RELATIONSHIP BETWEEN BAILEY AND DOMINANT AGGREGATE SIZE RANGE METHODS FOR OPTIMUM AGGREGATE PACKING AND PERMEABILITY LIMITATION

E HORAK*, H SEBAALY*[1], J MAINA*[1] AND S VARMA*

*Engineering /Technical staff of ANAS SpA, Doha, Qatar
[1] Department of Civil Engineering, University of Pretoria, Pretoria, South Africa

ABSTRACT

The Bailey method and the Dominant Aggregate Size Range (DASR) method were developed to optimize aggregate skeleton packing for enhancement of structural strength designs of Hot/Warm Mix Asphalt (HMA/WMA). These design support methods are not always properly correlated with each other. They aroften perceived as giving conflicting or confusing descriptions of the same aspects of the HMA/WMA. To help clarify and improve the correlation, the aggregate skeleton is broken into macro, midi and micro level aggregate subset skeletons to evaluate the contributions of various aggregate fraction ranges to structural strength of the mix. Rut resistance and fatigue cracking limitation are traditional design objectives of any HMA mix design. Permeability of HMA is linked with durability effects such as stripping. Permeability is however not directly controlled via the aggregate skeleton packing efficiency methods. The Bailey method, and more so the DASR method, show promise to understand this link or help to control permeability. The Bailey method is discussed as a reference by looking at new ratios and attempting to verify the aggregate skeleton packing in a logical fashion. The DASR principles of porosity are used to explain the impact of the numerator and denominator, particularly the new or rational Bailey ratios, in terms of porosity as separate and combined contiguous aggregate fraction ranges. The logical filling of voids of the macro, midi and micro aggregate skeleton subsets can thus be traced as well. These aggregate skeleton subsets combined or infilled, constitute the overall matrix of the aggregate mix. Data sets of published papers on this subject were reworked / re-analysed to help illustrate the concepts and trends observable for improved aggregate packing as well as limiting permeability. New improved criteria for permeability control are also presented in DASR and rational Bailey ratio terms to help optimize the design outcome.

1. INTRODUCTION

The aggregate volume in a Hot Mix Asphalt (HMA) or Warm Mix Asphalt (WMA) makes up 85% on average of the total asphalt mix volume. If measured by mass this is in fact up to 95%. Therefore, the aggregate packing and particle orientation are expected to be able to carry the bulk of the traffic load effectively. Even though the focus here is on gradation related methods to improve the aggregate packing efficiency it is acknowledged that aggregate shape, surface texture, type and amount of compactive effort and the layer thickness are all factors that also have an influence. The aggregate gradation must be designed to provide a strong stone skeleton to resist repeated load applications and resist rutting or fatigue cracking. The Bailey method (Vavrik et al, 2001) as well as the DASR (Kim et al, 2006, 2009; Roque et al, 2006) were developed to help optimize the aggregate packing of gradings used in HMA/WMA. The main aim of both methods is to enhance the understanding of the complexities of designing or creating such an effective load bearing aggregate skeleton.

DASR and Bailey principles are based on volumetric packing optimization, but their calculations of indices or ratios follow different approaches with different concepts associated with describing the desired optimized aggregate packing. The Bailey method, for example, identifies large and fine aggregate fraction ranges based on an established volumetric ratio. The method uses various ratios of coarse, fine and very fine aggregate to develop an optimum grading using trial and error methods. The DASR method, on the other hand, makes use of porosity, as a fundamental property, to evaluate the packing efficiency. In this regard, the DASR method is theoretically more fundamental in explaining the issues with regards to packing of the aggregate grading. Porosity relates not only the packing efficiency, but also the voids in the mix and, therefore, also more directly related to permeability of the mix.

In-place density and the derived voids in the HMA/WMA are, generally, the main parameters measured in quality control and quality assurance (QC/QA) procedures of constructed asphalt layers. Density is related to HMA/WMA permeability as it is also linked to the voids in the mix. Sadasivam and Khosla (2006) quote other researchers stating that permeability gives a better measure of durability than density of an HMA/WMA pavement layer. Typically, low densities achieved with an HMA/WMA mix tend to have higher %ages of air voids. When these air voids are interconnected, they allow water to flow through the voids. Higher air voids content (%) increases the probability that the voids can in effect be interconnected (Mallick, et al. 1999). Porosity is obviously linked to air voids content, but permeability is linked to the interconnectedness of the air voids.

The focus in normal mix design procedures is on the design objective of resisting rut and fatigue cracking. Durability (e.g. stripping) is directly linked to permeability of the HMA and should also form part of these primary design objectives regarding rut and fatigue cracking.

The Bailey and DASR methods have not been properly correlated. They are often perceived as giving conflicting or confusing descriptions of the same aspects of the HMA/WMA. Therefore, a clearer description and link between the two methods are needed. This paper reviews the Bailey method as a reference by looking at new ratios and attempting to verify the aggregate skeleton and packing in a logical fashion. The DASR principles of porosity are used to explain the impact of the numerator and denominator of the Bailey ratios in terms of porosity as well as the logical filling of voids of the macro (large and oversized aggregate fractions), midi (middle range of large aggregate fractions) and micro (the fines range) aggregate skeleton subsets and voids associated with these aggregate packing subsets. These aggregate skeleton subsets combined or infilled constitute the overall matrix of the aggregate mix. Data sets of published papers on this subject were reworked / re-analysed to help illustrate the concepts and trends observable for improved aggregate packing as well as limiting permeability.

2. LINKING BAILEY METHOD AND DASR WITH PERMEABILITY

2.1. Bailey Principles and DASR methods

The detail background of the Bailey method and that of the DASR method is not covered here. However, the gradation curve, which is the basis of both concepts is illustrated in **Figure 1** showing some of the key concepts. **Figure 1** is shown for a typical or most common densely graded HMA/WMA with Nominal Maximum Particle Size (NMPS) that would range from 9.5 mm to 12.5 mm.

