RATIONAL BAILEY RATIOS AND DOMINANT AGGREGATE SIZE RANGE POROSITY CORRELATED WITH RUTTING AND MIXTURE STRENGTH PARAMETERS

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, South Africa

ABSTRACT

A study done on the correlation of the Bailey method and the Dominant Aggregate Size Range (DASR) method managed to describe and develop new Bailey ratios that better describe the aggregate skeleton packing efficiency. DASR porosity was found to be linked to permeability as well. The aggregate skeleton is ‘deconstructed’ at macro, midi and micro level aggregate subset skeletons to evaluate the contributions of various aggregate fraction ranges. Bailey ratios were brought in line with the concept of nominator and denominator aggregate fractions that suit the DASR concept of contiguous fraction ranges and were described as the rational Bailey ratios. A data set which was based on Bailey method mix design was reworked to include the DASR porosities and the new correlated and rational Bailey ratios. This enabled the Bailey ratios and the DASR porosities to be related to rutting measured with Hamburg Wheel Tracking (HWT) tests. Other structural design parameters such as the Indirect Tensile Strength (ITS), Effective Film Thickness (EFT) of the binder mastic of these mixes were also correlated with various Bailey ratios and DASR fraction porosity ranges. The main purpose of this study was to confirm the viability of these new rational and correlated Bailey ratios and DASR porosities with rutting potential for further future detailed modelling via stepwise multiple regression analyses or via Neural Network Analysis (NNA) and modelling.

1. INTRODUCTION

The Bailey Method for gradation selection considers the packing characteristics of aggregates. The parameters in this method are directly related to voids in the mineral aggregate (VMA), air voids, and compaction properties. The Bailey Method is a systematic approach to blending aggregates that provides aggregate interlock as the backbone of the structure and a balanced continuous gradation to complete the mixture. The Bailey method (Vavrik et al, 2001) as well as the Dominant Aggregate Size Range (DASR) (Kim et al, 2006, 2009 and Roque et al, 2006) were developed to help optimize the aggregate packing used in HMA. 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.

The focus of mix design procedures for Hot/Warm Mix Asphalt (HMA/WMA) is normally to design such mixes that resist the development of rutting and limit or resist fatigue related cracking. Durability (e.g. stripping) is directly linked to permeability of the HMA and can also form part of these primary design objectives. In an initial companion study (Horak et al, 2017) it was shown how Bailey ratios can be reformulated to correlate better with DASR porosity values for various aggregate fraction ranges. The aggregate skeleton was also subdivided into subsets of infill aggregate skeletons at macro, midi and micro levels. This deconstruction of the aggregate skeleton allowed for a more logical and fundamental description of the contribution of various aggregate fractions to improve structural efficiency and packing as well as limit permeability.

This paper reworked a data set of mix designs for HMA which were designed with the Bailey method. The focus of the original study by Al Shamsi (2007) was primarily on compaction efficiency and various means to model and measure it. Rutting of the mixes were also measured by means of the Hamburg Wheel Tracking (HWT) test and therefore provided the opportunity to correlate with the set of rational Bailey ratios and the DASR porosity parameters identified by Horak et al (2017). Indirect Tensile Strength (ITS) results available could be correlated successfully with the relevant Bailey parameters and DASR porosity parameters. The Effective Film Thickness (EFT) was also determined by Al Shamsi (2006) and correlated with the rational Bailey and DASR ratios and parameters. Lastly the permeability control criteria previously developed could be illustrated as a good first level indicator of permeability propensity of the mixes.

2. BAILEY AND DASR METHOD PRINCIPLES

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 9.5mm to 12.5mm.

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.

Plugger range is the aggregate fraction between the HS and PCS sieves.

Interceptor range is the aggregate fraction between the NMPS and HS sieves.

From these the Bailey method traditionally calculated the following three ratios shown in equations 1, 2 and 3. These ratios are in essence fine/coarse aggregate ranges which is in line with the fundamental definitions of PCS,SCS and TCS reliant on the 0.23 ratio of fines/coarse aggregate fractions and thus should give an indication of packing efficiency relative to that.

$$\textbf{CA Ratio}=\frac{\%\,\boldsymbol{Passing\ half\ sieve}-\%\,\boldsymbol{passing\ PCS}}{\mathbf{100}-\%\,\boldsymbol{passing\ half\ sieve}} \quad \textbf{……………………………Equation 1}$$

$$\textbf{FA}_{\mathbf{c}}\ \textbf{Ratio} = \frac{\%\,\boldsymbol{Passing\ SCS}}{\%\,\boldsymbol{passing\ \ PCS}} \quad \textbf{…………………………Equation 2}$$

$$\textbf{FA}_{\mathbf{f}} = \frac{\%\,\boldsymbol{passing\ TCS}}{\%\,\boldsymbol{passing\ \ PCS}} \quad \textbf{……………………………………Equation 3}$$

