Contiguous aggregate packing as common principle for benchmarking asphalt density, stiffness and permeability control

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Highlights

- New approach described as CAP benchmark methodology.
- The CAP methodology allows benchmarking various designs and performance indicators to help refine asphalt mix designs.
- Prediction of stiffness, rut resistance, and permeability potential based on RBRs.
- Correlation of RBRs with compactability parameters of asphalt mixes.

Abstract

Contiguous aggregates are aggregate sizes that consecutively follow a typical aggregate grading curve. Porosity calculation is possible for a binary or longer ranges of contiguous aggregates. Porosity is a fundamental density indicator and can indirectly be an indicator of permeability potential. The traditional Bailey method follows the principle of the ratio of void size to aggregate or simulated sphere diameter that ensures optimal aggregate packing of the aggregate skeleton. In this paper, the Bailey method description of the grading curve and defined control sieves were used as a reference, allowing the description of various Rational Bailey Ratios adhering to contiguous aggregate fractions in these ratios. Thus, porosity calculations can be done for the contiguous aggregate fractions in these defined Rational Bailey Ratios on the normal aggregate grading curve. Recent research work on asphalt mix design compaction, air void distribution, stiffness, rut resistance, correlation with permeability predictors, and density indicate Rational Bailey Ratios can be used for the optimization of HMA mix designs via benchmarking. This approach is described as the Contiguous Aggregate Packing benchmark methodology.

Keywords

Contiguous
Aggregate fractions
Porosity
Benchmark methodology
Rut resistance
Stiffness
Permeability

1. Introduction

Good aggregate grading of freshly crushed aggregate is often the main contributor to stiffness under traffic loading in a variety of material types. In the field of concrete and asphalt mix designs, a typical design objective is a full matrix or lattice aggregate interlock ensuring high shear stiffness which ensures high density. This provides optimum stiffness and high durability (low permeability) in asphalt mixes. Aggregate grading envelopes are often specified as a control mechanism but has proven to be a blunt instrument to achieve the actual stiffness, and permeability design objectives [23]. The aggregate grading, therefore, needs to be enhanced as a control and/or design mechanism.

The application and articulation of packing optimisation of discrete aggregate particles are presented in support of the South African asphalt mix design guideline TG 35 [29]. All discrete design methods rely on the principle that aggregates need to be packed with the larger aggregate sizes making contact with each other to give an aggregate on aggregate interlock of the variety of aggregate sizes. It is often described as forming an aggregate skeleton that largely contributes to the structural stiffness of the asphalt mix. All these methods have their volumetric origin based on the theoretical study of spheres with various geometric three-dimensional packing configurations (Guerin, 2009 and [5]. It enables the determination of the ratio of the void size to the diameter of the same sized spheres to enable filling of the voids in between without disrupting the larger spheres [35].

Contiguous aggregates are aggregate sizes that consecutively follow a typical aggregate grading curve. Porosity calculation is possible for a binary combination or longer ranges of contiguous aggregates. Porosity is a fundamental density indicator and thus also of asphalt stiffness, rut resistance, and can indirectly be an indicator of permeability potential. In this paper, the state of the art approach to utilise Contiguous Aggregate Packing (CAP) as a basic principle is described. This CAP methodology allows for benchmarking various designs and performance indicators to help refine asphalt mix designs. The paper, therefore, presents the state of the art of current research and peer-reviewed information related to aggregate fraction ratios adhering to the contiguous aggregate packing principles. Such aggregate ratios follow the original Bailey method description of a typical asphalt mix grading curve defined as Rational Bailey Ratios (RBRs).

The paper is organized and structured as follows; this introduction section is followed by a background to contiguous aggregate packing, followed by in-depth discussions on the proposed use of the aggregate grading information. This is followed by three separate sections dealing with the linkage of the RBRs with stiffness and rut resistance, permeability potential, and compactability of asphalt mixes. Conclusions are presented at the end of the paper.

