AGGREGATE PACKING CHARACTERISTICS OF GOOD AND POOR PERFORMING ASPHALT MIXES

E. Denneman, B.M.J.A. Verhaeghe *, E. S. Sadzik **

CSIR, PO Box 395 Pretoria, 0001, South Africa, edenneman@csir.co.za
*CSIR, PO Box 395 Pretoria, 0001, South Africa, bverhaeg@csir.co.za
**GDPTRW, Private bag X3, 0039, South Africa elzbieta.sadzik@gauteng.gov.za

ABSTRACT

The aggregate structure of the compacted mix is a determining factor for the performance of Hot-Mix Asphalt (HMA). In this paper, the grading characteristics of good and poor performing HMA mixes are explored using the concepts of the Bailey method and related techniques for determining the porosity of the Dominant Aggregate Size Range (DASR) and the permeability characteristics of the mix. The aim is to assess the potential benefits of these new gradation analysis techniques for HMA performance in South Africa. The aggregate gradation of past mix designs, for which the field performance is known, are analysed and discussed in the paper. Typical properties of the aggregate structures of good and poor performing medium continuously graded asphalt (ACM) mixes are identified. The primary differences between the grading of the studied good and poor performing mixes lie in the grading of the coarser aggregate. While the poor performing mixes are coarser according to the classical definition, the good performers have a more voluminous DASR. The paper concludes that the grading analysis concepts allow the design engineer new insights into the structure of aggregates. The principles can be used to develop more specific guidelines for aggregate structure selection.

1. INTRODUCTION

This paper builds on the findings of a forensic investigation into the performance of Hot-Mix Asphalt (HMA) in South Africa (Denneman and Van Assen, 2006). In the forensic investigation, five HMA surfacings were subjected to a detailed investigation in an effort to identify typical characteristics of good and poor performing mixes. As part of the investigation, the mix designs of the HMA wearing courses were analysed using the Bailey method for gradation selection, as described in Vavrik et al (2001). The results point to a correlation between field performance of HMA and the theoretical insight into the characteristics of the mixes offered by the Bailey method. A guideline for the gradation selection for low-permeable, durable mixes by Khosla and Sadasivam (2005), which uses Bailey method principles, was also found to provide some insight in the characteristics of the investigated mixes. The findings of the investigation suggest that the performance of HMA in South Africa could benefit from the new insights in aggregate packing allowed by the Bailey method. The objective of this paper is therefore to evaluate the potential of new methods of gradation selection for improving HMA performance. The findings in the paper are based on analysis of a larger data set than the one used in the forensic investigation. The aggregate structure of a number of historical mix designs, for which the performance is known, is analysed using the concepts of the Bailey method, as well as the guideline developed by Khosla and Sadasivam (2005), and also according to the principles of Dominant Aggregate Size Range (DASR) introduced by Roque et al (2006).

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2. THEORETICAL FRAMEWORK

The structure of the aggregate skeleton is closely related to the rutting and fatigue characteristics, as well as the permeability, durability and compactability of HMA (Roque et al, 2006). The resistance against permanent deformation and the fatigue life of asphalt are improved by coarse aggregate interlock. While, on the other hand a dominant coarse aggregate portion can decrease the workability of the mix. Permeability and durability are closely related to the shape of the grading curve. Understanding the interaction between aggregate size fractions and mix performance will allow further advancements in HMA design. The next sections discuss the background and the concepts of the three methods used in this paper for the evaluation of HMA gradings.

2.1 The Bailey method

The Bailey method was originally developed to improve the rut resistance of HMA mixes. Bailey's method is not meant to be a complete design method for HMA mixes. Rather it allows the engineer to assess whether coarse aggregate interlock will exist in the mix (Vavrik et al, 2002). The method can also be used to assess the impact that changes in gradation will have on Voids in Mineral Aggregate (VMA).

The interim guidelines for the design of hot-mix asphalt in South Africa (Taute et al, 2001), define the coarse aggregate fraction as the material retained on the 4.75 mm sieve. This division between coarse and fine aggregate is independent of the distribution of stone size in the mix. The Bailey method uses a different approach to what constitutes the coarse and fine fraction in a blend. According to the method the division between coarse and fine aggregate depends on the nominal maximum particle size (NMPS) of the mix.

Vavrik et al (2002: p4) define coarse aggregate, under the Bailey method, as: Large Aggregate particles that when placed in a unit volume create voids, and fine aggregate as: Aggregate particles that can fill the voids created by the coarse aggregate in the mixture.