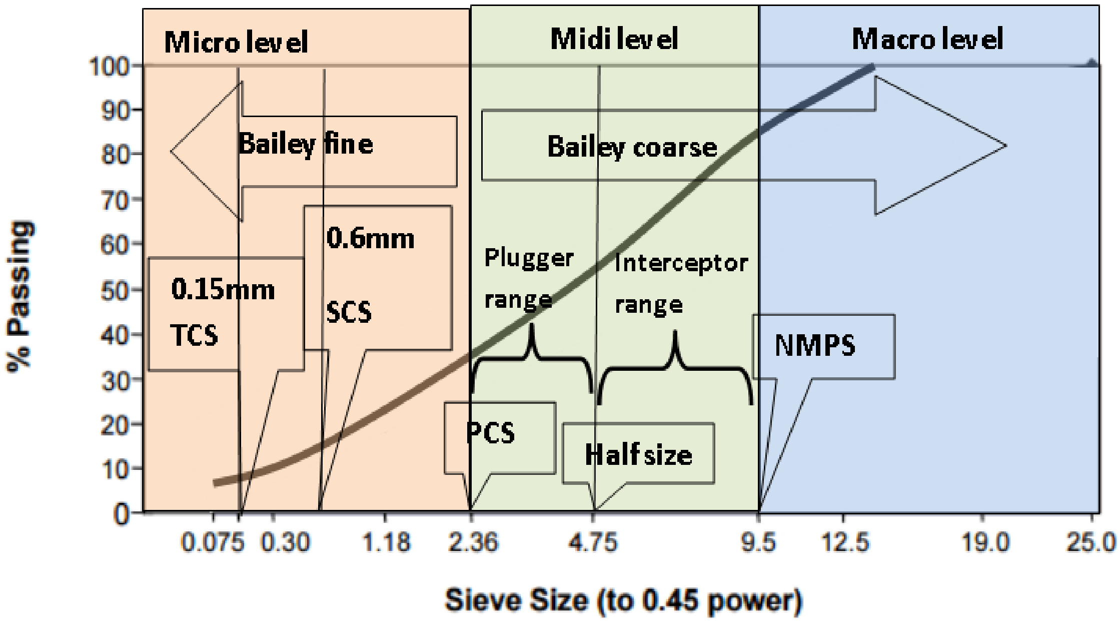


Figure 1. Typical grading with Bailey descriptors of division points and basis for ratios based on NMPS of 9.5mm

Normally the Loose Unit Weigth (LUW) and the Rodded Unit weights (RUW) are determined to help with the aggregate skeleton packing evaluation. However, in the examples reworked from published papers this information were not provided.

The Bailey method defines aggregate fractions larger than PCS as **Coarse Aggregate** and below PCS as **Fines** (see Figure 1). The fines portion coincides with 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 and overlaid in **Figure 1** with NMPS as the divider or control sieve between macro and midi levels. This additional definition of aggregate ranges enable better correlation between the Bailey method ratios and the DASR porosity concepts. Thus, the aggregate skeleton can be described as consisting of macro, midi (middle) and micro skeleton sets that fit together like Russian Matryoshka nesting dolls, each lower level (midi and micro) filling the voids of the previous level skeleton subset.

The DASR porosity concept and calculation is shown in **equation 4** to calculate porosity of a range of contiguous (in sequence and not overlapping) aggregate fractions. Porosity (η) is a dimensionless parameter widely used in the field of soil mechanics indicating the relative ratio of voids (V_V) to total volume (V_T). Kim et al. (2006, 2009) showed that porosity can also be used for asphalt mixtures to establish a criterion which ensures contact between the dominant particles.

$$\eta = \frac{\textit{Volume of Voids}}{\textit{Total Volume}} = \frac{V_V}{V_T}$$ ……..………………………………….**Equation 4**

In traditional soil mechanics, it has been determined that the porosity of granular materials should not be greater than 50 % ($\eta<0.5$) for soil particles to have contact with each other, therefore to be interactive and forming a load bearing skeleton (Freeze and Cherry, 1979 and Lambe and Whitman, 1969). The preferred range of porosity is approximately 45% to 50% and is true irrespective of particle size and distribution Roque et al (2006). The porosity related to asphalt mix aggregates should therefore also be preferably less than 50%. Kim et al (2006, 2009) concluded that the porosity of these dominant particles appeared to be a good tool for evaluating potential rutting performance as well as fracture resistance of asphalt mixtures. Consequently, the concept of a Dominant Aggregate Size Range (DASR) was developed for such a range of contiguous aggregate fractions that have a combined porosity values below 0.5.

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 5. 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 this published data in Denneman et al (2007) which gave credible values for the other published data and the influence is reduced due to the fact that it appears in the numerator as well as denominator in **Equation 5.**

$$\boldsymbol{\eta(4.75-2.36)} = \frac{\left[\left(\frac{\mathbf{PP2.36}}{\mathbf{100}}\right)(\mathbf{VTM-VMA})+\boldsymbol{VMA}\right]}{\left[\left(\frac{\mathbf{PP4.75}}{\mathbf{100}}\right)(\mathbf{VTM-VMA})+\boldsymbol{VMA}\right]}$$ (Denneman et al, 2007) …….**Equation 5**

Where:

$\eta_{(4.75-2.36)}$ = Porosity of a typical fraction passing 4.75mm sieve and retained on 2.36mm sieve
$PP_{2.36}$ = Percentage particles passing 2.36mm sieve
$PP_{4.75}$ = Percentage particles passing 4.75mm sieve
VMA = Voids in Mineral Aggregate
V_{TM} = Total volume of mix

The rational Bailey ratios associated with the macro, midi and micro aggregate skeletons with some logical correlation with DASR porosities are described in **Table 1** with reference to **Figure 1**. The traditional Bailey ratios , FA_c and FA_f, (see equations 2 and 3 as defined in Vavrik et al, 2001) cannot be properly monitored using DASR porosity values at the midi and micro levels of the skeleton subsets. Their nominator and denominators contain aggregate ranges which are overlapping and thus do not form a combined contiguous aggregate fraction range. Therefore, it is not described or discussed or used here. It is only the coarse aggregate ratio (CA) of the original Bailey ratios which has contiguous fraction ranges in the denominator and nominator. Thus, the impact on porosity of CA can be monitored and explained via the DASR porosity.