2. Background to contiguous aggregate packing

It is known that low porosity in an aggregate medium is directly related to high density as per the geotechnical description of soil structures. Therefore, low porosity objective via contiguous asphalt mix aggregate fractions has the same objective. The fundamental void size to sphere diameter ratio for optimum aggregate packing formed the basis of the Bailey Method (BM) originally developed by Robert Bailey. His proprietary method found broader application in the USA and subsequently elsewhere in the world, including South Africa [33], [30], [29] and SABITA [29]. The Dominant Aggregate Size Range-Interstitial Content

(DASR-IC) method was developed more lately at the University of Florida, USA, for the Florida Department of Transportation [27], [28], Guerin, 2009 and [5]. The origin of this DASR-IC method is based on the same volumetric description of void size to aggregate or sphere size ratio (Guerin, 2009 and [5] used in the BM.

The DASR definition is based on minimising porosity that can be determined for the upper or fine-to-large portion of the contiguous aggregate ranges in a normal aggregate grading curve. The contiguous aggregate range allows the calculation of porosity as a significant indicator of density and thus an indicator also of various aspects of structural stiffness of the aggregate contiguous range.

Work originally pioneered by Furnas [12], [13] with binary combinations of aggregates for concrete aggregate optimised packing density later found transfer to and application in the asphalt mix design field. Furnas originally determined the change in porosity of the variance in binary combinations of small and large aggregate size combinations. The original Binary Aggregate Packing (BAP) work and method in the concrete mix design field were subsequently further developed and applied by Baron et al. [4], [8], [7] for optimised concrete mixes. Perraton et al. [26], Olard [25] and Olard and Peraton [24] took this BAP method, applied it, and transferred it to the asphalt mix design field with success.

Lately, these three aggregate packing methods were successfully articulated by focusing on the determination of porosity of contiguous aggregate fractions and ranges [16] (a &b), 2019 and 2021, [17], [3], [20], [21], [32], [31], [22]. In this way, it was proven that combinations of contiguous aggregate fractions and ranges could be used to determine various aggregate fraction ratios of which the porosity can be determined and linked to density, rut resistance, asphalt stiffness and permeability potential.

The Bailey method was found to be the simplest discrete method application to accurately describe portions of the grading curve, which allows the definition of ratios of contiguous aggregate fractions or segments on the grading curve. The original Bailey method used various ratios of aggregate fractions, which can be utilized in a benchmark approach to guide the refinement of the aggregate grading to optimise stiffness (rut resistance) as the main focus. In essence, such contiguous aggregate ratios can typically be represented as binary aggregate fractions or ranges. Such binary contiguous aggregate fractions expressed in a ratio enable the application of the BAP knowledge. It allows the description of packing porosity, density and permeability potential at various levels in the grading curve. Some of the original Bailey method ratios did not allow porosity determination due to aggregate fractions overlapping in the numerator and denominator in the ratios defined, therefore not being contiguous.

3. Proposed use of aggregate grading information

3.1. Control sieve descriptors on the grading curve

The grading of a proposed asphalt mix design shown in Fig. 3.1 is used as a framework or reference to describe the RBRs as contiguous aggregate fraction ranges on such a grading curve. The 0.22 ratio of void size to diameter (or size) of the Nominal Maximum Particle Size (NMPS) or Nominal Maximum Aggregate Size (NMAS) is the starting point for such a grading curve analysis. The NMPs sieve size, by definition, is the closest sieve size through which 85% of the grading sample pass by mass (Appendix A of TG 35, 2020). The original

BM descriptors of the rest of the control sieves are retained as illustrated in Fig. 3.1 following the void to aggregate diameter ratio of 0.22 rule to define the Primary Control Sieve (PCS), the Secondary Control Sieve (SCS) and the Tertiary Control Sieve (TCS) [34].