The method divides the aggregate into different fractions using specific sieve sizes. The Primary Control Sieve (PCS) forms the dividing line between coarse and fine aggregate. The coarse aggregate is further divided into large and small particle portions by the Half Sieve. On the other side of the PCS the fine aggregate is divided in a coarse and a fine fraction by means of the Secondary Control Sieve (SCS). Finally the aggregate smaller than the SCS is once again divided into a coarse and a fine portion by means of the Tertiary Control Sieve (TCS). The control sieves for different NMPS sizes were selected based on a spatial analysis of aggregate packing. In theory, the particles just passing the PCS will fit the voids left by the particles just passing the NMPS, and the particles just passing the SCS will fit the voids left by the particles just passing the PCS, etc. The Half sieve is used to analyze the coarse aggregate in more detail. Coarse aggregate passing the half sieve is too large to fit in the voids left by the larger particles and will therefore spread those particles apart.

The ratios of the different portions between control sieves relate to the shape of the grading curve and the structure of the aggregate skeleton. The coarse aggregate ratio, or CA ratio, provides an indication of the packing of the coarse aggregate. The percentage of voids in mineral aggregate (VMA) is largely determined by the value of the CA ratio. The VMA increases as the CA ratio increases.

The packing of the fine aggregate, which fills the voids in the coarse aggregate, is in turn determined by the ability of the fine portion of the fine aggregate to fill the voids left by the coarse portion of the fine aggregate, this ratio is known as the FA_c ratio.

The last ratio to be determined is the fine portion of fine aggregate ratio, or FA_f ratio. The FA_f ratio provides insight in the packing of the very fine aggregate. This ratio provides an indication of how well the voids in the finest portion of the aggregate will be filled. The ratios are defined by the following equations:

$$\text{CA ratio} = \frac{\text{Percentage passing half sieve} - \text{Percentage passing PCS}}{100 - \text{Percentage passing half sieve}} \quad (1)$$

$$\text{FA}_\text{c} \text{ ratio} = \frac{\text{Percentage passing SCS}}{\text{Percentage passing PCS}} \quad (2)$$

$$FA_f \; ratio = \frac{\text{Percentage passing TCS}}{\text{Percentage passing SCS}} \quad (3)$$

The Bailey method can be used during the design phase to ensure that coarse aggregate interlock is present in the mixture. Coarse aggregate interlock occurs when the unit weight of coarse aggregate in the compacted mixture is around 100 per cent of the unit weight of that aggregate in a loose state. This can, however not be determined using the conventional parameters of mix design. The rodded and loose unit weights of the prospected aggregate material need to be determined. As this paper relied on data from existing mixes, it was not possible to assess whether aggregate interlock was achieved using the Bailey method.

2.2 Dominant Aggregate Size Range (DASR)

In a recent report, Roque et al (2006) used the insights of the Bailey method in developing a method to theoretically assess whether coarse aggregate interlock exists based on aggregate grading information only. The method applies the concept of porosity to determine whether the volume of particles retained on a certain sieve size, or on a range of interacting contiguous sieve sizes, is large enough to form a stable skeleton. The porosity, which is defined as the volume of voids in the selected aggregate portion, divided by the total volume of the mix, must be no greater than 50 per cent, for the particles of the portion to be in contact. Roque et al propose that the 50 per cent porosity of coarse aggregate requirement is equal to the 100% loose unit weight requirement for coarse aggregate interlock, used in the Bailey method. An important difference with the Bailey method is that the loose and rodded unit weights of the aggregate do not need to be determined to calculate the porosity. The porosity can be calculated for a single aggregate size or for a range of interacting sizes. It is proposed that the only mix parameters required for the calculation of aggregate porosity, are the grading of the aggregate and the VMA of the mix. The equations used by Roque et al (2006) to determine the porosity of an aggregate fraction can be rewritten as follows:

$$\eta_{(2.36\text{-}4.75)} = \frac{\left(\frac{PP_{2.36}}{100}\left(V_{tm} - VMA\right) + VMA\right)}{\left(\frac{PP_{4.75}}{100}\left(V_{tm} - VMA\right) + VMA\right)} \quad (4)$$

where:

$\eta_{(2.36-4.75)}$ = Porosity of fraction passing the 4.75 mm sieve, but retained on the 2.36 sieve)
$PP_{2.36}$ = Percentage of particles passing (2.36 mm) sieve
V_{tm} = Total volume of mix

VMA = Voids in Mineral Aggregate

Except in the case of open graded mixes, a stable aggregate skeleton in HMA will generally consist of more than a single particle size. The interacting aggregates sizes that together form the aggregate skeleton was named the Dominant Aggregate Size Range (DASR) by Roque et al (2006). Particles larger than the DASR are spread too far apart to contribute much to the strength of the skeleton, particles smaller than the DASR fill the voids in the DASR without forming part of the load bearing structure.