The most common Bailey control sieve sizes indicated in **Figure 1** are:

NMPS as per Superpave definition,
Half Size (HS), where HS = 0.5 x NMPS,
Primary Control Sieve (PCS), where PCS = 0.22 x NMPS,
Secondary Control Sieve (SCS), where SCS = 0.22 x PCS and
Tertiary Control Sieve (TCS), where TCS = 0.22 x SCS.

The Bailey method defines aggregate fraction larger than the NMPS as **Oversize Aggregate**; in addition, the aggregate fractions larger than PCS as **Coarse Aggregate** and below PCS as **Fines**. The fines portion is at the Micro level of the combined or total aggregate skeleton structure. The large aggregate range, in the Bailey method, can be logically subdivided into the Midi range and Macro range of aggregate fractions as demarcated on the right-hand side of **Figure 1** with NMPS as the divider or control sieve. These additional definitions of aggregate ranges are proposed to enable better correlation between the Bailey method ratios and the DASR porosity concepts, which will become clearer when the DASR concepts are also described and discussed.

The aggregate skeleton can thus be described as consisting of macro, midi (middle) and micro skeleton sets that fit together like Russian Matryoshka nesting dolls. In **Figure *2***, this is illustrated by means of zooming-in on the voids of the three levels consecutively filled with smaller and smaller aggregate grading groupings. In this way, the main structural elements of the consecutively smaller subsets of the aggregate skeletons can be clearly visualized in the absence of the finer aggregates filling the voids. The latter mainly provide stability to these subset skeletons.

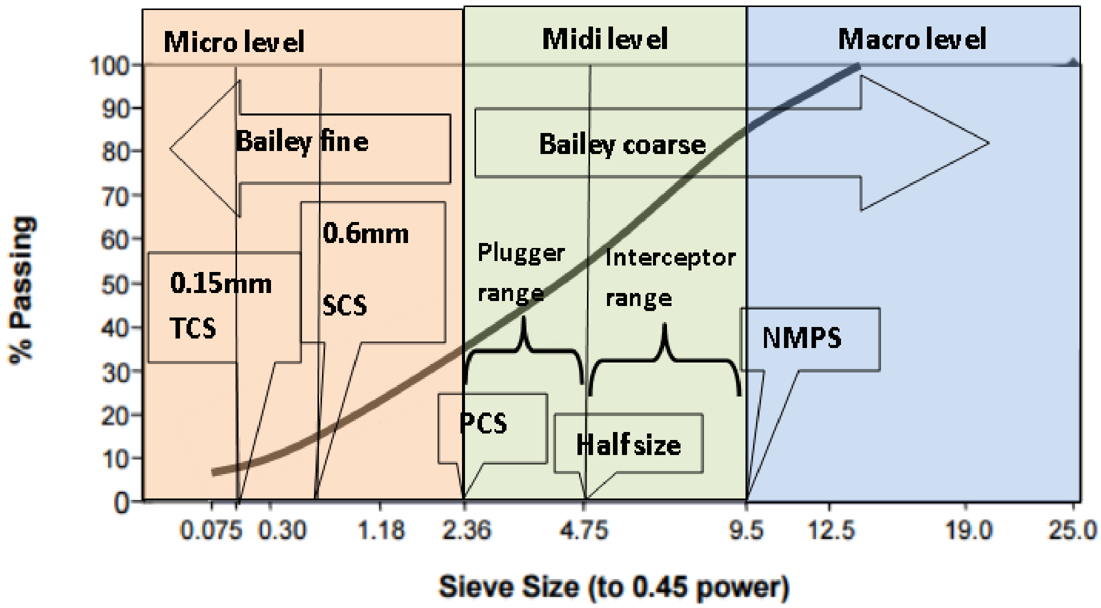

Figure 1. Typical grading with Bailey descriptors of division points and basis for ratios

The DASR porosity concept and calculation is shown in **Equation *1*** to calculate porosity of a range of contiguous (in sequence and not overlapping) aggregate fractions. Individual aggregate fractions have porosity values ranging from 0.7 to 0.9 on average. The basis of the volumetric relations is illustrated in **Figure *3***. The objective is to get the contiguous aggregate fractions combination to form the range known as the DASR with a porosity theoretically approaching or even below 0.5. The objective to approach 0.5 and below is from soil particle packing knowledge whiles being porous, maximum stability and structural efficiency can be achieved in an aggregate matrix at porosity values below 0.5 (Lamb and Whitam,1969) . Reduced porosity also implies lower air voids and, therefore, lower permeability. The DASR will, typically, be consisting largely of the midi range contiguous aggregate fractions combined. As illustrated in **Figure *3***, the aggregate skeleton of the DASR is filled with fines, called Interstitial Components (IC), which includes the bitumen binder and air voids as well.