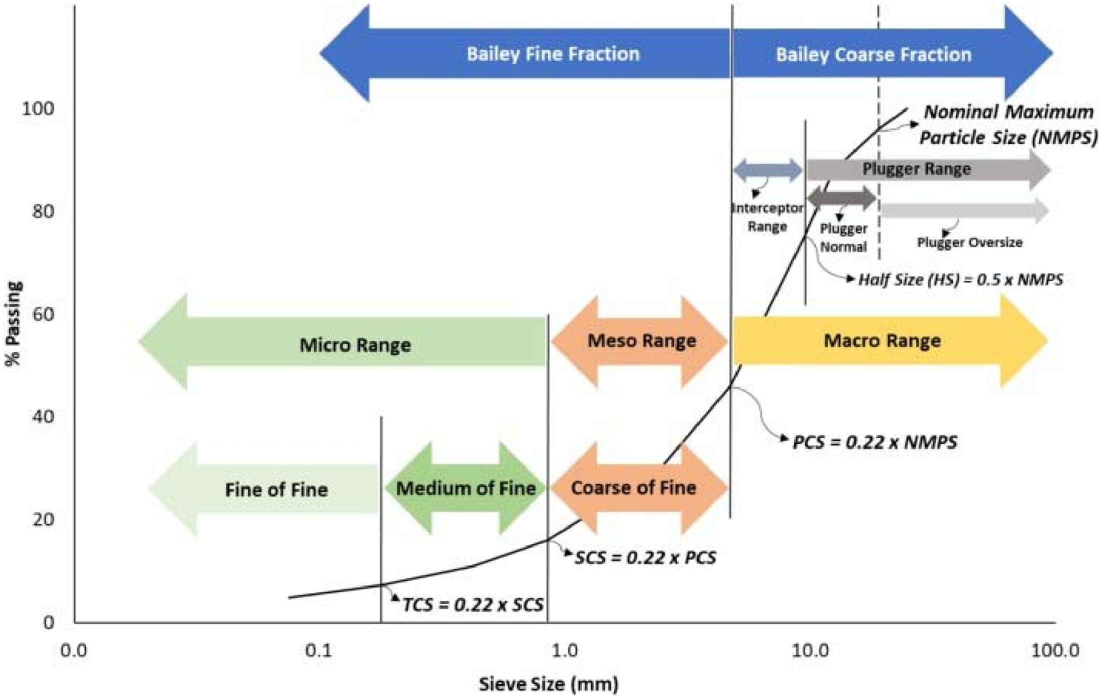


Fig. 3.1. Bailey method framework description of grading curve and control sieves.

A few additional aggregate ranges and sieve sizes also indicated in Fig. 3.1 are worth mentioning based on the BM framework to assist in the description of contiguous aggregate fraction ratios. Aggregates larger than the PCS are defined as the macro range in the aggregate matrix or grading curve (See column 1 in Table 3.1). The coarse fraction can be further described in terms of two distinct fraction ranges: The Interceptors (I) (between Half Size (HS) and PCS) and the Pluggers (P) (larger than HS). Horak et al. [19] further refined this Plugger range by describing the Pluggers Normal range (PN) as between HS and NMPS and Pluggers Oversize range (PO) as aggregates larger than NMPS. Aggregates smaller than PCS sizes up to SCS are described as the midi or rather meso range fraction. The BM fine fraction is composed of the meso range and the micro range. The meso range includes the fine fraction range coarse of fine (CF) between PCS and SCS sieve sizes. The fines smaller than SCS as well as TCS is described as the micro range. Horak et al. [19] subdivided the micro range into Medium of Fine (MF) between SCS and TCS and actual Fine of Fine (FF) smaller than TCS.

Table 3.1. Rational Bailey Ratios based on contiguous aggregate fractions defined by Bailey grading curve descriptors.

