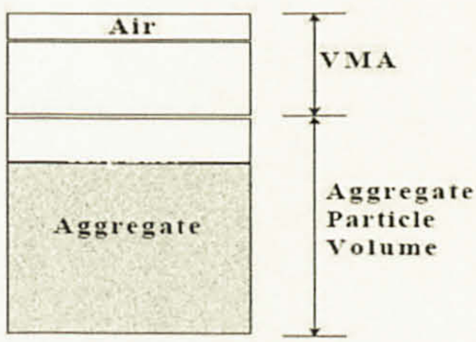

Figure 2.1.1 Illustration of VMA

VMA is calculated according to the following relationship:

$$VMA = 100 - \frac{P_s \times G_{mb}}{G_{sb}}$$

Where:

P_s = Aggregate content, percent by total mass of mixture

G_{sb} = Bulk specific gravity of total aggregate

G_{mb} = Bulk specific gravity of compacted mixture

If the VMA is too low, it can be increased by modifying the gradation, asphalt content, or particle angularity. Table 2.1.1 shows typical minimum VMA values recommended by the Asphalt Institute.

Table 2.1.1 Minimum VMA recommended by asphalt institute

Nominal Maximum Particle Size[1, 2]		Minimum VMA, percent		
		Design Air Voids, percent[3]		
mm	in.	3.0	4.0	5.0
1.18	No. 16	21.5	22.5	23.5
2.36	No. 8	19.0	20.0	21.0
4.75	No. 4	16.0	17.0	18.0
9.5	3/8	14.0	15.0	16.0
12.5	1/2	13.0	14.0	15.0
19.0	3/4	12.0	13.0	14.0
25.0	1.0	11.0	12.0	13.0
37.5	1.5	10.0	11.0	12.0
50	2.0	9.5	10.5	11.5
63	2.5	9.0	10.0	11.0

1 - Standard Specification for Wire Cloth Sieves for Testing Purposes, ASTM E11 (AASHTO M92)
2 - The nominal maximum particle size is one size larger than the firs sieve to retain more than 10 percent.
3 - Interpolate minimum voids in the mineral aggregate (VMA) for design air void values between those listed.

Analysis of the contribution of VMA to pavement durability, it is important to understand the parameters of an HMA that relate to the determination of VMA. Certain characteristics of an HMA mixture and its components can change the VMA and film thickness. These characteristics are summarized in Table 2.1.2

Table 2.1.2 The factors affecting VMA on an HMA

Factor	Effect on VMA
Aggregate Gradation	Dense gradations decrease VMA
Aggregate Shape	More rounded aggregates decrease VMA
Aggregate Texture	Smooth or polished aggregates decrease VMA
Asphalt Absorption	Increased asphalt absorption results in lower effective asphalt content and lower VMA (for the same level of compaction)
Dust Content	Higher dust contents increase surface area, decrease film thickness, and tend to lower VMA
Baghouse Fines/Generation of Dust	Increased fines and dust increase surface area, decrease film thickness, and tend to lower VMA
Plant Production Temperature	Higher plant production temperatures decrease asphalt binder viscosity, which results in more asphalt absorption, lower effective asphalt binder and lower VMA
Temperature of HMA during Paving	Higher temperatures during paving create soft mixtures, lower air voids, and lower VMA
Hauling Time	Longer hauling times allow for increased asphalt absorption, lower effective asphalt content and lower VMA
Aggregate Handling	More steps in aggregate handling increases potential for aggregate degradation, resulting in an increase in fines, and lower VMA

Material Properties

The extent to which an HMA mixture can be compacted is related to aggregate gradation, aggregate surface characteristics, amount of asphalt, and asphalt absorption by the aggregate. Aggregate gradation is the size distribution of the aggregate particles, including the amount of material passing the 75-mm sieve (dust content). Aggregate surface characteristics include the shape, angularity, and surface texture. Aggregate absorption of asphalt binder is dependent on the aggregate porosity, and pore size, as well as the viscosity of the asphalt binder.

Aggregate Gradation

When selecting an aggregate for an HMA mixture, the initial focus is on the aggregate gradation. Two factors relating to aggregate gradation having the most influence on VMA are density, or the ability of the aggregate particles to pack together, and the aggregate surface area.

Density

Figure 2.1 illustrates a 0.45 power plot of an aggregate gradation developed by the Federal Highway Administration (FHWA). It is used to estimate how densely a given aggregate mixture will compact. It consists of the particle size raised to the 0.45 power on the x-axis and the percent passing each sieve size plotted on an arithmetic y-axis. A line drawn from the origin of this plot through the nominal maximum aggregate size is estimated as the maximum density line for any given aggregate (The nominal maximum aggregate size is defined as the first sieve to retain between 0 and 10% of the aggregate). An aggregate having a gradation that produces a straight line on a 0.45 power gradation graph will have the maximum achievable density, and subsequently the lowest air void content and the lowest VMA in an HMA mixture. Deviating from the maximum density line in either the fine or the coarse direction will tend to increase the VMA of the compacted mixture shown in Figure 2.1.2. However, note that significant confusion exists concerning different methods used to draw aggregate gradation "maximum" density lines. Closely related to maximum density lines, and also in debate, is the definition of nominal aggregate maximum size. For the purposes of this paper, the definitions used for the maximum density line and the aggregate nominal maximum size are stated above.

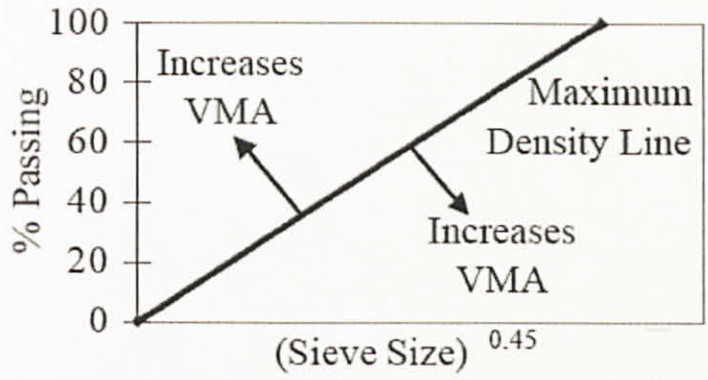

Figure 2.1.2 Maximum density line related to VMA

The "distance" as the absolute value of the difference in percent passing between the actual gradation and the maximum density line at a given sieve size. This value characterizes the actual deviation from the maximum density line. Increasing the sum of the distances between a gradation and the maximum density line will tend to increase the VMA. The distances for the 2.36-mm and smaller sieve sizes had the greatest effect on the VMA of the compacted mixture. The percent passing the 4.75-mm, 2.36-mm, 1.18-mm, 0.600-mm, 0.300-mm, 0.150-mm, and 0.075-mm sieves were the most practical predictive variables for VMA. This attempts to correlate "distance" to VMA. These two variables did not correlate well due to the many other factors that affect VMA. Consequently, the only way to be certain of the VMA of a mix is to produce a sample and measure the parameters from which VMA is calculated.