Based on spatial analysis of different aggregate sizes Roque et al (2006) found that when the proportion of particles retained on two consecutive sieves is less than 70/30 (large/small), the particles interact to form a skeleton. The DASR is the set of contiguous, interactive aggregate portions (larger than 1.18 mm) that, when taken together, have the lowest porosity.

2.3 Permeability

The performance of an HMA surfacing is related to the void structure in the mix. Large interconnected voids may lead to permeable mixes. On the other hand, a lack of voids may lead to poor rut resistance. Permeable HMA layers allow the penetration of air and water, which can result in premature stripping and/or binder ageing. The permeability of the mix is not only dependent on the volume of voids in the mix, but also on the grading of the aggregate and the packing of particles. Distinct differences in permeability may exist between mixes with identical void content, depending on the interconnectivity of voids. A study by Mallick et al (2003) indicates that permeability is also related to the thickness of the HMA layer. Thin layers, widely applied in South Africa, are more likely to be permeable than thick layers.

Using the principles of the Bailey method, Khosla and Sadasivam (2005) produced a guideline to design mixes with a low permeability, without sacrificing rut resistance. Using a model of the aggregate structure of sample mixes, based on the concepts of the Bailey method, it was found that, for 9.5 mm NMPS and 12.5 mm NMPS, permeability depends mostly on the aggregates retained on the 4.75 mm, the 2.36 mm and the 1.18 mm sieves. The guideline provides recommended ranges for the volume of aggregate size fractions to ensure low-permeability.

3. AGGREGATE GRADATION AND FIELD PERFORMANCE

The mix designs evaluated in this paper formed part of a 2005 preliminary forensic investigation into the performance of HMA surfacings by Verhaeghe (2005). The performance of these mixes was known from the Gauteng Provincial Pavement Management System (PMS). The data available from the PMS contain information from visual inspections. The reported distress, visible at the surface, however, is not necessarily due to failure of the HMA surfacing. Rutting may be caused by shear deformation in the deeper pavement layers, and cracking of the HMA wearing course may originate from stabilized substrate. Moreover, the performance of HMA depends on many factors besides grading (e.g. binder type, particle texture and strength, etc.). The objective of this paper is therefore, to look at overall trends, linking grading to performance, rather than to analyze individual mixes. Performance and mix design data of 17 continuously graded medium (ACM) mixes were used for this paper. The aggregate gradings of good and fair performing ACM designs are shown in Table 1 and in Figure 1. The gradings of the poor performers are shown in Table 2 and in Figure 2. Note that ACM mixes G8 and G9 are identical although they were used on different roads. The same goes for ACM P5 and P6. Some of the other mixes (P2 & G6 and G1, G4 & P7) have similar grading and void characteristics.

Table 1: Gradings and condition of good/fair performing ACM mixes (NMPS 9.5 mm)

Sieve size [mm]	**ACM G1**	**ACM G2**	**ACM G3**	**ACM G4**	**ACM G5**	**ACM G6**	**ACM G7**	**ACM G8**	**ACM G9**
13.2	100	100	100	100	100	100	100	100	100
9.5	99	98	98	98	99	95	99	95	95
6.7	79	89	79	79	86	74	81	80	80
4.75	64	73	66	64	72	58	68	70	70
2.36	42	48	47	42	48	41	47	50	50
1.18	29	32	34	29	33	31	34	35	35
0.6	23	21	24	23	24	23	25	24	24
0.3	19	15	17	19	18	16	17	15	15
0.15	13	9	10	13	11	10	10	9	9
0.075	5.8	5.7	6.2	5.8	6.6	6.2	5.8	6	6
VMA	15.3	15.7	16.9	15.3	16.8	15.7	16.3	16.9	16.9
Performance	Good	Fair	Fair	Fair/ Good	Good	Fair	Fair	Fair	Fair
Distress	Crack	Crack	Crack	Crack	None	Rut	Rut	Crack	Crack