Matrix Level	Rational Bailey Ratios
Macro	$\frac{\mathbf{\mathit{PN}}}{\mathbf{\mathit{PO}}} = \frac{(\%\mathbf{NMPS} - \%\mathbf{HS})}{(\%100 - \%\mathbf{NMPS})} = \frac{\%\mathbf{Pluggers(PN)}}{\%\mathit{OversizeorPluggers(PO)}}$ ***Equation 1***
	$\mathbf{CA} = \frac{(\%\mathbf{HS} - \%\mathbf{PCS})}{(\%100 - \%\mathbf{HS})} = \frac{\%\mathbf{Interceptors}}{\%\mathit{Allpluggers}}$ ***Equation 2***
	$\frac{\mathbf{I}}{\mathbf{PN}} = \frac{(\%\mathbf{HS} - \%\mathbf{PCS})}{(\%\mathbf{NMPS} - \%\mathbf{HS})} = \frac{\%\mathbf{Interceptors}}{\%\mathbf{Pluggers(PN)}}$ ***Equation 3***
Midi or Meso	$\frac{\mathbf{\mathit{C_f}}}{\mathbf{\mathit{F_c}}} = \frac{(\%\mathbf{\mathit{PCS}} - \%\mathbf{\mathit{SCS}})}{(\%\mathbf{\mathit{HS}} - \%\mathbf{\mathit{PCS}})} = \frac{\%\mathbf{Coarseportionoffines}}{\%\mathit{Interceptors}}$ ***Equation 4***
	$\frac{\mathbf{\mathit{F}}}{\mathbf{\mathit{C}}} = \frac{(\%\mathbf{PCS})}{(\%\mathbf{NMPS} - \%\mathbf{PCS})} = \frac{\%\mathbf{Fines}}{\%(\mathbf{Plugger(PN)} + \mathbf{Interceptors})}$ ***Equation 5***
Micro	$\mathbf{\mathit{FA_{cm}}} = \frac{(\%\mathbf{SCS} - \%\mathbf{TCS})}{(\%\mathbf{PCS} - \%\mathbf{SCS})} = \frac{\%\mathbf{Mediumfineoffines}}{\%\mathit{Coarseoffines}}$ ***Equation 6***
	$\mathbf{\mathit{FA_{mf}}} = \frac{(\%\mathbf{TCS} - \%\mathbf{Filler}}{(\%\mathbf{SCS} - \%\mathbf{TCS})} = \frac{\%\mathbf{Fineoffines}}{\%\mathit{Mediumfineoffines}}$ ***Equation 7***

3.2. Contiguous Rational Bailey ratio definition

The contiguous principle allows the definition and calculation of a set of RBRs shown in Table 3.1. The Bailey grading curve descriptors of the sieve sizes are used as best or common descriptors. These RBRs are not just based on the BM description of the grading curve, but also based on the sieve sizes used in South Africa. The sieve sizes tend to increase or decrease by a factor of two, e.g. 40 mm, 20 mm, 10 mm, 5 mm, etc. There is often more than one aggregate fraction size lumped together between some of these sieve sizes. The BAP principle allows the evaluation of the contribution of binary aggregate fractions if they can be defined by separate sieve sizes. By using additional available sieve sizes, it may be possible to expand on these RBRs currently described in Table 3.1 and fully utilise the knowledge that BAP can provide specifically related to investigating aggregate ranges that influence permeability [19]. The matrix level descriptors in column 1 of Table 3.1 are to facilitate the concept or even visualization of successive aggregate ranges that fit into each other's voids like the Matryoshka dolls [25] concept. These ranges of macro, meso and micro levels are approximately ranging respectively from maximum size sieve to PCS, from PCS to SCS, from SCS to TCS, and from TCS to the finest bottom of the grading curve as illustrated in Fig. 3.1. These matrix level descriptors are not rigidly defined as typically changes in NMPS (e.g. 20 mm or even 40 mm) may cause a shift of some of the control sieves linked to actual asphalt mix type or change in maximum aggregate size being used (See Appendix A of TG35, 2020).