Olard (2015) described how the original work on aggregate packing by Furnas (1928) for concrete aggregate packing efficiency was developed to include the concepts of binary aggregate packing. In such analyses the fundamental size ratio (diameter of equivalent aggregate fraction size) of fine/coarse was established to be 0.2 to enable the fine aggregate to fit into the coarse aggregate without pushing it apart. Thus, this volumetric or equivalent diameter fine/coarse value used in the Bailey method of 0.22 is fundamentally justified in the calculation of PCS, SCS and TCS.

However, in further analyses of the aggregate packing efficiency Olard (2015) showed that the ratio of coarse/fine by volume or mass of binary aggregates can enhance the evaluation of packing efficiency and can also been used as important parameter with porosity. In the case of material from the same geological source and therefore same specific gravity the ratio of coarse/fine can be expressed as the percentage passing the sieve sizes considered. The porosity determined for the individual aggregate fractions and for the combined fractions as a contiguous aggregate range can thus be determined similar to **equation 5** derived by Denneman (2007).

The original and rational Bailey method ratios discussed previously (Horak et al, 2017) and as originally defined (Vavrik, 2001) thus actually use the fine/coarse ratio similar to the original size ratio to measure the efficiency of fitting fine aggregates into the coarser aggregate voids. It is thus suggested that the rational Bailey ratios should also be presented as the inverse of the rational Bailey ratio as coarse/fine as well. In Table 1 these original and rational Bailey method ratios are described and in the column next to it their inverse as the revised ratios proposed to be co-used. The difference between the two sets of Bailey ratios are indicated with a subscript ($_r$) indicating the revised or inverse of the rational Bailey ratios. If the subscript ($_r$) is not occurring the abbreviation itself is self-explanatory; O/I instead of the previously described I/O etc.

It should be noted that not all possible fraction combinations and thus rational and revised Bailey ratios are shown in Table 1 purely as previous work had shown some of them not being meaningful. Therefore only those that are known to show good correlation with either aggregate efficient packing and rut and related to permeability are shown in Table1.

Table 1. Revised and Rational Bailey ratios to fit Binary fraction criteria

Matrix Level	Original rational Bailey ratios	Proposed Revised rational Bailey ratios in line with binary aggregate fraction packing principles
Macro	$\frac{I}{O}=\frac{(\%\text{NMPS}-\%\text{HS})}{(\%100-\%\text{NMPS})}$ $=\frac{\%\text{Interceptors}}{\%\text{Oversize}}$	$\frac{O}{I}=\frac{(\%100-\%\text{NMPS})}{(\%\text{NMPS}-\%\text{HS})}$ $=\frac{\%\text{Oversize}}{\%\text{Interceptors}}$
	$\text{CA}=\frac{(\%\ \text{HS}-\%\text{PCS})}{(\%\ 100-\%\text{HS})}$ $=\frac{\%\ \text{Pluggers}}{\%\ \text{All interceptors}\ \&\ \text{larger}}$	CA_r = 1/CA $=\frac{(\%\ 100-\%\text{HS})}{(\%\text{HS}-\%\text{PCS})}$ $=\frac{\%\ \text{All interceptors}\ \&\ \text{larger}}{\%\ \text{Pluggers}}$
Midi	$\frac{C_f}{F_c}=\frac{(\%\text{PCS}-\%\text{SCS})}{(\%\text{HS}-\%\text{PCS})}$ $=\frac{\%\text{Coarse portion of fines}}{\%\text{Pluggers}}$	$\frac{F_c}{C_f}=\frac{(\%\text{HS}-\%\text{PCS})}{(\%\text{PCS}-\%\text{SCS})}$ $\frac{\%\text{Pluggers}}{\%\ \text{Coarse portion of fines}}$
	$\frac{F}{C}=\frac{(\%\text{PCS})}{(\%\text{NMPS}-\ \%\text{PCS})}$ $=\frac{\%\text{Fines}}{\%(\text{Plugger}+\text{Interceptor})}$	$\frac{C}{F}=\frac{(\%\text{NMPS}-\ \%\text{PCS})}{\%\text{PCS})}$ $=\frac{\%(\text{Plugger}+\text{Interceptor})}{\%\text{Fines}}$
	$\frac{\text{P}}{\text{I}}=\frac{(\%\text{HS}-\ \%\text{PCS})}{(\%\text{NMPS}-\%\text{HS})}$ $=\frac{\%\text{Pluggers}}{\%\text{Interceptors}}$	$\frac{\text{I}}{\text{P}}=\frac{(\%\text{NMPS}-\%\text{HS})}{(\%\text{HS}-\ \%\text{PCS})}$ $=\frac{\%\text{Interceptors}}{\%\text{Pluggers}}$
Micro	$FA_{cm}=\frac{(\%\text{SCS}-\%\text{TCS})}{(\%\text{PCS}-\%\text{SCS})}$ $=\frac{\%\text{Medium fine of fines}}{\%\text{Coarse fines}}$	$FA_{rcm}=\frac{(\%\text{PCS}-\ \%\text{SCS})}{(\%\text{SCS}-\%\text{TCS})}$ $=\frac{\%\text{Coarse fines}}{\%\text{Medium fine of fines}}$
	$FA_{mf}=\frac{(\%\text{TCS}-\%\text{Filler}}{(\%\text{SCS}-\%\text{TCS})}$ $=\frac{\%\text{Fine of fines}}{\%\text{Medium fine of fines}}$	$FA_{rmf}=\frac{(\%\text{SCS}-\%\text{TCS})}{(\%\text{TCS}-\%\text{Filler})}$ $=\frac{\%\text{Medium fine of fines}}{\%\ \text{Fine of fines}}$