2.1.2 The bailey method of aggregate gradation selection and rutting resistance as described by Promwell et al. (2005)

In a study conducted at the University of Arkansas, which was an "Investigation of the use of the Bailey method of aggregate gradation selection for asphalt mix design in Arkansas" it was found that developing/creating Superpave mix designs using the Bailey Method for the selection of aggregate gradation proved to be more of a challenge than was expected . Difficulty was encountered in creating aggregate blends with favourable Bailey Method parameters using the current gradations of existing aggregate stockpiles Furthermore, in the process of adjusting the trial aggregate blends to achieve the specified volumetric property limits, the Bailey Method parameters commonly had to be adjusted to the limits of or slightly out of their recommended ranges. Furthermore, in terms of performance, the Bailey Method may improve rutting resistance more consistently and appreciably if ideal Bailey Method parameters (particularly the DUW) are met in the aggregate blends. However, more research is required to conclusively determine if this is the case. When altering the mixture volumetrics, the methods outlined in the Bailey Method procedure for attaining the desired mixture volumetrics appear to be very effective based on the experience in this research project. In every instance where the outlined methods were utilized to adjust the VMA of the mix, the VMA changed in the expected direction. Based on the results of this research project, it appears that the Bailey Method of aggregate gradation selection may provide some degree of improvement to the rutting resistance of Superpave mixes designed with aggregates as they exist in stockpiles common in Arkansas

2.1.3 Effect of aggregate grading on HMA properties adopted from Wald (2002)

Gradation is perhaps the most important property of an aggregate because it affects almost all the important properties of HMA, including stiffness, stability, durability, permeability, workability, fatigue resistance, frictional resistance, and resistance to moisture damage. The mixture volumetric properties including asphalt content, VMA, and VFA have been identified as important parameters for durability and performance. However, the VMA is considered the most important parameter and is used in the Superpave mixture design specifications to eliminate use of potentially poor-performing mixtures.

The Superpave mix design procedure controls the gradation of aggregate with a set of several specifications. The specifications were not developed from the results of actual, specific research but rather on a modified Delphi "questionnaire approach" among 14 aggregate experts. These specifications are based on a set of "standard sieves", a "mix-size" definition and control points on a 0.45 power chart. The set of standard sieves is used to define the gradation of the mix. The set of standard sieves consist of the sizes shown in Table 2.1.3.

Table 2.1.3 Superpave standard sieve size

Metric Units (mm)	U.S. Standard Size
50.0	2 in
37.5	1 1/2 in
25.0	1 in
19.0	3/4 in
12.5	1/2 in
9.5	3/8 in
4.75	#4
2.36	#8
1.18	#16
0.60	#30
0.30	#50
0.15	#100
0.075	#200

Superpave asphalt mixtures are always classified as one of the following sizes: 37 .5 mm, 25.0 mm, 19.0 mm, 12.5 mm, 9 .5 mm, or 4.75 mm. This classification, referred to as the Nominal Maximum Aggregate Size (NMAS) of the mix, is defined as being one sieve size larger than the first sieve that retains more than 10 percent of the aggregate blend.

The 0.45 power chart is a plot with an x-axis consisting of the standard sieve sizes raised to the 0 .45 power and a y-axis consisting of the percent of the aggregate blend passing the standard sieves. The x-axis has a minimum value of zero and a maximum value of the maximum aggregate size of the mix. Thus, the range of the x-axis of the 0 .45 power chart varies with NMAS of the Superpave mix. The y-axis always ranges from 0 to 100 percent with 100 percent being at the point of intersection with the x-axis. The Superpave 0 .45 power chart contains a "maximum density line" that runs from the origin (0mm, 100 percent passing) to the maximum x and y values (MAS 0 .45, 0 percent passing). This maximum density line on the 0 .45 power chart is based on the findings of several studies.

In the 1930 s, Nijboer discovered that a gradation plotted as a straight line on a plot with a log scale on both the x and y axis produced a very dense packing configuration. He found that both crushed and uncrushed aggregate particles alike produced the densest packing when the slope of the line on this plot was 0.45. In 1962, Goode and Lufsey further investigated Nijboer's findings and found that gradations similar to those used in actual road construction had the densest packing configuration when plotted at the same 0.45 slope on a log scale plot. Based on their findings, Goode and Lufsey developed what has become known as the 0 .45 power chart. In 1992, Huber and Shuler discovered that a gradation plotted on a 0 .45 power chart produced the densest packing when it created a straight line from the origin to the maximum x and y values on the 0 .45 power chart (MAS, 100 percent passing). This line is included on the Superpave 0 .45 power chart and is referred to as the maximum density line as it theoretically represents the densest possible aggregate gradation.

A set of control points is also included on the Superpave 0.45 power chart. These points delineate the allowable ranges through which the aggregate gradations may pass. The control points are located at the sieve sizes coinciding with the MAS and the NMAS of the mix, at the 2 .36 mm sieve and at the 0.075 mm sieve. The control points assure that the NMAS and MAS definitions are met to ensure that the mixtures are relatively dense graded, and dictate the amount of fine material that an aggregate blend may contain. The limits set by the control points vary depending on the NMAS of the mixture. An example 0 .45 power chart for a 12 .5 mm NMAS Superpave mix is shown in Figure 2.1.3