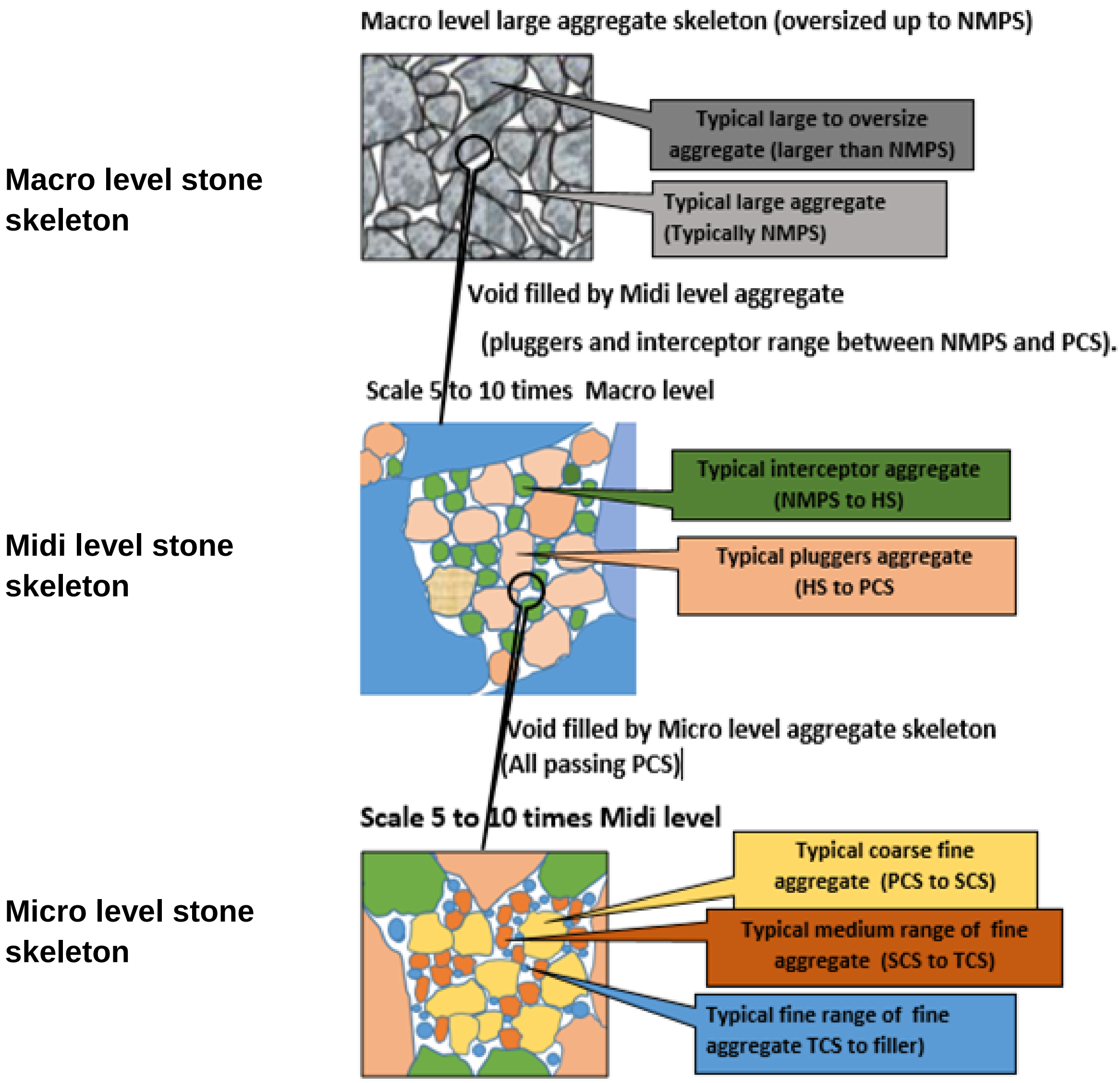

Figure 2. Three level aggregate skeleton infill illustration

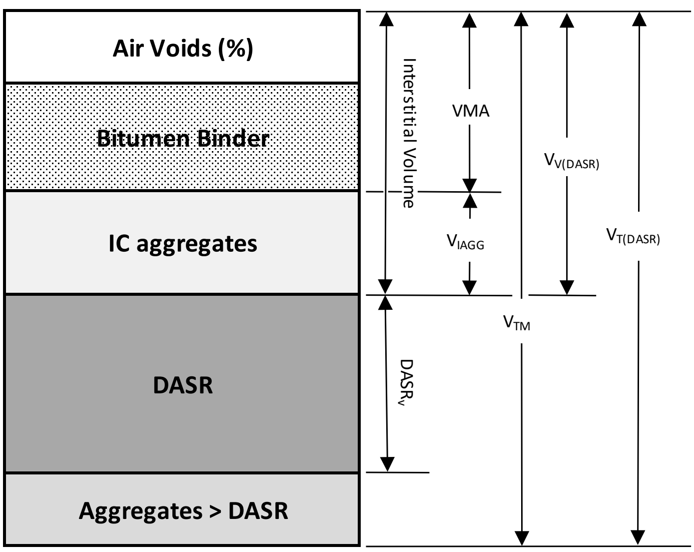

Figure 3. Illustration of DASR principles

The original DASR porosity equation was reworked by Denneman et al. (2007) to enable single aggregate fraction porosity calculation as well as other fraction combinations. The reworked relationship is shown in **Equation *2***. The latter equation will be used in the reworking of the data sets from published papers enabling a better explanation of the Bailey ratios. Typically V_{TM} could be back calculated from the published data in Denneman et al (2007) which gave credible values for the other published data as it appears in the numerator as well as denominator in **Equation 2.**

The contiguous aggregate fractions in **Figure *2*** are illustrated as fractions that combine the macro, midi and micro levels and each time cause the porosity to be reduced in the succeeding voids reduction. Thus, through porosity reduction, voids are reduced in size with the intention to reduce total voids and interconnectedness; subsequently this causes reduction of the permeability as well. In DASR terminology, the IC is deliberately not shown in these subsets to help clarify the structural main bearing components and influence on porosity progressively.

The Bailey ratios are verified as they associate with the macro, midi and micro aggregate skeletons as shown in **Table 1**. The nominator and denominator fractions are not contiguous for the Fine Aggregate Coarse (FA_c) and Fine Aggregate Fine (FA_f) ratios of the Bailey fines make correlation with the DASR porosities difficult. Therefore, the impact on porosity cannot be properly monitored using DASR porosity values at the midi and micro levels of the skeleton subsets. It is only the Coarse Aggregate (CA) ratio has contiguous fraction ranges in its denominator and nominator. Thus, the impact on porosity of the large aggregate fractions can be monitored and explained.