The ranges for the rational Bailey ratios and the DASR porosity fraction ranges suggested based on previous work (Horak et al, 2017) that may be linked to permeability control is shown in Table 2 . It is acknowledged that these ranges are serving as guidance as it also indicate structural packing efficiency and possibly indirectly also durability related permeability control aspects. The original control ranges of fractions suggested by

Sadasivam and Khosa (2006) and further adjustments made by Denneman et al (2007) indicated that the selected fraction criteria ranges may be very specific to the data sets analysed. It was suggested that a more fundamental analysis is still lacking for the control or analysis regarding permeability control. Nevertheless these criteria presented in Table 2 were also used to test which of the parameters actually agree with the permeability values also done by Al Shamsi (2007).

Table 2. Suggested criteria for rational 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
	C_f/F_C	<1.05	Pluggers	>0.7
	F/C	<0.9	Coarse of fines	0.65
Micro	FA_{cm}	<0.37	Fine of fines	<0.75
	FA_{mf}	>0.37	Fine to filler	<0.6

3. TESTING THE VALIDITY OF RATIOS VIA REWORKING EXISTING PUBLISHED WORK

3.1. Reworked data sets description

Al Shamsi (2007) data set from his PhD thesis was reworked to determine these rational Bailey ratios. The summary of the data set is shown in **Table 3** where the original grading information is also provided as well as all the original rational Bailey ratios. The measured Indirect Tensile Strength (ITS) test results, the Hamburg Wheel Tracking (HWT) rut results after 20,000 load repetitions, the Voids in the Mineral Aggregate (VMA) and the Equivalent Film Thickness (EFT) are all shown. In **Table 3** the DASR porosity values for all aggregate fractions and combinations are shown as calculated by means of equation 5 shown before.

Table 3. Original aggregate gradings from Al Shamsi data set (2007)

Sieve size	LS Coarse	LS Medium	LS Fine	SST Coarse	SST medium	SST fine	GR Medium	GR fine	Control sieves
19	100	100	100	100	100	100	100	100	
12.5	97.1	97	97.2	96	96.6	97.2	97.7	98.3	**NMPS**
9.5	80.3	80.2	81.7	80.7	83.8	86.5	82.5	86.8	
4.75	46.9	55.2	59.8	48.6	57.6	64.7	54.4	65	**HS**
2.36	31.5	39.6	46.1	32.8	41.6	48.4	39.5	49	**PCS**
1.18	21.8	27.9	34.7	22.2	31.5	36.9	27.8	35.4	
0.6	15.3	19.7	25.6	16.2	23.7	27.8	19.7	25.5	**SCS**
0.3	9.3	11.1	14.4	12.1	15.9	17.7	11.7	14.6	
0.15	6.6	7.4	9.3	6.7	11.2	12.1	7.4	9	**TCS**
0.075	5.5	6	7.2	4.2	8.4	9.1	5.4	6.5	

3.2. Permeability limitation benchmarking

The Bailey ratios in **Table 4** and the DASR porosity parameters values in **Table 5** were benchmarked against the permeability control ranges described in **Table 2**. A typical RAG benchmark system was used where **R**ed (**R**) is for values that are significantly over the suggested range in **Table 2**, **A**mber (**A**) is for values that marginally go over the suggested range limit and **G**reen (**G**) is for values that do meet the criteria set fully. The **RAG** indication for individual mixes as well as for the average value is indicated in **Tables 3** and ***4***.

From this benchmark analysis, it seems that the mixes are not entirely impervious or with uniformly low permeability. The mixes would therefore in general rate low to normal or medium permeable. The design air voids was set at 4% by Al Shamsi (2007) as per Superpave mix design requirements, but normal variability may have result in different actual air voids in reality. The actual void content or check on the real values are not provided in the data set. Permeability was measured by Al Shamsi (2007) but measured permeability values for these mixes were registered as low.

The permeability tests done by Al Shamsi (2006) seem to be done with a small diameter stand pipe while the sides were sealed off. This test method or procedure with such a small diameter stand pipe is measuring horizontal directional flow of permeability. Harris (2007) reported that horizontal permeability may be as much as 10 to 30 times more than vertical flow permeability and the diameter of the actual water to asphalt contact area must at least be 300mm for the horizontal flow to be neutralized. In this case the sides were further totally sealed off (Al Shamsi, 2006) meaning limited permeability could in effect be read (horizontal or vertical). It is also of interest that the permeability values are not used by Al Shasami (2006) in any of the further analyses done by him in his thesis.

Table 4. Original rational and revised rational Bailey ratios for Al Shamsi data set average values.