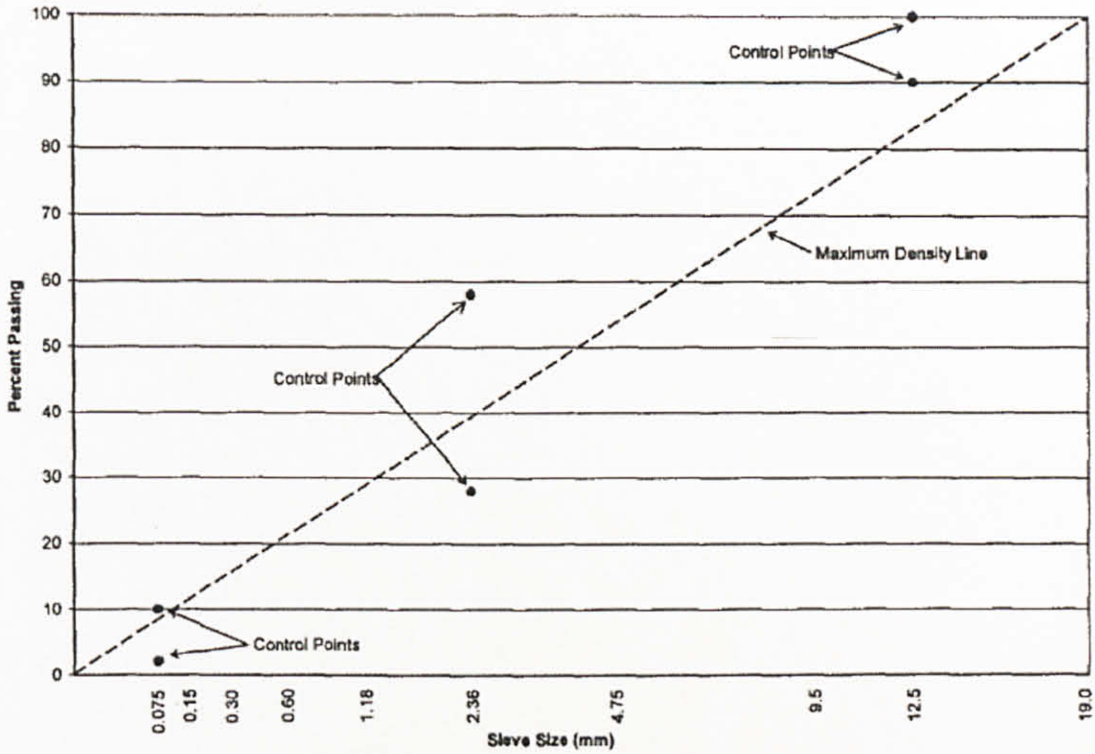

Figure 2.1.3 Superpave "0.45 power chart" for a 12.5 mm NMAS mix

The Superpave mix design procedure specifies that aggregate gradations must pass through the control points of the 0 .45 power chart for the respective NMAS of the asphalt mixture. Beyond this, no guidance is offered to mix designers on choosing the specific aggregate gradations for a Superpave mix. Figure 2 .1 demonstrates the open-endedness of the specification for choosing

the aggregate gradation . Mix designers are left to rely on experience and rules of thumb about the shape and location of the gradation curve when choosing the gradation of the aggregate blend. A specific procedure for choosing a proper aggregate gradation is desirable so that the mix design procedure will become more standardized and performance of the mixes may be optimized.

2.2 Bailey Method Principles

According to Correro (2002) the Bailey method has been internationally used in a laboratory asphalt research program in Dubai, United Arab Emirates, to improve the rutting performance of their mixtures. Field trials have been placed in Dubai, France, Canada and the United States of America.

The approach/basic principle here is to produce a HMA (preferably using an aggregate mix supplied by a source/manufacturer to design HMA for a particular type/class of traffic loads) then use the Bailey method for combining aggregates to optimize the aggregate interlock of the latter mentioned HMA and provide the proper volumetric properties using the four main principles of the Bailey method..

According to Jones (2006), The Four Main Principles of the Bailey Method are as follows:

Principle 1

Provides an entirely new definition of what is coarse and fine, and how to determine the volume of each:

- What coarse particles create voids and which ones fill them?
    - The Bailey Method utilizes the Nominal Maximum Aggregate Size (NMAS) to estimate the void size within the coarse fraction. The definition of NMAS is – the first sieve larger than the first sieve to retain more than 10% by weight. From this, a determination of the break between the coarse and fine fractions can be done, which is defined as the Primary Control Sieve (PCS).
- Which fraction (coarse or fine) is in control of the overall structure?
    - If the majority (>50.0%) of its gradation is retained above the PCS of the combined blend, then it will be treated as a coarse aggregates CA. If the

majority (<= 50.0%) of it's gradation passes the PCS of the combined blend, then it will be treated as a fine aggregate FA.

Principle 2

Concentrates on the coarse fraction of the overall aggregate blend and how the particle sizes are distributed i.e.:

- How does the coarse fraction pack together and what is the volume of voids in the coarse aggregate?
- How does the fine fraction pack?
- To what extent is the coarse fraction compactable or susceptible to segregation?

Principle 3

Concentrates on the coarse part of the fine fraction and how it relates to the packing of the overall fine fraction.

Principle 4

Looks at the fine part of the fine fraction and how it relates to the packing of this portion of the combined blend

The bailey's principles must be monitored for changes because they are interactive, meaning when one is altered then the remaining 3 will also change. Thus all of the four principles should be reviewed if a gradation changes.

Furthermore, the bailey method only mainly focuses if not limited to aggregate packing which is a major factor for the aggregate skeleton structure, this skeleton structure contributes to rut resistance strength but this is influenced by:

- Gradation
- Particle (aggregate) characteristics.

- Type and amount of compactive effort

This in turn influences the VMA, Density and workability of the whole structure thus it is connected to a number of variables.

CHAPTER 3

METHODOLOGY

3.1 Elements Determination, Sample Preparation and Testing

The objectives of this study are to sample, test, and analyze the aggregate source using the JKR standards for road works and also using the Bailey Method then to do a full Marshal mix on the HMA constructed using the JKR standards and repeat the mix design on the Bailey method optimized mix and ultimately compare the performance between the two mixes. The methodology used to accomplish these objectives will consist of the following tasks:

1. Determination of the loose unit weight (LUW) and the dry rodded unit weight (RUW) and specific gravity properties of the individual fractionations/aggregate stockpile as per AASHTO T 19.
2. Performing of the sieve analysis on the aggregates as per AASHTO T 27.
3. Determination of the control sieves.

4. Determine the chosen unit weight (CUW) for each stockpile.
5. Blend aggregate volumetrically from stockpile.
6. Determine the amount of fine aggregates (FA) needed to fill the voids created by the coarse aggregates (CA).
7. Determination of the initial blend percentage by weight.
8. Adjustment of the blend percentages for coarse aggregates (CA) in fine aggregates (FA) stockpile and also fine aggregates (FA) in coarse aggregates (CA) stockpile
9. Adjust amount of fines with mineral filler if desired.
10. Evaluate trial aggregate blends.
11. Adjust as necessary to obtain desired volumetric properties.