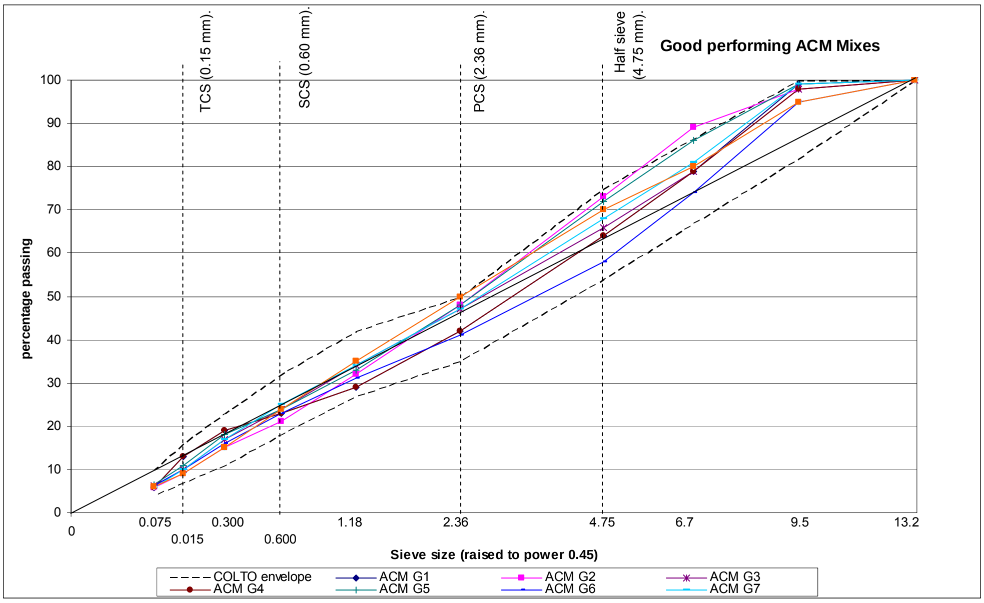

Figure 1: Gradings of good performing ACM mixes

Table 2: Gradings and condition of poor performing ACM mixes (NMPS = 9.5 mm)

Sieve size [mm]	**ACM P1**	**ACM P2**	**ACM P3**	**ACM P4**	**ACM P5**	**ACM P6**	**ACM P7**
13.2	100	100	100	100	100	100	100
9.5	99	95	93	97	97	97	99
6.7	85	74	75	76	74	74	79
4.75	70	58	57	60	64	64	64
2.36	50	41	48	47	49	49	42
1.18	33	31	36	35	35	35	29
0.6	22	23	27	26	24	24	23
0.3	17	16	20	20	17	17	19
0.15	9	10	13	12	11	9	13
0.075	4.7	6.2	6.6	8	5.2	5.2	5.8
VMA	16.4	15.8	15.9	15.8	16.6	16.6	15.3
Performance	Poor	Poor	Poor	Poor	Poor	Poor	Poor
Distress	Crack/ Rut	Crack/ Rut	Crack	Rut	Crack/ Rut	Crack	Crack/ Rut

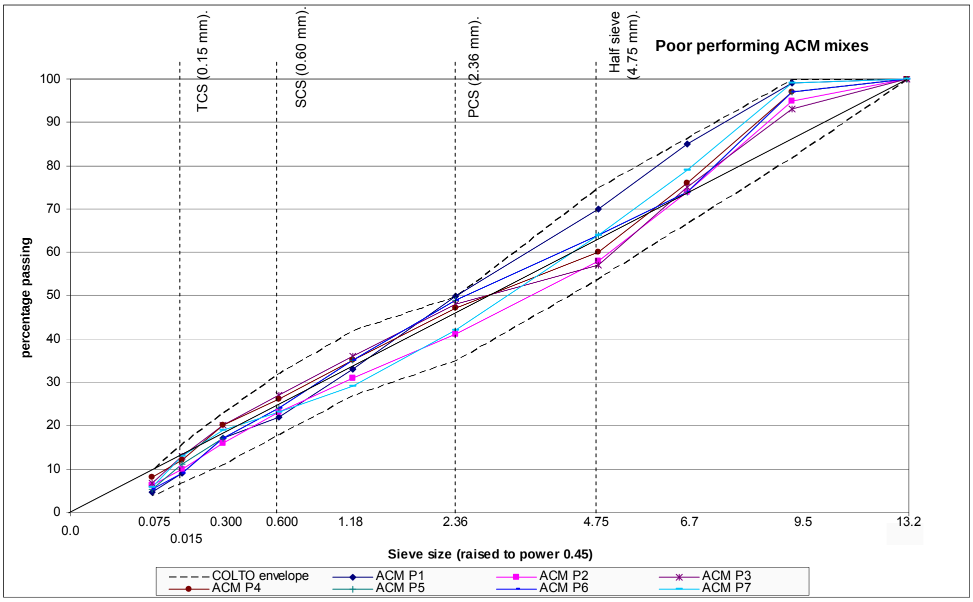

Figure 2: gradings of poor performing ACM mixes

3.1 Bailey method aggregate ratios for studied mixes

The Bailey ratios that provide insight in the packing of the different aggregate portions were calculated, and are shown in Table 3 for the good performing mixes and in Table 4 for poor performing mixes. The empirically-determined recommended ranges for aggregate ratios as reported by Pine (2006) are also included in the tables. The shape of the grading curves as well as the Bailey method ratios and the high percentage of aggregate passing the PCS, indicate that the ACM mixes studied in this paper are most probably fine graded mixes. Interlock of the coarse aggregate (>2.36 mm) does not occur in fine graded mixes. Therefore, the structure of the aggregate portion passing the PCS sieve was analyzed separately by re-defining the control sieves for this portion of aggregate. New CA and FA_c ratios were determined for the aggregate passing the PCS. However, these new ratios were excluded from the paper as there were no statistically significant differences between poor and good performers for these ratios and the ratios were generally within the recommended range.