Equation 1 *(Kim et al., 2006)*	**Equation 2** *(Denneman et al., 2007)*
$\eta_{DASR} = \frac{V_{V(DASR)}}{V_{T(DASR)}} = \frac{V_{ICAGG} + \text{VMA}}{V_{TM} - V_{AGG} > \text{DASR}}$ Where: $\eta_{DASR} = DASR_{porosity}$ $V_{\text{Interstitial volume}}$ = Volume of IC aggregates plus VMA, thus inclusive of bitumen binder volume; $V_{AGG>DASR}$ = Volume of particles bigger than DASR; V_{TM} = Total volume of mix; $V_{T(DASR)}$ = total volume available for DASR particles; $V_{V(DASR)}$ = volume of voids within DASR; V_{ICAGG} = volume of IC aggregates; VMA = voids in mineral aggregate; V_{ICAGG} = volume of IC aggregates.	$\eta_{(4.75-2.36)} = \frac{\left[\left(\frac{\text{PP2.36}}{100}\right)(V_{TM} - \text{VMA}) + VMA\right]}{\left[\left(\frac{\text{PP4.75}}{100}\right)(V_{TM} - \text{VMA}) + VMA\right]}$ Where: $\eta_{(4.75-2.36)}$ = Porosity of a typical fraction passing 4.75mm sieve and retained on 2.36mm sieve $PP_{2.36}$ = %age particles passing 2.36mm sieve $PP_{4.75}$ = %age particles passing 4.75mm sieve VMA = Voids in mineral aggregate V_{TM} = Total volume of mix

Table 1. Existing Bailey ratios description

Matrix Level	**Gradation Ratios** (See gradation graph **Figure 1** with associated indications for proper reference)	**Summary explanation of Bailey ratios and parameters**
Macro	**Coarse aggregate ratio (CA)** $\mathbf{CA} = \frac{(\%\ \mathbf{HS} - \%\mathbf{PCS})}{(\%\ \mathbf{100} - \%\mathbf{HS})}$ $= \frac{\%\ \mathbf{Pluggers}}{\%\ \mathbf{All\ interceptors}\ \&\ \mathbf{la}}$	The pluggers are the finer of the coarse aggregate range between HS and PCS. Pluggers tend to 'plug' and reduce the larger aggregate framework or skeleton. Coarse aggregate between half size (HS) and primary control sieve (NMPS) are called interceptors. Large aggregates tend to have large porosity values and the same is true for the pluggers on their own. However, when combined they show a significant reduction in the combined range of aggregate fraction porosity. Therefore, as these fractions do not overlap in size and the pluggers tend to fill voids of the large aggregate skeleton, they should have a significant impact on the void size reduction and porosity.
Midi	**Fine aggregate coarse ratio (FAc)** $\boldsymbol{FA_c} = \frac{\%\mathbf{SCS}}{\%\mathbf{PCS}}$	This ratio provides an indication of the stability of the sandy fraction range in support of the larger aggregate packing (macro structure). Original value of 0.35 was recommended for structural stability. Range is however typically 0.25 to 0.5 in practice. It is, therefore, expected that this ratio may be insensitive to permeability control.
Micro	**Fine aggregate fine ratio (FAf)** $\boldsymbol{FA_f} = \frac{(\%\mathbf{TCS})}{(\ \%\mathbf{SCS})}$	Original FAf value of 0.35 was recommended for structural stability. Range is, however, typically 0.25 to 0.5 in practice. This ratio's fractions, though, fill the voids in the midi structure and, thus, will have a further reduction potential on the size of the voids, but will not necessarily have a clear influence on the interconnectedness of these voids.

The way forward was pointed by a recent study by Al-Mosawe et al. (2015) who used the existing Bailey ratio method to develop structurally strong asphalt mixes measured in terms of modulus values. They identified the inability of the Bailey ratios in explaining contributions of the various subset skeleton infills as well as overall aggregate skeleton to the structural strength of the mix. Therefore, they developed new ratios that better describe the load bearing characteristics of the inner aggregate skeleton (in the midi range). It appears these new Bailey ratios were developed in analogy to some of the DASR principles as the nominator and denominator were contiguous fraction ranges. The correlation relationship developed offered clearer logical explanation of the role of the particles filling the larger aggregate skeleton as illustrated in **Figure *2***. The relationship developed by Al-Mosawe et al., correlating the old and new Bailey ratios with modulus values is shown in **Equation 3**.

$$E = 4412 - 245CA + 337\left(\frac{C_f}{F_c}\right) + 1784\left(\frac{F}{C}\right)$$ **Equation 3**

Where:

$E = Modulus, MPa$

$$\frac{F}{C} = \frac{(\%PCS)}{(\%NMPS - \%PCS)}$$

$$\frac{C_f}{F_c} = \frac{(\%\mathrm{PCS} - \%\mathrm{SCS})}{(\%\mathrm{HS} - \%\mathrm{PCS})}$$

The logic and description of these new and proposed Bailey ratios are explained in **Table 2**. The numerator and denominator of each ratio are formulated to facilitate clear correlation with the DASR porosity principles. As can be seen these fraction ranges are independent from each other and if combined as a range of aggregate fractions can be monitored in terms of their impact on porosity reduction towards 0.5.