12. Determination of a suitable binder content for use in an asphalt mix as per (asphalt institute: Manual series no. 2) and in accordance with JKR 4.2.4.3 - (a)
13. Performing of the Marshall method test and analysis in accordance with the JKR standards 4.2.4.3 (a) (i), (ii), (iii) and (iv):.
14. Determine the volumetric properties of the mixes using the various blends per AASHTOT 166 and T 209 (*AASHTO 2004*).
    a. Determination of the bulk relative density (BRD) of a compacted bituminous mixture and the calculation of the voids content as per JKR 4.2.4.3 (a) (ii).
    b. Determination of the maximum theoretical density of the asphalt mixes as per ASSHTO T209.
15. Make recommendations for implementation of the Bailey design blend process and Bailey criteria.

CHAPTER 4

RESULTS & DISCUSSION

4.1 Aggregate and Binder Testing

The aggregates and binder tests are in accordance with the JKR standard of road works for Malaysia.

Standard Penetration Test

JKR 4.2.4.2 (c):

Bituminous binder for asphaltic concrete shall be penetration graded bitumen of 80-100 grade conforming to M.S. 124.

Table 4.1.1: Standard Penetration Test

Standard Penetration Test				
Temperature : 25°C		Load : 100 g	Time : 5 seconds	
Trial No.	Determination 1	Determination 2	Determination 3	
A	88	88	85	
B	86	86	84	

Particle Density and Water Adsorption (Sand)

JKR 4.2.4.2 (a):

ii. The water absorption when tested in accordance with M.S. 30 shall be not more than 2%.

Table 4.1.2: Particle Density and Water Absorption (Sand)

		Test No.	
		1	2
Mass of saturated surface-dry sample in air A	(g)	497	494
Mass of vessel containing sample and filled with water B	(g)	1860	1856
Mass of vessel filled with water only C	(g)	1557	1555
Mass of oven-dry sample in air D	(g)	495.0	491.1

		Test No.		
		1	2	Average
Particle density on an oven-dried basis	$\frac{D}{A-(B-C)}$	2.55	2.54	2.545
Particle density on a	$\frac{A}{A-(B-C)}$	2.56	2.56	2.560

saturated and surface-dried basis				
Apparent particle density	$\frac{D}{D-(B-C)}$	2.58	2.58	2.580
Water Absorption (% of dry mass)	$\frac{100(A-D)}{D}$	0.40%	0.59%	0.495%

Particle Density and Water Adsorption (Granite)

JKR 4.2.4.2 (a):

iv. The water absorption when tested in accordance with M.S. 30 shall be not more than 2%;

Table 4.1.3: Particle Density and Water Absorption (Granite)

		Test No.	
		1	2
Mass of saturated surface-dry sample in air A	(g)	991	1075
Mass of vessel containing sample and filled with water B	(g)	2170	2212
Mass of vessel filled with water only C	(g)	1556	1562
Mass of oven-dry sample in air D	(g)	984	1065

		Test No.		
		1	2	Average
Particle density on an oven-dried basis	$\frac{D}{A-(B-C)}$	2.61	2.51	2.56
Particle density on a saturated and surface-dried basis	$\frac{A}{A-(B-C)}$	2.63	2.53	2.58
Apparent particle density	$\frac{D}{D-(B-C)}$	2.66	2.57	2.62
Water Absorption (% of dry mass)	$\frac{100(A-D)}{D}$	0.71%	0.94%	0.83%

Flakiness Index (Granite)

JKR 4.2.4.2 (c):

iv. The flakiness index when tested in accordance with M.S. 30 shall be not more than 25;

Table 4.1.4: Flakiness Index (Granite)

Flakiness Index					
Size Fraction	Square Mesh Grading		Mass of fraction to be tested, M_2 (g)	Flakiness Gauge	
	Mass Retained (g)	Percent Passing (%)		Mass retained by gauge (g)	Mass passing gauge (g)
28.0 – 20.0	96	4.84	- (discarded)	- (discarded)	- (discarded)
20.0 – 14.0	1102	55.63	1102	1013	89
14.0 – 10.0	607	30.64	607	564	43
10.0 – 6.30	176	8.88	176	160	16
Total Masses, M_1 (g)	1981	100	$\Sigma M_2 = 1885$	1737	$\Sigma M_3 = 148$

Table 4.1.4: Flakiness Index (Granite)

$$FlakinessIndex = \frac{\Sigma M_3}{\Sigma M_2} x100\%$$

$$= \frac{148}{1885} x100\%$$

$$= 7.85\%$$

Sieve Analysis

According to the JKR standards, a mix gradation should follow or be within the limits of the table below

Table 4.1.5: Gradation Limit for Asphaltic Concrete adopted from JKR standards Clause 4.2.4.2

Mix Type	Wearing Course	Binder Course
Mix Designation	ACW 20	ACB 28
B.S Sieve	% Passing by weight	
37.5 mm		100
28.0 mm	100	80 - 100
20.0 mm	76 - 100	72 - 93
14.0 mm	64 - 89	58 - 82
10.0 mm	56 - 81	50 - 75
5.0 mm	46 - 71	36 - 58
3.35 mm	32 - 58	30 - 52
1.18 mm	20 - 42	18 - 38
425 um	12 - 28	11 - 25
150 um	6 - 16	5 - 14
75 um	4 - 8	3 - 8

Aggregate gradation

Table 4.1.6: Combined gradation of the mix

		% passing					
sieve size	coarse	fine	filler	%passing	min	max	
28	100	100	100	100	100	100	
20	99.4	100	100	99.75	76	100	NMAS
14	51.45	100	100	79.61	64	89	
10	13.35	100	100	63.61	56	81	HS
5	0.1	100	100	58.04	46	71	PCS
3.35	0	98.6	100	57.3	32	58	
1.18	0	65.2	100	40.6	20	42	SCS
0.425	0	18.6	100	17.3	12	28	
0.15	0	1.4	94	8.22	6	16	TCS
0.075	0	1.4	49	4.62	4	8	

The resulting gradation curve is plotted/shown in the figure below.