Table 3: Bailey method aggregate ratios for good performing ACM mixes

	ACM G1	ACM G2	ACM G3	ACM G4	ACM G5	ACM G6	ACM G7	ACM G8	ACM G9	Avg	Recom-mended
CA ratio	0.61	0.93	0.56	0.61	0.86	0.40	0.66	0.67	0.67	0.66	0.40-0.55
FA_c ratio	0.55	0.44	0.51	0.55	0.50	0.56	0.53	0.48	0.48	0.51	0.35-0.50
FA_f ratio	0.57	0.43	0.42	0.57	0.46	0.43	0.40	0.38	0.38	0.45	0.35-0.50

Table 4: Bailey method aggregate ratios for poor performing mixes

	ACM P1	ACM P2	ACM P3	ACM P4	ACM P5	ACM P6	ACM P7	Avg	Recom-mended
CA ratio	0.67	0.40	0.21	0.33	0.42	0.42	0.61	0.44	0.40-0.55
FA_c ratio	0.44	0.56	0.56	0.55	0.49	0.49	0.55	0.52	0.35-0.50
FA_f ratio	0.41	0.43	0.48	0.46	0.46	0.38	0.57	0.46	0.35-0.50

3.1.1 Coarse Aggregate ratios (CA ratios)

Figure 3 shows a plot of the original coarse aggregate ratios for the ACM mixes. The blue bar represents the recommended range for the CA ratio of 9.5 mm NMPS mixes. There is a statistical difference ($\alpha = 0.05$) between the average CA ratio for the good performing mixes, which is 0.66, and the average CA ratio for poor performing mixes, which is 0.44.

The difference in the CA ratio is caused by the fact that the poor performing mixes have a larger fraction of particles passing the 9.5 mm sieve but retained on the 6.7 mm sieve, while the good performing mixes have a larger fraction of particles passing the 4.75 mm sieve but retained on the 2.36 mm sieve. The importance of this for performance will become apparent in the discussion of the DASR later in this paper.

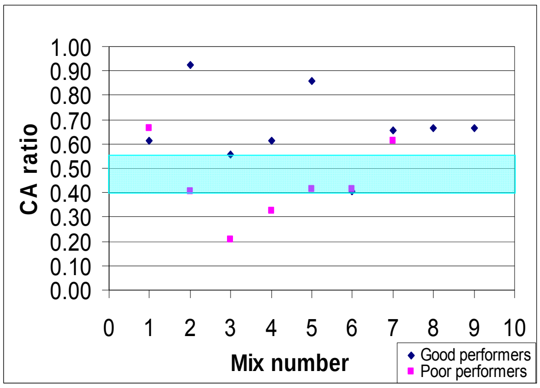

Figure 3: CA ratios for ACM mixes

All but one of the good performing mixes have original CA ratios above the recommended range. A higher than recommended CA ratio indicates an unbalanced and less continuous coarse aggregate structure. Coarse graded mixes with a high CA ratio may be difficult to compact. This does not apply however to the studied fine graded mixes. The continuity of coarse aggregate portion may also be of less importance since in a fine graded mix the coarse aggregate does not contribute to the primary load bearing skeleton. For fine graded mixes the original coarse aggregate ratio does give an indication of segregation susceptibility. Although the mean of the original CA ratio for the poor performing mixes is 0.44, five of the mixes have ratios that are at the bottom of or below the recommended zone. Mixes with a low CA ratio are also known to have a tendency to segregate (Vavrik et al 2002).

3.1.2 Coarse portion of fine aggregate (FA_c)

The mean scores for the original FA_c ratio of the good and poor performing mixes lie close together and slightly above 0.50; the top of the recommended range for coarse graded mixes. For coarse graded mixes a higher than recommended FA_c ratio indicates that the grading curve approaches the Superpave restricted zone and the mix could potentially be tender. The restricted zone however, is only relevant when high volumes of natural sands are used, which is generally not the case in South Africa. For fine graded mixes an original FA_c ratio of more than 0.45 typically indicates that fine fraction (the material passing the original PCS) is also fine graded, i.e. there is no stable aggregate skeleton formed by the coarser particles in the fine aggregate fraction. Almost all of the studied mixes have an FA_c of more than 0.45. The means of the FA_c ratios for the good and the poor performers lie close together, and can therefore not be linked to difference in performance of the studied mixes.