3.3. Voids in mineral aggregate influence

Influence on Voids in Mineral Aggregate (VMA) is a significant aspect in the volumetric analysis of asphalt gradings. As per TG 35 (2021), VMA is calculated as shown in Equation 8 and also TG 35 (2020).

$$\mathbf{VoidsinMineralAggregate(VMA)} = \mathbf{V_{TM}} - \mathbf{V_{AGG}} \tag{8}$$

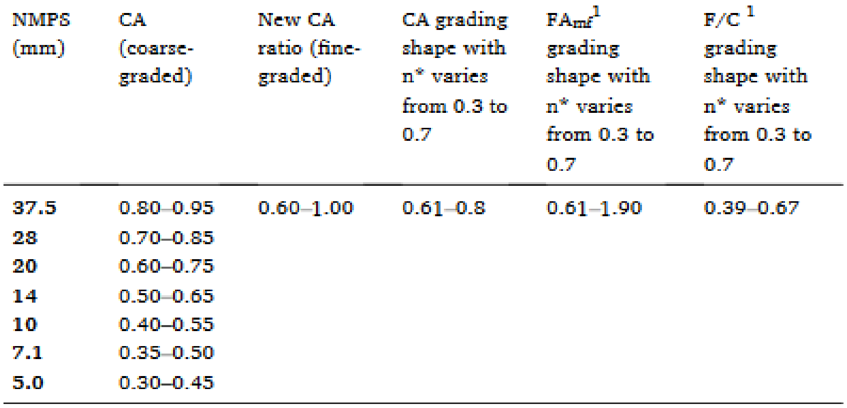
where,

V_{TM} = Total volume of mix; and

V_{AGG} = Volume of all the aggregate.

In Table 3.2, the variance in coarse aggregate (CA) ratio is shown as described in TG 35 (2020) for coarse and fine graded type asphalt mixes. Only the CA ratio is shown as a true RBR, the other two traditional Bailey ratios have overlapping aggregate fractions and their value ranges are shown in the TG35 (2020) Appendix A. Guidance regarding typical meso and micro levels' RBRs like F/C and FA_{mf} are based on limited data sets from Komba [22]. Note that Komba [22] did not test for SMA type mixes, and therefore, Table 3.2 only relates to recommendations for the original CA ratio described in Appendix A of TG 35 (2020).

Table 3.2. Recommended ranges of RBR.



NMPS (mm)	CA (coarse-graded)	New CA ratio (fine-graded)	CA grading shape with n* varies from 0.3 to 0.7	FA_{mf}[1] grading shape with n* varies from 0.3 to 0.7	F/C [1] grading shape with n* varies from 0.3 to 0.7
37.5	0.80–0.95	0.60–1.00	0.61–0.8	0.61–1.90	0.39–0.67
28	0.70–0.85				
20	0.60–0.75				
14	0.50–0.65				
10	0.40–0.55				
7.1	0.35–0.50				
5.0	0.30–0.45				

Note 1. These are provisional ranges based only on the limited dataset from Komba [22] PhD research and can be expanded or updated as new research information becomes available. **Note n*.** The classic Fuller Thompson maximum density equation $Pi = (di/Dmax)^{n}$ where Pi is the percentage aggregate passing sieve size with diameter di, Dmax is the maximum size of aggregates and n is a gradation shape factor".

3.4. Porosity of main load-bearing aggregate skeleton

In soil mechanics, the porosity of loose granular materials is approximately 45 to 50 percent regardless of particle size or distribution (Greene et al., 2014). This implies that the porosity of aggregate particles within an asphalt mixture must not be >50 percent for the particles to be in contact with each other. By assuming that an asphalt mixture has a certain effective asphalt content and air voids for a given gradation (i.e. VMA), porosity can be calculated for any single sieve size, or any two or more contiguous sieve sizes within the mixture.