Rational Bailey ratios		**Rational revised Bailey ratios**	
I/O	14.74	**O/I**	0.07
CA	0.60	**CA_r**	1.66
P/I	0.39	**I/P**	2.57
F/C	2.66	**C/F**	0.38
C_f/F_c	1.26	**$F_{c/}\ C_f$**	0.80
FA_{cm}	0.66	**FA_{rcm}**	1.51
FA_{mf}	0.17	**FA_{rmf}**	5.88

As pointed out by Horak et al (2017) low to medium permeability values tend to show significant variances under normal circumstances due to effects like interconnectedness of voids at the same voids content ranges as well as the influence of horizontal permeability on measurements. Therefore, even if the benchmark analysis as per **Table 2** is not entirely correlating with the measured permeability values, it demonstrates that this control criteria can be used as a first level indicator of permeability potential

Table 5. Al Shamsi data set average values of porosity calculated for fraction ranges

DASR range	Porosity
Interceptor	0.63
Large Agg	0.61
Pluggers	0.77
Coarse of fine	0.63
Intercs +Pluggrs	0.49
Fine of Fine	0.62
Fine to Filler	0.89

3.3. Rut correlations

The average Bailey ratios and DASR parameters shown in **Table 4 and 5** were correlated with the rut values determined from the Hamburg Wheel Track (HWT) tests. Rut measurements are all taken dry and at 20,000 repetitions. The average rut after 20,000 HWT repetitions is a relatively low 2.46mm. Thus, these asphalt mixes generally were rated as good rut resistant mixes by Al Shamsi (2006). In **Figure 2**, the scatter diagrams are shown for all Bailey ratios and DASR porosity parameters listed in **Table 4 and 5** that may have a good correlation with aggregate skeleton, packing efficiency and structural strength.

The correlations of **Figure 2** (A, B and C) for the revised rational Bailey ratios are the factors that were proposed by Al-Mosawe et al (2015) in their correlation study with modulus value of the original rational Bailey ratios. Their correlation study produced **equation 6** below for the original rational Bailey ratios. The new Bailey ratios developed by Al-Mosawe et al (2015) **Figure 2** (A and C) give the best correlations with rutting confirming their value as structural strength indicators. Their R^2 values for the revised rational Bailey ratios **C/F** and **F_c/C_f** are 0.63 and 0.46 respectively. **C/F** as midi range revised rational Bailey ratios tend to correlate relatively well with rut measurements and thus indicative of efficient aggregate packing as an aggregate skeleton subset. **F_c/C_f** can actually only be seen as a supportive parameter as shown in **equation 6** and may therefore also feature in multiple regression analyses or ANN modeling with other datasets.

$$E = 4412 - 245CA + 337\left(\frac{C_f}{F_c}\right) + 1784\left(\frac{F}{C}\right)$$ **Equation 6**

The correlation of the revised CA_r (CA was the original Bailey ratio for coarse aggregate) in **Figure *2*** (B) has the least reliable correlation and shows clear variation with a low R^2 value (0.3). It must be noted the CA and CA_r values in Table 4 also differ from those originally determined by Al Shamsi (2006) as there are unexplainable differences in the Al Shamsi calculations of the CA value in particular. Therefore, these CA and CA_r values are not used with confidence here, but are not ruled out as possible parameter which may correlate well with rut resistance as. The CA value proved to be a lesser indicator or contributor of structural strength in the Al-Mosawi et al (2015) analysis before as shown in **equation 6**.

In **Figure 2** (D, E and F) the other revised rational Bailey ratios are shown versus rut which were expected to correlated better with rut. The I/P ratio (**Figure 2**(D)) at the midi level skeleton subset gave a good R^2 = 0.76 indicating data spread is also well accommodated. This is a confirmation that this I/P aggregate fraction combination forms the real crux of the load bearing aggregate skeleton subsets. The O/I ratio at the macro level subset (**Figure 2** (E)) had a very low R^2 value indicating the structural strength contribution does not come from this oversized material in the aggregate grading.

Figure 2 (F) shows that the revised rational coarse to fine portion of the fines (FA_{rcm}) at the upper range of the micro level skeleton subset (see **Figure 1**) also contribute to the structural strength significantly with an R^2 value of 0.6. This tends to confirm the Al-Mosawi et al (2015) analysis which pointed towards midi level and micro level contribution towards support and structural stability.

Figure 2 (G and H) show the correlations of the interceptor porosity and the interceptor plus plugger range porosity respectively. The latter is also known as the ”DASR crux” (Horak et al , 2017). with R2 value of 0.68. This correlates with the I/P revised rational Bailey ratio as it is in essence the same aggregate fraction range, just expressed as their combined porosity which is below 0.5 as shown in **Table 5**. Therefore, it is expected that the plugger and interceptor range porosity would correlate well with the rut development. The plugger porosity alone, not shown, had a weak correlation versus rut, while the interceptor correlation had a R^2 value above 0.71 (**Figure 2** (G)).

What is noted is that these Bailey ratios and DASR parameters are generally in narrow bands or low gradients of the correlation functions. This tendendcy can be interpreted as low sensitivity if used as single indicator of rut resistance. If the data set had high rut values in as well it may possibly have shown better correlations with the various Bailey ratios individually. As in the case of Al-Mosawe (2015) the best correlation would be possible via multiple regression analysis or Neural Network Analysis (ANN) and modelling. That is not done here due to the limitations of the data set. Nevertheless this simplified single correlation is used as a ‘scouting exercise’ which can be followed up with multiple regression and ANN modelling foreseen with better defined data sets and information.