3.1.3 Fine portion of fine aggregate (FA_f)

The fine portion of fine aggregate ratio provides insight in the packing of the finest aggregate that fills the voids left by the other aggregate fractions. The VMA increases as the FA_f decreases. There is no significant difference between the mean of this ratio for the good and the poor performing mixes. The original FA_f is close to 0.45, which is a further indication that the fraction passing the original PCS is also fine graded, which entails that the voids left by the coarse portion of finest aggregate are overfilled and the very finest aggregate takes part in load dissipation.

3.2 Aggregate fraction porosity for studied mixes

Tables 5 and 6 show the porosity values calculated for the ACM mixes. The top of the tables show the porosities of single sieve size fractions. The porosities of the single size fractions are all above 50 per cent and therefore none of the mixes has a stable aggregate skeleton consisting of a single aggregate size. The interaction analysis of the different coarse aggregate sizes (> 1.18 mm) is shown in Figure 4. Analysis reveals that for all mixes included in this study there is interaction of all aggregate retained on 1.18 mm sieve and passing the 9.5 mm sieve. The DASR is determined by calculating the porosity for different combinations of interacting contiguous sizes; the results are shown in the bottom parts of Tables 5 and 6. The DASR for all mixes is formed by the whole range of aggregate sizes passing the 9.5 mm sieve and retained on the 1.18 mm sieve. The porosity for this range is smaller than 50 per cent and therefore forms a stable aggregate skeleton. From the table it can also be seen that the interacting particles larger than 4.75 or even 2.36 mm do not have enough volume to form such a skeleton. The mixes are therefore not coarse graded according to the classic definition (>4.75 mm), or according to the Bailey definition of coarse for 9.5 mm NMPS mixes (>2.36 mm). This finding confirms the assumption made in Section 3.1 that the mixes are most probably fine graded.

The good performing mixes have on average, less porous coarse fractions than the poor performing mixes. In other words, for the good performing mixes a larger portion of the total volume of aggregate forms part of the interacting sizes that form the DASR. This can be related back to the difference in CA ratio, the good performing mixes have more aggregate between the half sieve and PCS and that fraction constitutes a major part of the DASR.

Table 5: Aggregate portion porosity of good performing mixes

Aggregate Size (mm)	ACM G1	ACM G2	ACM G3	ACM G4	ACM G5	ACM G6	ACM G7	ACM G8	ACM G9	Average
9.5 - 13.2	99.2%	98.3%	98.3%	98.3%	99.2%	95.8%	99.2%	95.8%	95.8%	97.5%
6.7 – 9.5	82.9%	92.3%	83.9%	83.6%	89.1%	81.5%	84.8%	87.0%	87.0%	85.3%
4.75 – 6.7	84.5%	85.1%	86.9%	84.5%	86.8%	82.7%	87.1%	90.0%	90.0%	86.9%
2.36 – 4.75	**73.2%**	**72.7%**	**78.0%**	**73.2%**	**74.0%**	**77.8%**	**76.0%**	**77.9%**	**77.9%**	**76.4%**
1.18 - 2.36	78.4%	76.0%	80.7%	78.4%	78.0%	83.2%	80.4%	78.7%	78.7%	79.7%
1.18 - 6.7	48.5%	47.0%	54.7%	48.5%	50.1%	53.6%	53.2%	55.2%	55.2%	50.8%
2.36 - 9.5	51.3%	57.1%	56.9%	51.8%	57.2%	52.5%	56.1%	61.0%	61.0%	54.7%
1.18 - 9.5	**40.2%**	**43.4%**	**45.9%**	**40.5%**	**44.6%**	**43.7%**	**45.1%**	**46.0%**	**46.0%**	**43.9%**

Table 6: Aggregate portion porosity of poor performing mixes

Aggregate Size (mm)	ACM P1	ACM P2	ACM P3	ACM P4	ACM P5	ACM P6	ACM P7	Average
9.5 - 13.2	99.2%	95.8%	94.1%	97.5%	97.5%	97.5%	99.2%	97.2%
6.7 – 9.5	88.2%	81.5%	83.9%	81.9%	80.3%	80.3%	82.9%	82.7%
4.75 – 6.7	85.7%	82.7%	**80.8%**	83.1%	89.4%	89.4%	84.5%	85.1%
2.36 – 4.75	77.7%	**77.8%**	88.1%	83.5%	82.1%	82.1%	**73.2%**	80.7%
1.18 - 2.36	**75.6%**	83.3%	82.1%	**81.8%**	**79.7%**	**79.7%**	78.4%	**80.1%**
1.18 - 6.7	50.3%	53.6%	58.5%	56.7%	58.5%	58.5%	48.5%	54.9%
2.36 - 9.5	58.7%	52.5%	59.8%	56.8%	58.9%	58.9%	51.3%	56.7%
1.18 - 9.5	**44.4%**	**43.7%**	**49.1%**	**46.4%**	**47.0%**	**47.0%**	**40.2%**	**45.4%**