An important aggregate skeleton stiffness aspect lifted out by Yanqui [35] is the link between porosity and implied internal shear angle, as demonstrated in Fig. 3.2. The lower the porosity, the higher the effective internal angle of shear for a specific aggregate and material origin. This implies that shear characteristics can be enhanced by low porosity aggregate mixes to its fullest internal shear angle value at the lowest porosity that is possible to be attained.

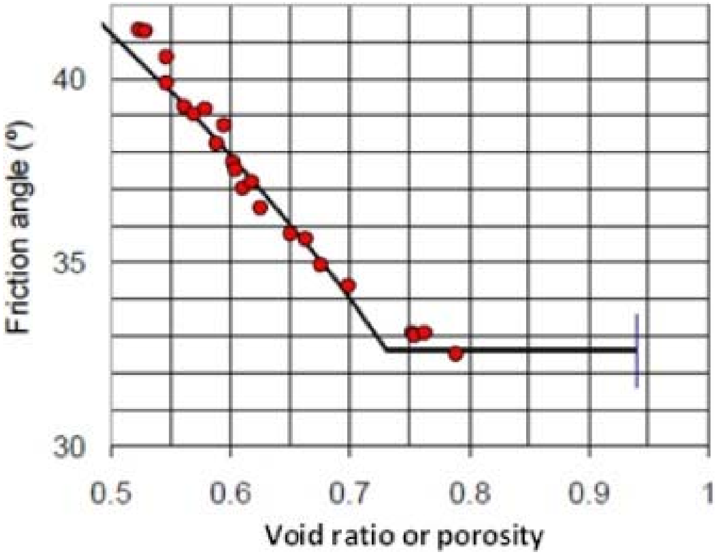


Fig. 3.2. Relationship between internal void ratio (porosity) and internal friction angle for a brasted sand [35].

Equation 9 can be used to calculate the porosity of a contiguous range of aggregate fractions (Greene et al., 2014, [27], [15] based on basic volumetric parameters identified or demonstrated in Fig. 3.3 originally defined for DASR-IC mix design methodology.Fig. 6.1

$$\eta_{\mathrm{DASR}} = \frac{\mathrm{V}_{\mathrm{V(DASR)}}}{\mathrm{V}_{\mathrm{T(DASR)}}} = \frac{\mathrm{V}_{\mathrm{ICAGG}}+\mathrm{VMA}}{\mathrm{V}_{\mathrm{TM}}-V_{AGG>DASR}} \tag{9}$$