It needs to be noted that the rational Bailey ratios adhering to nominator and denominator as combined contiguous aggregate fractions are expressed as fine/coarse aggregate fractions. This is based on the 0.22 ratio of fine/coarse that determine fitting of the fine portion into the voids created by the coarse aggregate fraction skeleton. The inverse of this ratio,;therefore coarse/fine can also be used for description of the rational Bailey ratios. The latter is the approach used in binary aggregate fraction packing (Olard, 2015) and have merit to be explored in combination with the associated combined porosity of the aggregate contiguous fraction ranges. Space do not allow for this exploration here and may contribute to confusion with the traditional Bailey ratios used in the reworking of published datasets.

2.2. Permeability in HMA/WMA

Previous research has shown that permeability of normal HMA/WMA (typical NMPS size 12.5 mm to 9.5 mm) is very low at air void contents less than 6 %. Between 6 and 7 % air voids, permeability increases significantly. It has been found by various researchers in general that asphalt pavement layers become excessively permeable between 8 and 8.5 % air voids (Hainin, et al. 2003). This is often referred to as the threshold air void value where after the 'lift-off' in permeability is literally exponential.

The threshold value is however not a constant value of 8 % for all HMA/WMAs. Such air void threshold values are influenced by factors such as the quantum of the NMPS. Cooley et al (2002) have shown that as NMPS increases, a pavement can become excessively permeable with lower in place air voids than those mentioned above. Thus, the threshold value may even move to 4 % air voids for a NMPS of 25mm on one extreme and progressively increases to the known 8 % air voids as NMPS reduces to 9.5 mm on the other extreme of the NMPS range.

Consequently, the potential for more interconnected voids is increased with larger individual void size with such larger NMPSs. Choubane, et al. (1998) previously determined that this variance in threshold value is due to the creation of larger individual air voids with larger NMPS type HMA mixes. Layer thickness also implies a direct influence on permeability due to the known relation between NMPS and layer lift thickness. Thinner layers tend to have higher permeability potential for various reasons related to compaction efficiency, heat retention/loss, etc.

Table 2. ***New and proposed Bailey ratios description***

Matrix Level	**Gradation Ratios** (See gradation in **Figure 1** with associated indications for proper reference)	**Explanation of new and proposed Bailey ratios and parameters**
Macro	$\mathbf{CC} = \frac{(\%\mathbf{100} - \%\mathbf{NMPS})}{\%\mathbf{100}} = \frac{\%\mathbf{Oversize}}{\%\mathbf{100}}$	**New Bailey Ratio** (Al Mosawe et al, 2015). This is **the oversize or coarse of coarse ratio of % in the grading** typically larger than the NMPS as described.
	$\frac{\boldsymbol{I}}{\boldsymbol{O}} = \frac{(\%\mathbf{NMPS} - \%\mathbf{HS})}{(\%\mathbf{100} - \%\mathbf{NMPS})} = \frac{\%\mathbf{Interceptors}}{\%\mathbf{Oversize}}$	**Proposed New Bailey Ratio** (Extending the Al Mosawe et al, 2015 approach). This can be called the **interceptor to oversize (large) aggregate ratio.** This is actually a ratio that bridges the macro and midi ranges.
Midi	$\frac{\boldsymbol{C_f}}{\boldsymbol{F_c}} = \frac{(\%\mathbf{PCS} - \%\mathbf{SCS})}{(\%\mathbf{HS} - \%\mathbf{PCS})} = \frac{\%\mathbf{Coarse\ portion\ of\ fines}}{\%\mathbf{Pluggers}}$	**New Bailey Ratio** (Al Mosawe et al, 2015) Proposed name: **Plugger stability ratio**. Was developed as standard Bailey ratios but does not describe packing and the matrix stability adequately on its own.

	$\frac{\boldsymbol{F}}{\boldsymbol{C}} = \frac{(\%\mathbf{PCS})}{(\%\mathbf{NMPS} - \%\mathbf{PCS})}$ $= \frac{\%\mathbf{Fines}}{\%(\mathbf{Plugger} + \mathbf{Interceptor}}$	**New Bailey ratio** (Al Mosawe et al, 2015). This ratio is a true midi range ratio as it is simply the fine portion relative to the medium coarse portion range (the pluggers plus the interceptors combined)
	$\frac{\mathbf{P}}{\mathbf{I}} = \frac{(\%\mathbf{HS} - \%\mathbf{PCS})}{(\%\mathbf{NMPS} - \%\mathbf{HS})}$ $= \frac{\%\mathbf{Pluggers}}{\%\mathbf{Interceptors}}$	This is **the plugger to interceptor ratio**. The logic for optimal structural or skeleton packing is that the pluggers fill the interceptor voids to act as the main structural element of the middle (midi) portion of the aggregate matrix. It can thus be called the 'crux' of the overall aggregate skeleton fitting together.
Micro	$\boldsymbol{FA_{cm}} = \frac{(\%\mathbf{SCS} - \%\mathbf{TCS})}{(\%\mathbf{PCS} - \%\mathbf{SCS})}$ $= \frac{\%\mathbf{Medium\ fine\ of\ fines}}{\%\mathbf{Coarse\ fines}}$	**Suggested new ratio** based on the logic promoted by Al Mosawe et al. (2015). This ratio may provide an indication of the **stability of the coarse range of the fine portion** (typically fine sand range) in support of the whole fines range of the aggregate.
	$\boldsymbol{FA_{mf}} = \frac{(\%\mathbf{TCS} - \%\mathbf{Filler}}{(\%\mathbf{SCS} - \%\mathbf{TCS})}$ $= \frac{\%\mathbf{Fine\ of\ fines}}{\%\mathbf{Medium\ fine\ of\ fines}}$	**Suggested new ratio**. This portion may, in effect, give an indication of the finer portion of the fines (without the filler component) versus the overall fines portion. It is suggested to be referred as the **Mastic Control Ratio**.