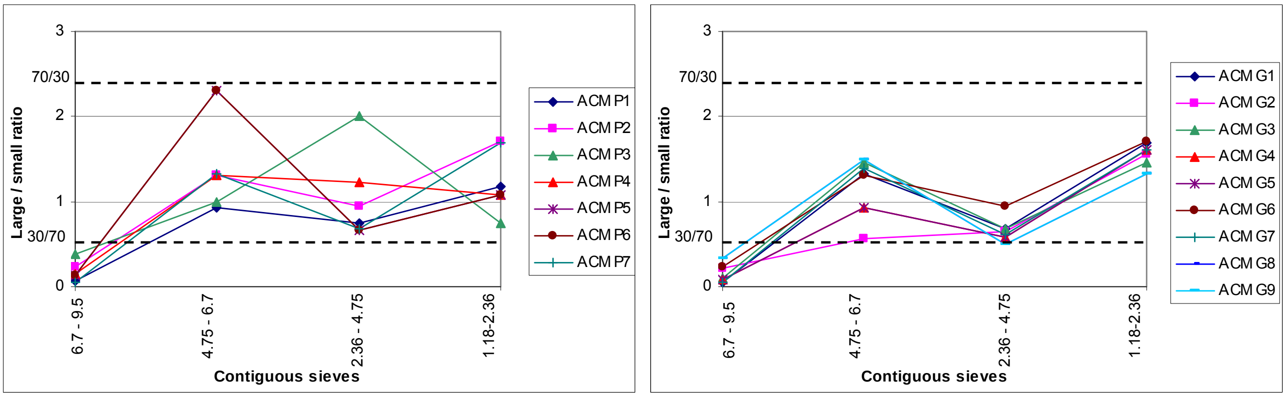

Figure 4: Interaction diagram mixes

3.3 Permeability characteristics of studied mixes

The guideline for low-permeability, durable mixes by Khosla and Sadasivam (2005) provides recommended ranges for the relative volume of key aggregate fractions important to the permeability of HMA mixes. The ranges pertain to the percentage passing (PP) certain sieves, and the per cent fraction (PF), that is the fraction retained on a sieve (passing the sieve directly above it) for certain sieves. Tables 7 and 8 show the permeability indicators for the ACM mixes. The column on the right contains the recommended values from the guideline.

According to the guideline, an “original” CA ratio of above 0.5 is an indicator of a low permeability mix. Most of the good performing mixes satisfy the criteria, most of the poor performing mixes do not.

According to the guideline, a characteristic of highly permeable 9.5 mm NMPS mixtures is a percent fraction of 2.36 mm particles of between 10 and 18 per cent. The values for many of the poor performing mixes fall in this range. The mean for the PF 2.36 mm for the good performing mixes is 21 per cent, while the mean value for the poor performing mixes lies at 16 per cent. The statistic probability that the true means differ is 95 per cent. This indicates that the good performing mixes have a larger amount of particles in the 2.36 mm to 4.75 mm range, as could be expected from the distributions of the “original” CA ratios.

The limit for the percentage passing the 1.18mm sieve is based on the SUPERPAVE restricted zone and is not relevant for South African mixes that typically do not contain natural sand.

Another requirement from the guideline is that the combined per cent fractions of the 2.36 mm and 1.18 mm sieves is higher than 35 per cent. The poor performers have a significantly (α= 0.05) lower combined fraction of 1.18 mm and 2.36 mm aggregate, which as discussed under the porosity section forms, part of the DASR.

Table 7: Permeability indicators for good performing mixes

Permeability Indicators	ACM G1	ACM G2	ACM G3	ACM G4	ACM G5	ACM G6	ACM G7	ACM G8	ACM G9	AVG.	Guideline 9.5 mm NMPS
CA ratio	0.61	0.93	0.56	0.61	0.86	0.40	0.66	0.67	0.67	0.66	> 0.5
PP 4.75 mm	64	73	66	64	72	58	68	70	70	67.2	60 – 67
PF 4.75 mm	35	25	32	34	27	37	31	25	25	30.1	23 – 30
PP 2.36 mm	42	48	47	42	48	41	47	50	50	46.1	32 – 47
PP 1.18 mm	29	32	34	29	33	31	34	35	35	32.4	< 30
PF 2.36 mm + PF 1.18 mm	35	41	32	35	39	27	34	35	35	34.8	> 35
Ratio PF 2.36/ PF 1.18	1.4	1.5	1.4	1.4	1.5	1.3	1.4	1.4	1.4	1.4	1.5 – 2.0