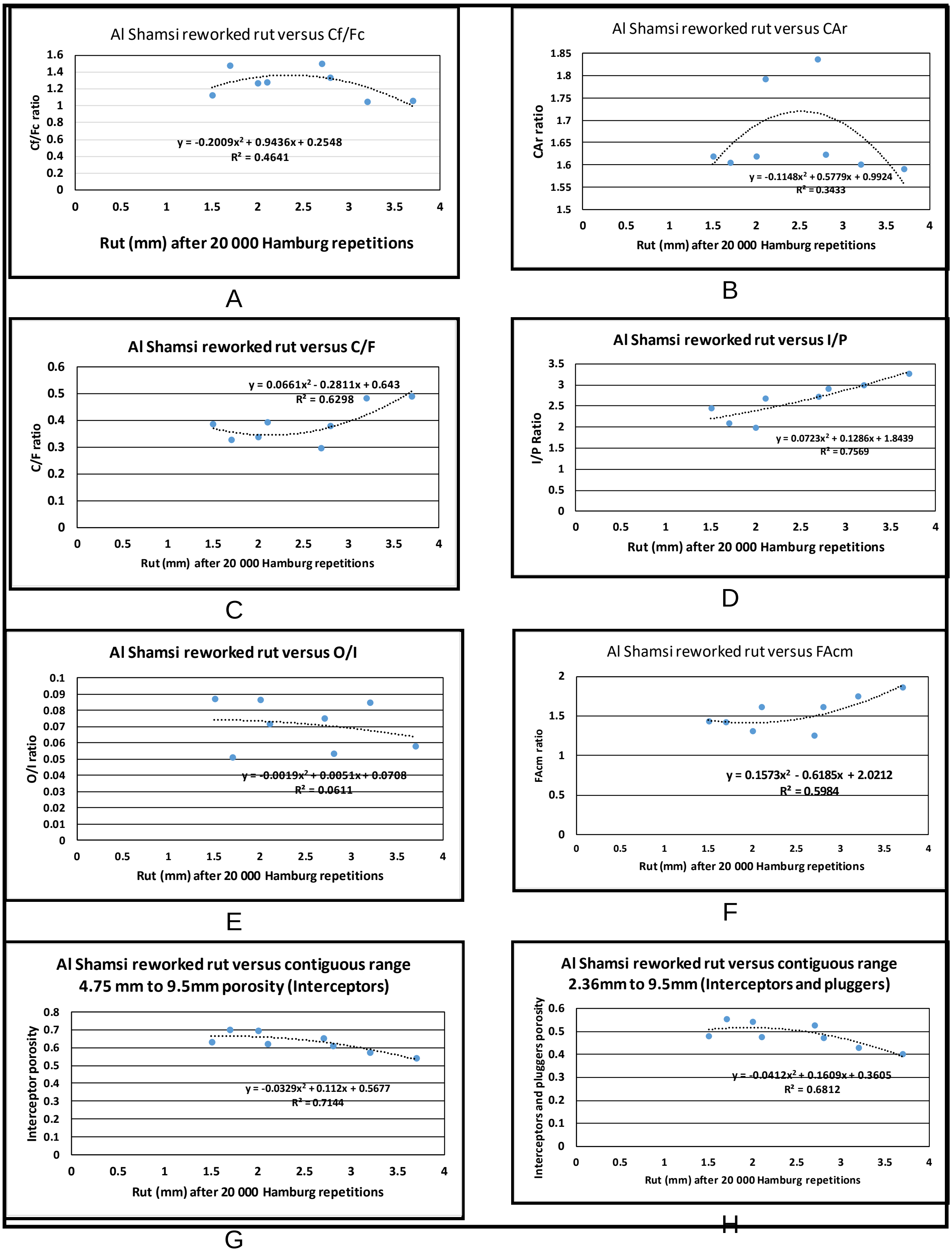


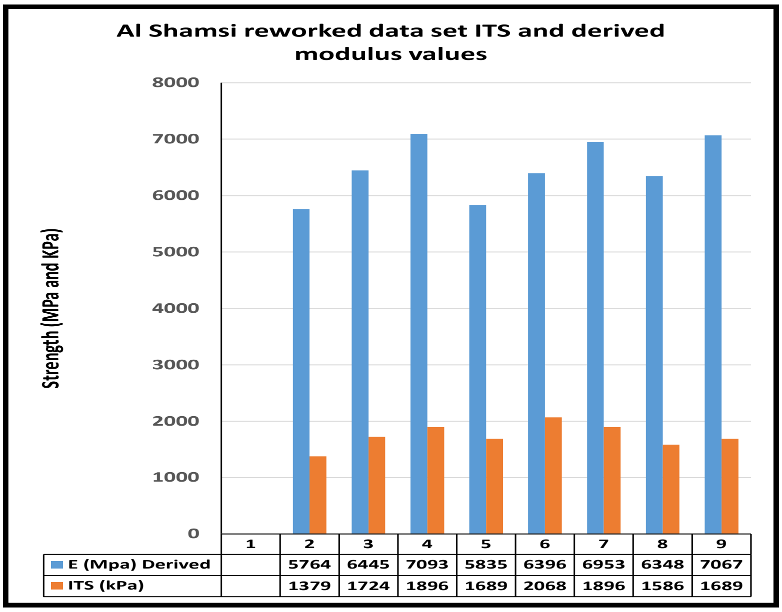
Figure 2. Bailey ratios and DASR porosities correlations with HWT rut

3.4. Modulus and Indirect Tensile Strength Values

The data set of Al Shamsi (2006) had Indirect Tensile Strength (ITS) values determined It has an average value of 1740 MPa which indicate good structural strength. As intimated before the Al-Mosawi et al (2015) correlation equation shown in equation 6 shows good correlation of the modulus (MPa) with the rational Bailey ratios, CA, F/C and C_f/F_c. These Bailey ratios were used to derive a modulus value for the reworked data set shown in **Table 3**.