A study conducted by Hainin, et al. (2003) investigated the effects of the majority of the aforementioned factors on permeability. The Bailey method was followed in the mix preparations and allowed the Coarse Aggregate ratio (CA) determination of the aggregate packing which proved to be an influential factor for the permeability. The regression equation (see **Equation 4** below) was developed and includes all the major factors that can influence such HMA permeability:

$$\boldsymbol{ln\ (k) = -19.2 + 5.96ln(CL) + 1.47(CA\ Ratio) + 0.078(P12.5) + 0.0485(P1.18) + 0.00928(N_{des}) - 0.0124(AT)}$$ **… Equation 4**

where:

ln = Natural logarithm
k = Coefficient of permeability (cm/s)
CL = Air voids from Corelok machine
CA Ratio = Coarse aggregate ratio
P12.5 = % passing 12.5 mm sieve

P1.18 = % passing 1.18 mm sieve
Ndes = Design number of gyrations from gyratory compactor
AT = Average thickness

This correlation approaches a universal relationship to determine permeability. It recognizes at least one Bailey method ratio, the Coarse Aggregate ratio (CA). Obviously, the CA would reflect the known impact of the larger aggregate on permeability. The Corelock method to determine if air voids content is laudable, but restricts the universal use of this relationship due to current limited use in practice. Further to that, density determined by the gyratory compaction also limit this correlation to laboratory prepared mixes only and therefore excludes field samples.

A study by Sadasivam and Koshla (2006) attempted to link the Bailey method ratios and parameters to measured permeability of various Superpave designed HMAs. It transpired that the standard Bailey ratios did not offer clear influence on the limitation of the permeability. Instead, certain fraction sizes and % passing or retained on sieves were proposed for the control and limitation of permeability. This is shown later in Table 5 in the discussion on results from the same reworked data sets. Denneman et al. (2007) subsequently refined the criteria proposed by Sadasivam et al. (2006) to check whether the data set of good performing (cracking) HMA layers are not only dense and structurally strong, but also had acceptably low permeability.

Denneman et al. therefore looked at the basic DASR principles and ratios to see if they agreed with typical fine densely graded (sand skeleton with NMPS 9.5 mm and 12.5 mm) type HMA. They did not perform actual permeability measurements on their samples, but checked if the HMA samples meet the permeability improvement or restriction criteria. Denneman et al. proved that the porosity principles did apply in parallel to the Bailey method criteria, but none of their ratios or criteria were in effect analysed in depth or offered as a logical method to control permeability of the HMA. It appears that the main reason behind diluting the value of the data set to some extent is not measuring the permeability.

Research by Norembeura-Contreras et al. (2013) enable the development of a universal relationship between hydraulic conductivity or coefficient of permeability (k in cm/s) and void content of a variety of HMA types (Fine, Dense, up to Open and even Porous asphalt HMA). No Bailey method or DASR principles were applied and therefore no reference is made of them. The mix designs did follow Superpave guidelines with NMPS of a variety of mix types ranging from 19 mm to 9.5 mm. The spread of void content also accommodated the variability of void interconnectedness statistically. Laboratory as well as published work and other field measurements were included in the study. This relationship is shown in **Equation 5**.

$$-\boldsymbol{ln}(\boldsymbol{k}) = \mathbf{45.97}\left(\frac{\mathbf{1}}{A_{vc}}\right) + \mathbf{1.82}$$ **Equation 5**

Where:

ln = Natural logarithm,

k = Coefficient of permeability

A_{vc} = the air void content.

3. Reworking existing published work

The recent research described before offers the possibility to rework the HMA basic information such as the grading information provided by Sadasivam and Khosla (2006) Denneman et al. (2007) as well as that of Al-Mosawe et al. (2015). The porosity values for all data sets could be determined using the reworked relationship (equation 2) provided by Denneman et al. (2007). Bailey ratios and DASR porosity values for all the data sets could thus be determined.

Al-Mosawe et al. (2015) data set had voids content (%) included and, therefore, permeability was derived using **Equation 5**. However, as found by Sadasivim and Khosla (2006), the Bailey parameters do not provide such a good correlation with permeability for the full data set. It is suspected that this variability in this range may be due to measuring technique as well as variance in interconnectedness of voids and an-isotropy of the permeability.

The trends in variability, in the mid to low permeability range, led to the decision to target only data sets with proven high permeability or low permeability values as the two extreme ends of the permeability of the overall data sets. The medium range of permeability data sets were thus not included in the further reworking of the data sets.

Al-Mosawe et al. (20015) data set had bigger NMPS (16 mm) than the Sadasivim and Koshla (2006) (NMPS of 12.5 mm and 9.5 mm) and Denneman et al. (2007) (NMPS of 9.5 mm). The various aggregate values for the coarse and fine divisions for the Bailey method, therefore, differ and make the inclusion of the Al-Mosawe et al. (2015) data set, for inclusion with the rest, problematic. For that reason, this data set was not included in the reworking of the high permeability data set despite the obvious generally high permeability of the Al-Mosawe et al. (2015) data set.

The data sets of Sadasivam and Khosla (2006) and Denneman et al. 2007) were thus combined for both the high and low permeability. In the case of the Denneman et al data sets actual permeability was not measured and no void contents were presented. In the 2007 evaluation by Denneman et al. the proposed permeability limitation criteria (see **Table *5***), were used to infer low and high permeability. Low permeability was inferred by the data sets that met all the tolerances of the criteria. High permeability was inferred for data sets which met only one or maximum two of the tolerances of the set criteria. Therefore, they may have by implication high permeability. The data sets were, thus, reworked and the results for the Bailey parameters and the DASR porosity values are shown in **Tables 3** and **4**. The sensitivity of the ratio or porosity value is evaluated in relative terms using the RAG benchmark method (red for apparent no sensitivity, amber for apparent low sensitivity and green for apparent sensitivity.)