Table 8: Permeability indicators for poor performing mixes

Permeability Indicators	ACM P1	ACM P2	ACM P3	ACM P4	ACM P5	ACM P6	ACM P7	Avg.	Guideline 9.5 mm NMPS
CA ratio	0.67	0.40	0.21	0.33	0.42	0.42	0.61	0.44	> 0.5
PP 4.75 mm	70	58	57	60	64	64	64	62.4	60 - 67
PF 4.75 mm	29	37	36	37	33	33	35	34.3	23 – 30
PP 2.36 mm	50	41	48	47	49	49	42	46.6	32 – 47
PP 1.18 mm	33	31	36	35	35	35	29	33.4	< 30
PF 2.36 mm + PF 1.18 mm	37	27	21	25	29	29	35	29.0	> 35
Ratio PF 2.36/ PF 1.18	1.5	1.3	1.3	1.3	1.4	1.4	1.4	1.39	1.5 – 2.0

4. CONCLUSIONS

Aggregate grading is only one of the many parameters determining HMA performance. Nevertheless, the data presented in this paper show a direct correlation between the structure of aggregate fractions and field performance. The main conclusions from the analysis of the aggregate packing of sixteen fine graded ACM mixes with a 9.5 mm NMPS are:

- The differences in the grading of the poor and good performing mixes lie in the portions of the aggregate larger than 2.36 mm. Below the 2.36 mm sieve the average grading of the poor and good performers is similar. Even though the mixes studied in this paper are fine graded, the original CA ratio is a strong predictor of field performance. The poor performing mixes are coarser with more aggregate larger than 4.75 mm. This results in a lower CA ratio for these mixes. Both the Bailey method and the DASR porosity principles indicate that for fine graded mixes the coarsest aggregate simply floats in the finer aggregate and therefore does not form part of the stable aggregate skeleton that carries most of the load. A low CA ratio is also an indicator of segregation susceptibility. It is possible that the poor performance of some of the mixes was related to segregation problems.
- An advantage of the DASR porosity approach over the Bailey method, is that analysis is not limited to sets of predefined control sieves. Instead interaction of all contiguous aggregate sizes larger than 1.18 mm is investigated. Analysis of the porosity of the aggregate portions and determining the DASR porosity learns that the mixes are controlled by a skeleton formed by particles retained on the 1.18 mm sieve and passing the 9.5 mm sieve. This entails that much of the coarse aggregate that would be neglected under the Bailey method analysis of fine graded mixes does in fact form part of the skeleton.

- The porosity of the DASR of the good performing mixes is lower than that of the poor performing mixes, the DASR porosity value may provide an indication for performance. However, since all mixes have DASR porosity values of less than 50 per cent, all should have stable skeletons consisting of aggregate larger than 1.18 mm.
- The good performing mixes have a significantly less porous aggregate fraction passing the 6.7 mm sieve and retained on the 1.18 mm sieve, and the advantages of having a stable skeleton formed by a smaller range of aggregate sizes could be investigated.
- The grading of the aggregate passing the 4.75 mm sieve and retained on the 1.18 mm sieve result in a better score of the good performers in terms of the guideline for durable, low permeability mixes developed by Khosla and Sadasivam (2005). Since the aggregates of the good performing mixes are less porous for this particle size range, less permeability could be expected.
- Controlling permeability can help to prevent premature binder ageing. This is expected to become more important with the expected growth in the use of coarser mixes to combat permanent deformation.

The Bailey method and DASR porosity concepts allow the designer better insight in the relevance of the packing of different fractions for the overall performance of the mix. The Bailey aggregate ratios, although only intended as a guideline, provide a useful addition to mix design procedures. The assessment of coarse aggregate interlock during design, which is the primary objective of the Bailey method was not included in this paper. It is more than likely that local implementation of this particular feature of the Bailey method would yield additional benefits for mix performance. It needs to be mentioned however that a coarse graded mix does not necessarily exhibit better rut resistance (refer Kandhal & Cooley, 2002). It is more important to investigate the packing of different aggregate portions, for which the Bailey method principles can be used in combination with DASR porosity analysis.

Guidelines based on the Bailey method and DASR porosity concepts discussed in this paper would be a valuable addition to existing South African guidelines for the design of HMA. The concepts will be applied in analyzing the results of the HMA research project, which is currently in progress, with the aim to develop design guidelines for low permeability, durable, rut resistant, HMA mixes.

5. REFERENCES

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