The average modulus value thus derived is 6,487MPa, which tends to confirm the good structural strength of the mixes in general. In **Figure 3** the ITS and derived modulus values are paired in a bar chart. It can be seen that the trends of the ITS and derived moduli values are the same confirming these rational Bailey ratios correlate well with structural strength also for the Al Mosawi (2007) data set.

However, ITS does not correlate with the rational Bailey ratios, CA, F/C and C_f/F_c well, but it did correlate well with the modulus values. The parameters that did show good correlation with ITS values (R^2 more than 0.5) are shown in **Figure 4**. The rational Bailey ratios FA_c, FA_{cm} and porosity values of the 0.075mm to 0.15mm aggregate fines range correlate well as shown in **Figure 4** (A, B and C). This is a logical fraction range that would be influenced by the adhesion and cohesion provided by the bitumen binder in the mastic combination. For that reason, it is no surprise that the equivalent film thickness (EFT) values correlate well with the ITS as seen in **Figure 4** (D). The bottom line is that the ITS strength is gained from additional aspects of the HMA/WMA mix than what the modulus is derived from.



	1	2	3	4	5	6	7	8	9
🟦 E (Mpa) Derived		5764	6445	7093	5835	6396	6953	6348	7067
🟧 ITS (kPa)		1379	1724	1896	1689	2068	1896	1586	1689

Figure 3. ITS and derived modulus values for reworked dataset.

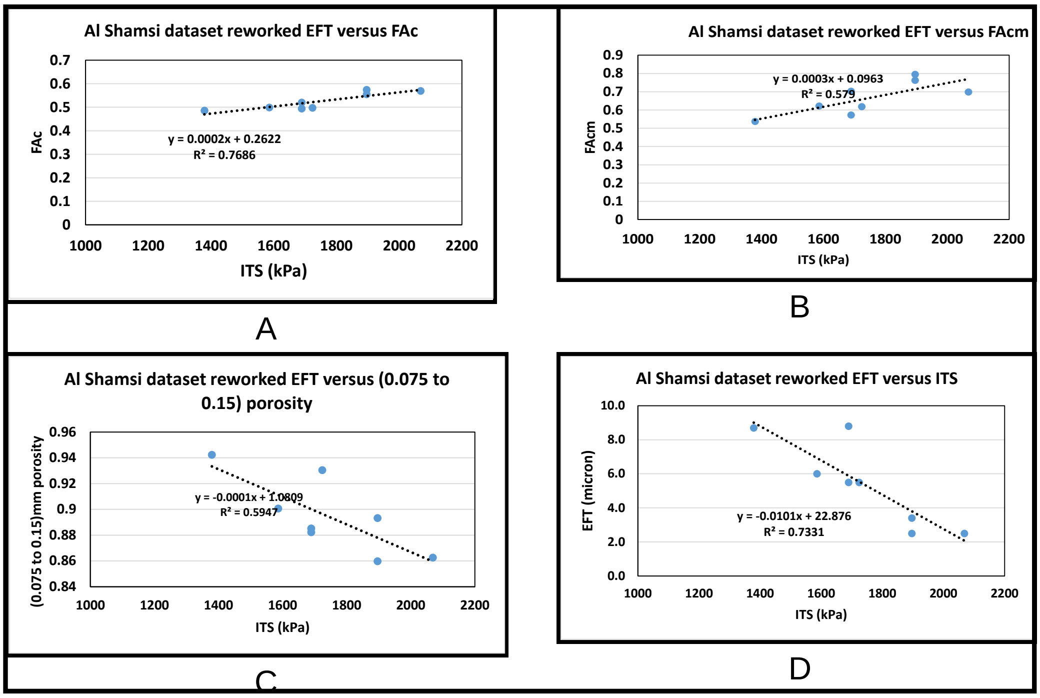


Figure 4. ITS correlations with relevant parameters

4. CONCLUDING REMARKS

Rational Bailey method ratios have been correlated with DASR porosity for individual and combinations of aggregate fraction ranges. This is based on a ‘deconstruction’ of the total aggregate skeleton or matrix in macro, midi and micro level subsets where the voids of the skeleton subsets are filled by the smaller aggregate fractions (fines) progressively. These correlated and rational Bailey ratios and DASR porosity parameters have been used to rework a data set of mixes that were originally designed with the Bailey method. This dataset included measurements of permeability, rutting measured with the HWT and ITS values.

Original work by Furnas (1928) on the pairing of aggregate fractions for concrete aggregate packing efficiency proved that a fine/coarse size ratio of 0.2 provides for fines that are small enough to fit into the voids created by the coarse fraction. However, further development work to achieve efficient concrete aggregate packing showed that the coarse/fine ratio based on percentage passing their relevant sieve sizes correlate well with porosity of the individual as well as the combined aggregate fraction ranges. This binary fraction combination work had been transferred to the asphalt mix design with great success (Olard , 2015) and can enhance the Bailey and DASR approach to asphalt mix design.