Table 3. Average porosity values of aggregate fraction ranges for reworked data sets for low and high permeability mixes

Descriptions*	Permeability	
	Low	High
DASR	0.54	0.53
Interceptor range	0.73	0.78
Large Aggregate range	0.72	0.51
Pluggers range	0.74	0.66
Coarse of fine aggregate range	0.65	0.65
Interceptors + pluggers range	0.55	0.51
Fine of Fine aggregate range	0.72	0.86
Fine to Filler aggregate range	0.41	0.96

*** See Tables 1 and 2 for descriptions and use Equation 3 for porosity calculations**

Table 4. Average Bailey ratios for reworked data sets for low and high permeability mixes

Bailey	Permeability	
Ratios*	Low	High
CC	0.04	0.04
I/O	8.63	4.25
P/I	0.71	0.43
CA	0.61	0.41
FA_c	0.56	0.49
FA_f	0.49	0.47
C_f/F_c	1.02	1.29
F/C	0.87	0.92
FA_{cm}	0.35	0.40
FA_{mf}	0.40	0.36

*** See Tables 1 and 2 for definitions and descriptions**

Data sets from Sadasivam and Khosla (2006) and Denneman et al., (2007)

Key to rating benchmark	
Apparent sensitivity	(green)
Apparently less sensitive	(yellow)
Apparently low sensitivity	(orange)

4. DISCUSSION ON REWORKED DATA SETS

4.1. Sadasivam and Khosla permeability control measures

Sadisivam and Khosla (2006) apparently found the Bailey ratios for the mixes with NMPS of 9.5 mm and 12.5 mm too variable and difficult to explain in terms of simple correlations. It is already clear from the discussion in **Table 1** that the original Bailey ratios do not correlate well with the porosity principles of the DASR methodology. However, the basic influence of the midi range aggregate fraction was identified as possible guidelines for structural strength as well as for permeability control. The ranges are shown in **Table 5** as originally suggested by Sadasivam and Khosla (2006). Denneman et al. (2007) suggested some adjustments to these ranges, also indicated in **Table 5**. Denneman et al. (2007) considered the porosity aspects indirectly, but could possibly not relate it to the original Bailey ratios. These suggested criteria can thus be applied as a first level control mechanism on permeability.

4.2. DASR potential as permeability control measure

It appears that these criteria or control ranges shown in **Table 5** may have logical validity as they relate to important elements identified in the DASR fraction ranges and new Bailey ratios. The DASR described in **Table 5** is basically the bulk of the actual DASR components that largely defines an efficient aggregate packing for structural optimization. This DASR range is not sensitive to permeability control though as shown in **Table 3**. The possible reason is that this DASR calculation still needs to have their voids to be filled with micro-level fines which should reduce porosity and permeability more. Therefore the Interstitial Components (IC) still need to be fitted in the voids as well.

Table 5. Suggested permeability control ranges and ratios

Permeability indicator	**Range for low permeability**	**Range for high permeability**	**DASR fraction range associated**
CA	>0.5 (D)	<0.5 (D)	
% passing 4.75 mm sieve	60% to 65% (67% D)	45% to 53%	Effectively the plugger range with fines included
% retained on 4.75 mm sieve	23% to 30%		Interceptor range
% passing 2.36 mm sieve	35% (32%D) to 45% (47%D)	30% to 35%	Fines range or all material passing the PSC
% passing 1.18 mm sieve	20% to 25%(<30% D)		Coarse fines plus tail
% retained on 1.18 mm sieve	>10%	<10%	Coarse fines range
% passing 1.18 mm sieve and % passing 2.36 mm sieve	>35% (D)		Coarse fines and pluggers
Ration of 2.36 mm sieve /1.18 mm sieve	1.5 to 2 (D)		Apparently to ensure the ratio between coarse and fine are also well graded and filling the finer voids structure
(***D) adjustments and ranges suggested by Denneman et al. (2007)***			

4.3. Macro level permeability control

The porosity values of the large aggregate and that of the interceptors clearly influence the macro level void size and, therefore, porosity control. The low permeability data set in **Table 3** shows lower porosity for the interceptor range and high porosity for the large aggregate range than that of the high permeability data set. This interplay is best illustrated by the I/O ratio, a new Bailey ratio. The lower I/O ratio values imply higher permeability in **Table 4** when the large aggregate fraction increase proportionally. This is in line with the concept that if more large aggregates are present in the aggregate grading (therefore, low I/O values), more large voids are created with a higher probability of being interconnected and thus permeable. It is also clear that the combination of large aggregate with sizes bigger than 0.22 in the fines/coarse ratio also influence this porosity of the combined fractions.

The basis of the Bailey method is the 0.22 ratio of fine/large aggregate to ensure that the finer aggregate will effectively fill the voids of the large aggregate. Therefore the size ratio of interceptor range aggregates (HS = 4.75 mm) to large aggregate (NMPS = 9.5 mm) imply a 0.5 ratio. Thus, interceptors need to be limited on the macro level purely as it limits the void reduction due to size which interrupts, disrupts or disturbs the macro aggregate skeleton structure.

4.4. Midi level permeability control

It is also of interest that when the porosity values for the large aggregate, interceptors and pluggers range are considered separately all their individual porosities are above 0.70 as shown in **Table 3**. This is to be expected. However, when the interceptors and pluggers are combined as contiguous aggregate fraction range their porosity of 0.55 in **Table 3** is nearly the same as the actual DASR porosity of 0.54 for the low permeability data set. This portion between the NMPS and the PCS thus, in effect, forms the crux or basis of the DASR and thus providing stability to the actual midi range aggregate skeleton infill or subset. This 'DASR crux range' is thus a critical structural element in the overall aggregate skeleton packing efficiency. This is in line with the rationale behind the development of the new Bailey ratios proposed by Al-Mosawe et al (2015).