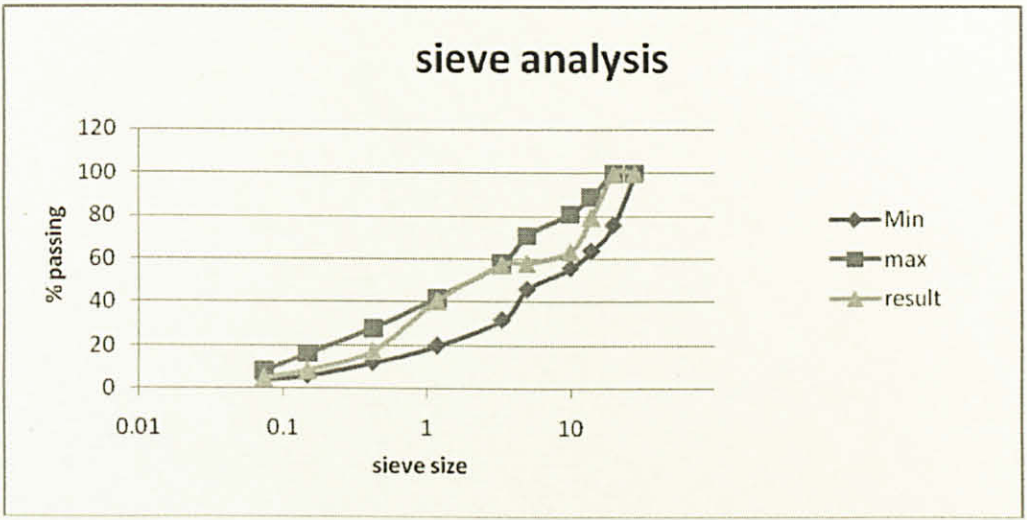

Figure 4.1.1: Combined gradation plot of the mix

The resulting gradation curve is well within the limit of the JKR standard and follows similar regime as a dense to open graded mixes which are suitable for all pavement layers and for all traffic conditions. They work well for structural, friction, levelling and patching needs.

The Materials that could be used for this type of gradation are well-graded aggregate if not crushed stone or gravel and manufactured sands, asphalt binder (with or without modifiers), Reclaimed Asphaltic Pavement (RAP) and be manufactured with mix design procedures such as Superpave, Marshall or Hveem.

Binder Content

As per JKR standards clause 4.2.4.3 (a), the design bitumen content will usually be in the appropriate range given in the table below

Table 4.1.7: Design Bitumen Content

ACW 14 – Wearing Course	5.0 – 7.0 %
ACB 14 – Binder Course	4.5 – 6.5 %
ACW 20 – Wearing Course	4.5 – 6.5 %
ACB 28 – Binder Course	4.0 – 6.0 %

The following are the results from the Marshall tests.

Table 4.1.8: Combined Average Results from Marshall Tests (20 mm NMAS continuously graded Asphalt)

AV %	VMA %	VFA %	Bitumen ratio %	Flow (mm)	flow 0.25mm	Stability (KN)	SG	SG.KG/ M3
11.2	18.8	40.8	3.5	1.100	4.400	6.4	2.265	2265
9.5	18.4	48.3	4	1.395	5.580	7.4	2.290	2290
8.1	18.1	55.6	4.5	1.670	6.680	7.8	2.309	2309
6.4	17.7	63.9	5	1.383	5.533	8.0	2.333	2333
5.1	17.7	70.9	5.5	1.940	7.760	7.7	2.347	2347
4.5	18.2	75.3	6	2.180	8.720	6.8	2.345	2345
3.8	18.6	79.7	6.5	2.480	9.920	6.2	2.346	2346
3.8	19.6	80.8	7	2.590	10.360	4.9	2.329	2329

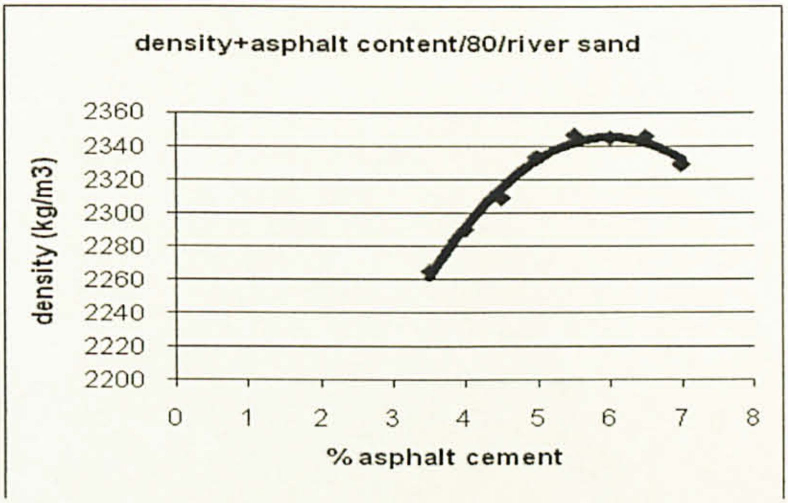

Figure 4.1.2: Bulk Relative Density vs. Asphalt Cement Content curve

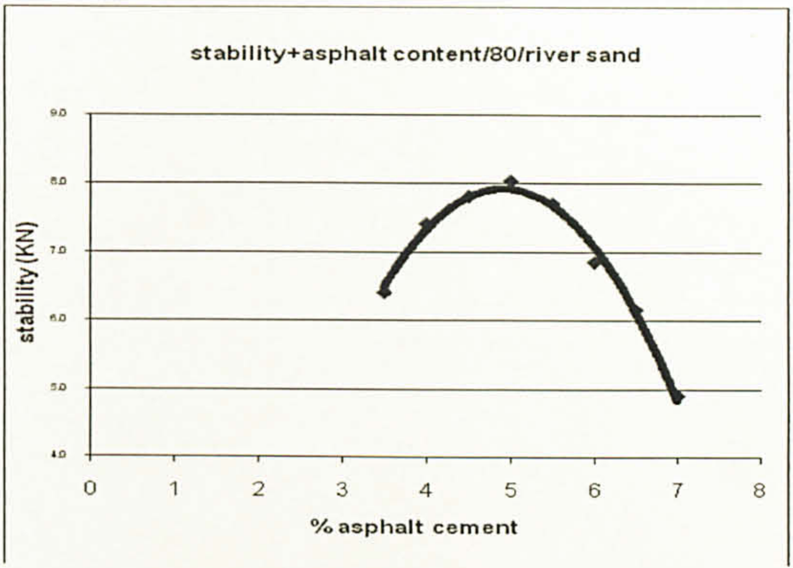

Figure 4.1.3: Marshall Stability vs. Asphalt Cement Content curve

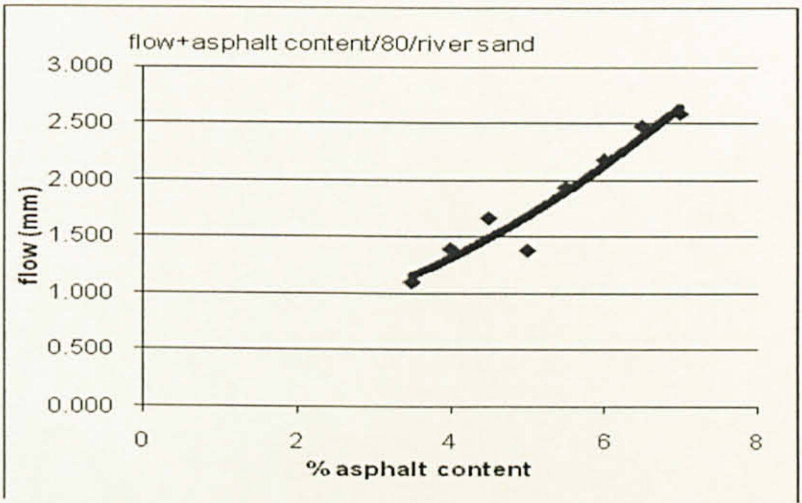

Figure 4.1.4: Marshall Flow vs. Asphalt Cement Content curve

Calculation for Voids in mineral aggregates (VMA) is as follows:

VMA = 100 – ((100 – AC Content) BRD/RDA)

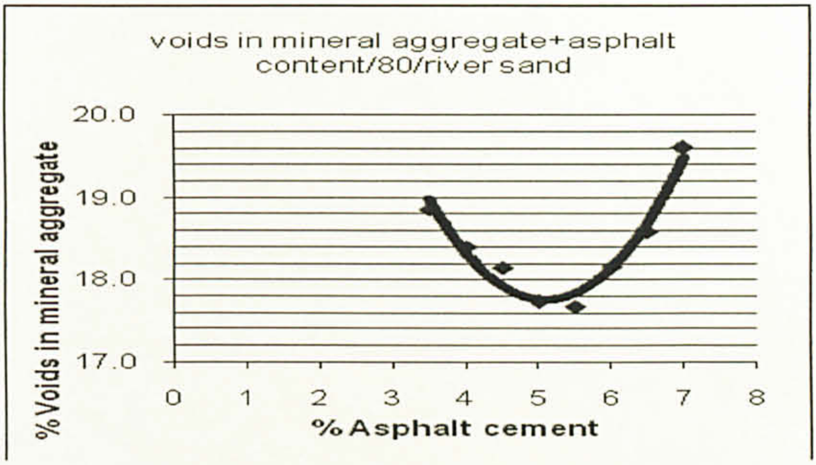

Figure 4.1.5: Voids in Mineral Aggregate vs. Asphalt Content curve

Calculation of Voids is as follows:

Voids = 100 ((MTRD – BRD)/MTRD)

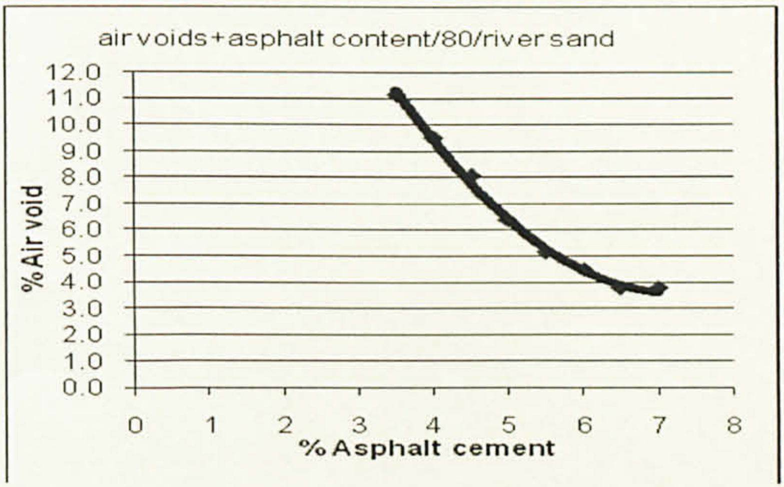

Figure 4.1.6: Voids vs. Asphalt Cement Content curve

Calculation of Voids Filled with Bitumen/Asphalt cement (VFB/A) is as follows:

VFB = 100 (100 – VMA – voids)/ VMA

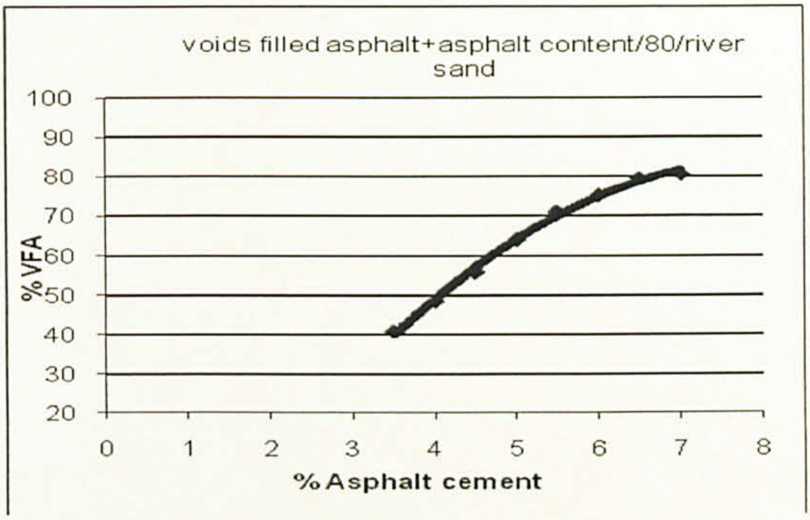

Figure 4.1.7: Voids Filled With vs. Asphalt Cement Content curve

The optimum Bitumen Content which is the average of the above figures was chosen to be 5.30%. The chosen value is well within the limits as per JKR standards clause 4.2.4.3 (a). Furthermore the wheel tracking devices which simulates traffic condition to predict qualities of an HMA, in this case rutting susceptibility, yielded an average rut depth of 4.2mm.

Following the AASHTO T19 the Loose Unit Weights (LUW) and rodded unit weights (RUW) for the coarse aggregate (CA) and fine aggregate (FA) were found to be:

CA LUW = 13537.7 kg

CA RUW = 1513.4 kg

FA RUW = 1682.5 kg

And the control sieves for the combined blend are as follows:

Primary Control Sieve (PCS) = 0.22 * NMAS = 20 mm

Half Sieve (H.S.) = 0.5 * NMAS =10mm

Secondary Control Sieve (SCS) = 0.22 * PCS = 1.18 mm

Tertiary Control Sieve (TCS) = 0.22 * SCS = 0.15 mm

The mix is fine graded because majority of the material passes the PCS. The coarse aggregate is divided into the coarse portion of the coarse aggregate and the fine portion of the coarse aggregate. The coarse portion of the coarse aggregate is referred to as "plugger" sized particles because they are the larger particles in the coarse aggregate segment which can pack together relatively tightly. The fine portion of the coarse aggregate is referred to as "interceptor" sized particles. No particle within the fine portion of the coarse aggregate (interceptors) should be able to fit within the voids created by the coarse portion of the coarse aggregate (pluggers). Thus interceptor sized particles within the coarse aggregate spread out the pluggers in the coarse aggregate, preventing them from packing as tightly together and creating more void space. The ratio of the percent "interceptors" to the percent of "pluggers" in the coarse aggregate is defined as the CA ratio which is as follows.