The original Bailey ratios are based on the dimension aspect of fine/coarse ratio and therefore actually the inverse of the Furnas ratios of coarse /fine. For that reason the rational Bailey ratios were revised to determine their inverse ratios as well to reflect coarse/fine ratios. No further analysis is done on this binary combination analysis here due to space, but clearly it points to more insight may be possible regarding the fundamental aspects of aggregate packing efficiency. This aspect will form the subject of a next investigation to be published elsewhere.

The Bailey ratios previously identified to help limit permeability were benchmarked with this reworked data set and found to confirm that the mixes are low to medium permeability. This conclusion os possible in spite of concerns about the actual permeability measurement technique used by Al Shamsi (2006) .

The scatter-gram correlations identified and confirmed the ratios and parameters that would contribute to rut resistance and strength in the aggregate skeleton as well as limiting permeability of the HMA/WMA as well. Thus, rut and permeability can be better controlled largely by improving aspects of the aggregate grading by monitoring it via the Bailey ratios and porosity principles of the DASR method.

The Bailey ratios and DASR porosities of the plugger range of aggregates (between the PCS and HS sieves) as well as the interceptor range of aggregates (between the HS and NMPS sieves) in the midi range of the aggregate skeleton subsets proved to be the best correlated individually with the rut measurements. This is in line with the rationale of the correlation with modulus values previously determined by Al-Mosawe et al (2015). Such modulus value correlation is obviously highly temperature dependent, but here serves to indicate probability of good correlation with the revised rational Bailey ratios and DASR porosity ranges.

Individual Bailey ratios show narrow bands of correlation with rut in general. This is not a concern as it is used here with the available published datasets to merely indicate potential for correlation and it is expected to have the same type of good combined multiple stepwise correlation found by Al-Mosawi et al (2015) as illustrated by **equation 6**. The possibility of using Neural Network Analysis (NNA) or modelling will also now be possible with a better defined data set.

The modulus derived by the Al-Mosawe et al (2015) equation also correlated with ITS values determined in the original data set. However, the ITS values correlate better with Bailey ratios and DASR porosity values at the micro level of the aggregate skeleton subset. This is logical as tensile strength would be strongly linked to the mastic portion of the HMA/WMA. When the equivalent film thickness (EFT) is correlated with ITS, it confirms that the adhesion and cohesion component is linked with the effective bitumen mastic portion represented by th EFT.

5. REFERENCES

Al –Mosawe H, Thom N, Airey G and Albayati A . 2015. Effect of Aggregate Gradation on Stiffness od Asphalt Mixtures Originally published in International Journal on Pavement Engineering & Asphalt Technology, December 2015.

Al Shamsi K . 2006. Development of a mix design methodology for asphalt mixtures with analytically formulated aggregate. Ph D Thesis with the Department of Civil and

Environmental Engineering with the Agricultural and Mechanical College, Louisiana State University,

Denneman E, Verhaeghe BMJA and Sadzik ES . 2007. Aggregate packing characteristics of good and poor performing asphalt mixes. Proceedings of the 26th Southern African Transport Conference (SATC) , ISBN number 1-920-01702-X, Pretoria, South Africa (9 to 12 July 2007).

Freeze AR and Cherry JA . 1979. Groundwater. Prentice Hall. USA.

Furnas CC (1928) Relations between Specific Volume Voids and Size Composition on Systems of broken Solids of Mixed Sizes. US Bureau of Mines, report of Investigations, 2894, pp1-10, 1928

Harris CH .2007. Hot Mix Asphalt Permeability: Tester Size Effects and Anisotropy. Virginia Polytechnic Institute and State University. Thesis in partial fulfillment of the requirements for the degree Masters of Science in Civil and Environmental Engineering. November 14, 2007, Blacksburg, VA

Horak E, Seebaly H, Maina J and Varma S . 2017. Relationship between Bailey and Dominant Aggregate Size Range Methods for Optimum Aggregate Packing and Permeability Limitation. Paper submitted for inclusion in the proceedings of SATC, July 2017, CSIR, Pretoria, South Africa.

Lambe T W and Whitman RV . 1969. Soil Mechaninics. John Wiley & Sons, New York.

Kim, S., Roque, R., and Birgisson, B. (2006) Identification and Assessment of the Dominant Aggregate Size Range (DASR) of Asphalt Mixture. Journal of the Association of Asphalt Paving Technologists, Vol. 75, 2006, pp. 789-814.

Kim, S., Roque, R., and Birgisson, B., and Guarin, A. 2009. Porosity of the Dominant Aggregate Size Range to Evaluate Coarse Aggregate Structure of Asphalt Mixtures. Journal of Materials in Civil Engineering, Volume 21, No. 1, ASCE, 2009.

Olard F . 2015. GB5:Innovative design of High-Performance Asphalt Mixes for Long-Life and Cost –effective Pavements by Oprimizing Aggregates and using SBS Modified Bitumens. Proceedings of the Conference on Asphalt Pavements in Southern African (CAPSA). August 2015 Sun City, South Africa.

Roque, R., Birgisson, B. Kim, S and Gaurin A. 2006. Development of Mix Design Guidelines for Improved Performance of Asphalt Mixtures. Final report to Florida Department of Transportation, Contract BD545 (RPWO#16).

Sadasivam S and Khosa NP. 2006. Proceedings of Transportation Research Board (TRB) Annual Conference, January 2006, Washington, USA

Vavrik, W.R., W.J.Pine, G.Huber, S.H.Carpenter and R.Bailey. 2001. The Bailey Method of Gradation Evaluation, Journal of the Association of Asphalt Paving Technologists, Vol.70, 2001.