The high permeability data set shows a more dramatic reduction to 0.51 in **Table 3** for this 'DASR crux range' which implies it may compact with more difficulty and, therefore, even at this midi level of the total aggregate matrix the plugger and interceptor combination needs to be controlled better. In this regard, the sensitivity exhibited by the new proposed Bailey ratio, Pluggers/Interceptors (P/I), in **Table 4** verify this as one of the potential effective control mechanisms for permeability in HMA. Low permeability is associated with high P/I ratios (0.71 which implies a low relative interceptor %age) while high permeability is associated with low P/I ratios (0.41 which implies a high % interceptor). More interceptors tend to create the stronger possibility of larger voids created in the matrix at this midi range, thus higher porosity and the possibility of the voids being interconnected and, thus, implying also higher permeability.

It appears that Sadasivam and Khosla (2006) were correct in suggesting stronger control of the plugger and interceptor range. The proof is in **Table 3** where the low permeability data set has a plugger porosity of 0.74 while that of the high permeability data set, the plugger range porosity is lower at 0.61. It implies probably more pluggers may cause lower porosity, but it may limit the voids being filled with good graded fines to reduce the voids size as well as their interconnectedness. It is acknowledged that particle form and surface morphology may clearly play a stronger role here, but no information on this is available which makes it a suspected influence only.

Both the new Bailey ratios, C_f/F_c and F/C have nominators linked to the fines and coarse fines. The denominators are linked to the pluggers and interceptor fraction ranges. Even though they are clearly significant in their structural strength contribution (Al-Mosawe et al, 2015) they seem to be highly influential in permeability control due to the coarse fines and fines filling the voids in the plugger range aggregate particles and thus providing matrix stability as well.

4.5. Micro-level permeability control

The most significant difference in the fines range particles appears to be in the fine to filler range (therefore below the TCS). This range of particles in **Table 3** shows the porosity for the low permeable data set to drop to 0.41 while the high permeable data set equivalent range only hovers around 0.91. Therefore, it appears this range of fines may have a very significant impact on the permeability control while its role in the structural stability of the matrix may be more of indirect structural stability enhancement. **Tables 3** and **4** show that the coarse portion of the fines do not have a distinct sensitivity based on their porosity values, but the FA_c Bailey ratio does show limited sensitivity. This ratio is, however, not well correlated with the DASR porosity principles and therefore does not seem to be a primary indicator or control mechanism for permeability.

The bottom part of the fines (fine to filler or 'tail') shows a significant effect on the porosity ranges, which is to be expected. If it is accepted that the macro skeleton and the midi skeletons have been put in place which progressively reduced the voids in size and distribution. The smaller voids thus left must be filled effectively to ensure porosity is finally reduced. Therefore, it appears the grading of this portion of the fines tail should receive more attention for permeability control. It clearly finally reduces void size and with this size also being taken up in the effective binder film thickness as mastic, it clearly can further 'plug' the interconnectedness of voids efficiently if well graded.

4.6. Correlated Bailey and DASR porosity permeability control

It is accepted that the Sadasivam and Khosla (2006) as well as the Denneman et al. (2007) criteria for permeability control may be specific to the mixture type and maximum aggregate size (NMPS size). Therefore, these permeability control measures should not be construed as universal permeability control measures.

Despite this cautionary statement of the possible limited value of criteria proposed for permeability control, **Table 6** proposes Bailey ratios that are correlated to DASR descriptors. It deliberately only focuses on the parameters that showed clear sensitivity to permeability control. It also shows those parameters which can explain the porosity impact of the nominator and denominator of the Bailey ratios separate and combined.

Table 6. Suggested permeability control criteria for Bailey ratios and DASR fraction porosity ranges

Skeleton level	Bailey Ratios	Suggested range	DASR descriptor	Suggested range
Macro	CA	>0.5	Large Aggregate	>0.65
	I/O	>6	Interceptor	<0.75
Midi	P/I	>0.65	Interceptors + pluggers	>0.52
	Cf/FC	<1.05	Pluggers	>0.7
	F/C	<0.9	Coarse of fines	0.65
Micro	FAcm	<0.37	Fine of fines	<0.75
	FAmf	>0.37	Fine to filler	<0.6

5. CONCLUDING REMARKS

The Bailey ratio ranges and DASR porosity type ranges are presented for the macro, midi and micro skeleton subsets or ranges to show how the porosity and permeability can be controlled progressively from the macro level to the micro levels. If a larger data set was available for various types of HMA/WMA mix designs inclusive of open graded HMA like Stone Mix Asphalt (SMA) mixes, more universal criteria set may be possible.

It is argued that the new Bailey ratios and the possible correlation with the associated porosity of the numerator and denominator provides for a mechanism to understand what the new Bailey ratios imply in terms of the more fundamental parameter of porosity. This makes sense if these independent numerator and denominator aggregate fraction ranges are treated as contiguous ranges of aggregate fractions as per the DASR principle and thus allow evaluation of the impact in the porosity reduction thus achieved. The structured approach to the total aggregate skeleton via the macro, midi and micro levels also offer better understanding where the structural strength comes from as well as how to control the permeability even down to the finer portion of the grading.

It is clear that the correlated DASR porosity with rational Bailey ratios may need an additional perspective to describe the interconnectedness of the voids at the various sub-skeleton levels (macro, midi and micro levels). Interconnectedness and not merely porosity or voids are enough to fully describe permeability. Interconnectedness create opportunity for water to flow between voids and thus causes permeability.

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