$$\text{CA Ratio} = \frac{(\%\text{ Passing Half Sieve} - \%\text{ Passing PCS})}{(100\% - \%\text{ Passing Half Sieve})}$$

CA Ratio = 0.153 [segregation susceptibility]

As the CA ratio of an aggregate blend decreases below 1.0, fewer interceptors are available to limit the compaction of larger coarse aggregate particles, so compaction of the fine aggregate increases. At a CA ratio less than 0.40, the resulting asphalt mixture may become susceptible to segregation.

$$FA_c = \frac{\%\ \text{Passing SCS}}{\%\ \text{Passing PCS}}$$

Fine Aggregate coarse portion ratio, (FA_c) = 0.7 [possibility of tendering in mix]

As this ratio increases, the fine aggregate in the overall blend packs together with increasing density, due to the increased volume of the fine portion of the fine aggregate. It is generally desirable to have an FA_c ratio in the range of 0.35 - 0.50, because at levels higher than 0.50, the excessive amount of the fine portion of the fine aggregate may lend to a tender mix which can easily become over-compacted in the field and result in a pavement with poor durability.

$$FA_f = \frac{\%\ \text{Passing TCS}}{\%\ \text{Passing SCS}}$$

Fine Aggregate fine portion ratio, (FA_f) = 0.192 [may be difficult to compact]

Similar to the FA_c ratio, it is desirable to have values in the range of 0.35 - 0.50 for the FA_f ratio, in order to prevent overfilling of the voids created by the coarse fraction of the fine portion of the fine aggregate.

Blending of aggregates

The blending of aggregates volumetrically from stockpile requires step 6 of the methodology which is as follows:

For CA, the voids created in the LUW condition

The CA chosen unit weight (CUW) is 89% because the combined blend is a fine-grained (F-G) mix therefore the weight per unit volume contributed by the CA's = 1353.7 kg/m^3 therefore weight contributed by the CA's = 1353.7 kg

The voids in the CA at the CUW condition i.e. 89% LUW is as follows

CUW condition = 89% CA LUW = 89% of 1353.7 kg/m^3

CA Gsb = 2.56

Solid Volume = 1204.8/ (2.56 * 1000) = 0.471m^3

Voids Volume = 1 m^3 - 0.471 m^3 = 0.529m^3

Voids = 52.9%

The weight per volume of FA required for filling the CA voids at the FA RUW:

FA RUW = 1682.5 kg/m^3

FA Mass = 0.529 m^3 * 1685kg/ m^3 = 890.04 kg

The percentages of CA and FA by weight

CA = 1204.8 kg

FA = 890.04 kg

Total = 2094.24 kg

%CA = (1204.8 kg/2094.24kg) * 100 = 57.5%

%FA = (890.04/2094.84) * 100 = 42.5%

The percentage of "opposite" sized material in each stockpile

CA = 57.5% * 0.1% = 0.06% FA in CA stockpile

FA = 42.5 * 0% = 0% CA in FA stockpile

The stockpile percentage correction for opposite sized material

CA = 57.5 + 0.06 – 0 = 57.56%

FA = 42.5 + 0 – 0.06 = 42.44%

The material passing the 0.075mm sieve contributed by the CA's and FA's

0.075mm contribution from CA = 57.56% * 0% = 0%

0.075mm contribution from FA = 42.44% * 1.4% = 0.59%

Total 0.075mm from CA and FA = 0% + 0.59% = 0.59%

The percentage mineral filler (MF) needed to achieve the total material passing the 0.075mm sieve desired:

Amount desired in final blend = 8%

Amount needed from MF = 8% - 0.59% = 7.41%

Amount of MF needed to contribute 7.41% = 7.41%/80% = 9.26%

The final aggregate percentage by weight:

Only the FA percentage is revised to account for MF being added

FA = 42.44 – 9.26 = 33.18%

Final aggregate percentage by weight =

CA = 57.56

FA = 33.18

MF = 9.26

Table 4.1.9: The new control sieves for the 20 mm NMAS aggregate

		% passing					
sieve size	coarse	fine	filler	Blend	min	max	
28	100	100	100	100	100	100	
20	99.4	100	100	99.75	76	100	$NMAS_{New}$
14	51.45	100	100	79.61	64	89	
10	13.35	100	100	63.61	56	81	
5	0.1	100	100	58.04	46	71	
3.35	0	98.6	100	57.3	32	58	HS_{New}
1.18	0	65.2	100	40.6	20	42	PCS_{New}
0.425	0	18.6	100	17.3	12	28	SCS_{New}
0.15	0	1.4	100	8.7	6	16	
0.075	0	1.4	80	7.1	4	8	TCS_{New}

The new control sieves yield new final aggregate percentages by weight when a CA CUW of 100% and those aggregate percentages are:

CA = 75.9
FA = 14.52
MF = 9.58

From these new final aggregate blends (new blend) the Bailey method ratios are in the required ranges except for the CA ratio.

New CA Ratio = 0.4 (increased by 0.25)
New FA_c Ratio = 0.43 (decreased by 0.2)
New FA_f Ratio = 0.41 (increased by 0.22)

Compared to the initial ratios this suggests that we have

- decreased the susceptibility to tenderizing
- Require less effort to compact the mix
- Decrease the segregation susceptibility

Evaluation and adjustment of trial aggregate blends is a trial and error undertaking that ultimately will put the CA Ratio, FA_C Ratio and FA_f Ratio in acceptable or recommended bailey method ranges whereby from this point the marshal mix design and also the wheel tracking test should be executed for the sole purpose of analyzing compactibility and susceptibility to rutting to compare of the optimized mixes.

Although so far a procedure for systematically altering the volumetric properties of an asphalt mix is provided by the Bailey method we are yet to see the justification in terms of significant performance improvement for the extra effort this method demands from the user.

CHAPTER 5

CONCLUSION

5.1 Conclusion

The objectives of the project which were to:

- Incorporate an analytical gradation design and evaluation method into the Marshal mix design procedure
- Analyze, theoretically, the compaction and performance characteristics of the resulting hot mix asphalt mixture(s)
- Design a new blend and compare the latter mix (Bailey method) to the JKR standard HMA.

Based on the findings of this research, it is recommended that 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. More research should be undertaken to further validate the Bailey method by using wheel tracking test devices to confirm any improvements in rut resistance.

Also further research into the use of the Bailey Method to improve HMA rutting performance appears to be feasible at this point. And as other agencies and academic institutions investigate the use of the Bailey Method and gain experience with the use of this procedure, refinements will be made that enable to Bailey Method to more consistently and significantly improve the rutting performance of HMA. If this does not turn out to be the case, then further research into the use of the Bailey Method may not be justified. On the other hand, research into the development of a simplified procedure to alter mixture volumetric properties may be well warranted. A systematic, rational approach to the modification of mixture volumetrics could provide a very valuable enhancement to the Superpave Volumetric Design Procedure. Such a procedure could utilize the principles of aggregate packing that are the basis of the Bailey Method procedure.

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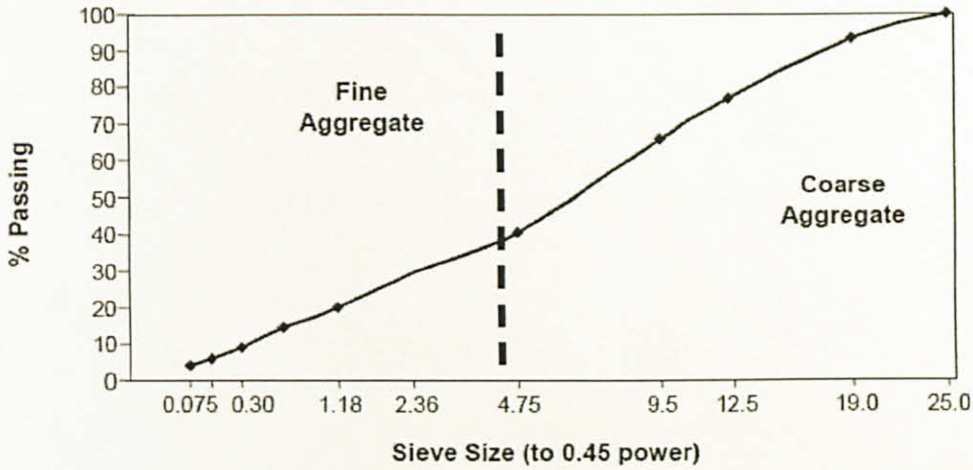
APPENDICES

Appendix I

The following figure, adopted from TRB (2002), shows an **example of break between coarse and fine aggregate for 19.0 NMPS mixture**. Whereby the Primary Control Sieve is at 0.22 * NMPS or NMAS 19 mm and the closest sieve is 4.75 mm.



And that The value of 0.22 used in the control sieve equation was determined from a two- (2-D) and three-dimensional (3-D) analysis of the packing of different shaped particles. The 2-D analysis of the combination of particles shows that the particle diameter ratio ranges from 0.155 (all round) to 0.289 (all flat) with an average value of 0.22 (*1,2,3,4*). The 3-D analysis of the combination of particles gives a similar result with the particle diameter ratio ranging from 0.15 (hexagonal close-packed spheres) to 0.42 (cubical packing of spheres) (*5,6,7*). In addition, research on particle packing distinctly shows that the packing of particles follows different models when the characteristic diameter is above or below 0.22 ratio (*8,9,10,11*). While 0.22 may not be exactly correct for every asphalt mixture, the analysis of gradation is not affected if the value ranges from 0.18 to 0.28. The 0.22 factor is the average condition of many different packing configurations.

Appendix II

TABLE 1 Recommended Ranges of Aggregate Ratios

	NMPS, mm					
	37.5	25.0	19.0	12.5	9.5	4.75
CA Ratio	0.80–0.95	0.70–0.85	0.60–0.75	0.50–0.65	0.40–0.55	0.30–0.45
FA_c Ratio	0.35–0.50	0.35–0.50	0.35–0.50	0.35–0.50	0.35–0.50	0.35–0.50
FA_f Ratio	0.35–0.50	0.35–0.50	0.35–0.50	0.35–0.50	0.35–0.50	0.35–0.50

NOTE: FA_c = fine aggregate coarse; FA_f = fine aggregate fine. These ranges provide a starting point where no prior experience exists for a given set of aggregates. If the designer has acceptable existing designs, they should be evaluated to determine a narrower range to target for future designs (see Evaluating Existing Mixture Designs with the Bailey Method).

When the aggregate ratios fall below their ranges the mix tends to segregate and when they fall above their ranges the mix tends to require more compactive effort.

TABLE 2 Control Sieves for Various Asphalt Mixes

	NMPS, mm					
	37.5	25.0	19.0	12.5	9.5	4.75
Half Sieve	19.0	12.5	9.5	**	4.75	2.36
PCS	9.5	4.75	4.75	2.36	2.36	1.18
SCS	2.36	1.18	1.18	0.60	0.60	0.30
TCS	0.60	0.30	0.30	0.150	0.150	0.075

** The nearest "typical" half sieve for a 12.5-mm NMPS mixture is the 4.75 mm. However, the 6.25 mm sieve actually serves as the breakpoint. Interpolating the percent passing value for the 6.25-mm sieve for use in the CA Ratio will provide a more representative ratio value.

Appendix III

TABLE 4 Fine-Graded Mixture Control Sieves

	NMPS, mm					
	37.5	25.0	19.0	12.5	9.5	4.75
Original PCS	9.5	4.75	4.75	2.36	2.36	1.18
New Half Sieve	4.75	2.36	2.36	1.18	1.18	0.60
New PCS	2.36	1.18	1.18	0.60	0.60	0.30
New SCS	0.60	0.30	0.30	0.150	0.150	0.075
New TCS	0.150	0.075	0.075	—	—	—

TABLE 5 Aggregate Ratios for the Adjusted Blend for Fine-Graded Mixtures

NMPS, mm	Ratio		
	CA	FA_c	FA_f
37.5	$\frac{4.75-2.36}{100\%-4.75}$	$\frac{0.60}{2.36}$	$\frac{0.150}{0.60}$
25.0	$\frac{2.36-1.18}{100\%-2.36}$	$\frac{0.30}{1.18}$	$\frac{0.075}{0.30}$
19.0	$\frac{2.36-1.18}{100\%-2.36}$	$\frac{0.30}{1.18}$	$\frac{0.075}{0.30}$
12.5	$\frac{1.18-0.60}{100\%-1.18}$	$\frac{0.150}{0.60}$	**
9.5	$\frac{1.18-0.60}{100\%-1.18}$	$\frac{0.150}{0.60}$	**
4.75	$\frac{0.60-0.30}{100\%-0.60}$	$\frac{0.075}{0.30}$	**

** For these mixes, only the new CA and FA_c Ratios can be determined.