where,

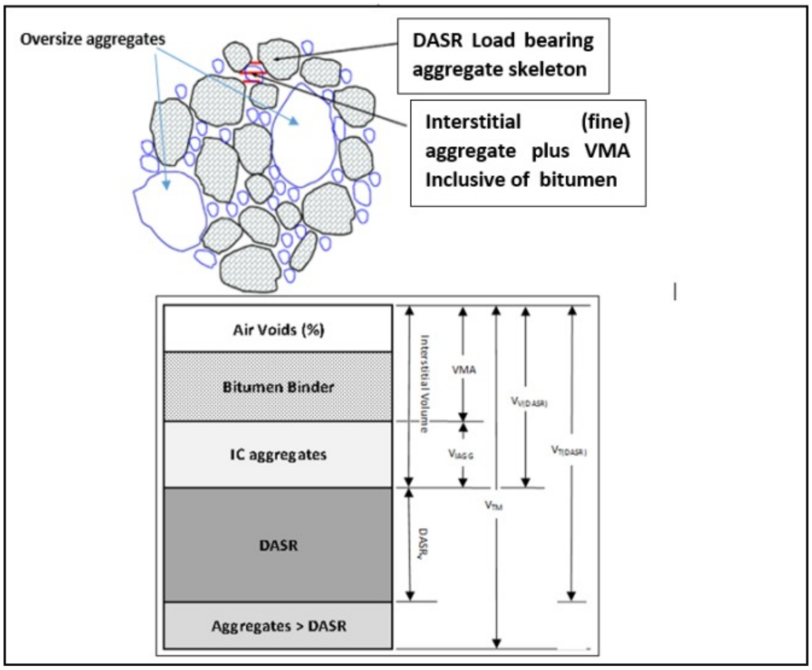
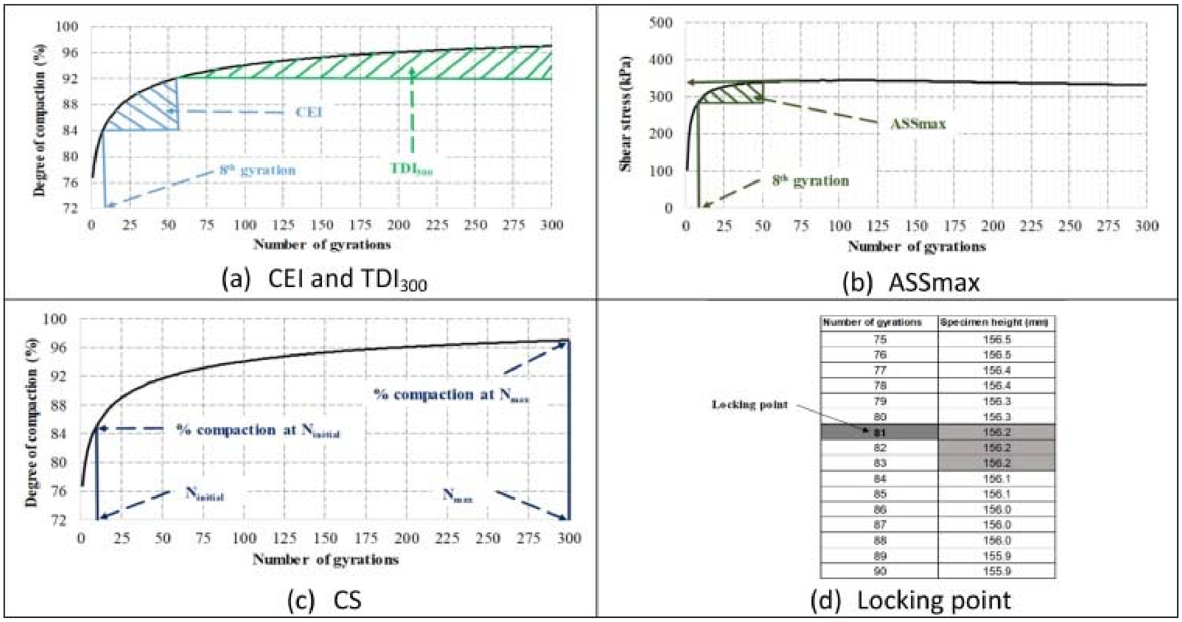


Fig. 3.3. Asphalt mixture components or phases diagrammatically and conceptually (Chun, 2011).



(a) CEI and TDI_{300}

(b) ASSmax

(c) CS

Number of gyrations	Specimen height (mm)
75	156.5
76	156.5
77	156.4
78	156.4
79	156.3
80	156.3
81	156.2
82	156.2
83	156.2
84	156.1
85	156.1
86	156.0
87	156.0
88	156.0
89	155.9
90	155.9

(d) Locking point

Fig. 6.1. Conceptual illustration of Compactability Parameters [22].

η_{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;

$V_{T(DASR)} = V_{TM} - V_{AGG>DASR}$ = 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; and

V_{ICAGG} = Volume of IC aggregates.

Denneman et al. [9] simplified the DASR-IC porosity calculation when limited to a single or combination of two contiguous aggregate fractions, as shown in Equation 10.

$$\eta_{(4.75-2.36)} = \frac{\left[\left(\frac{\mathbf{PP}_{2.36}}{100}\right)(\boldsymbol{V_{TM}} - \mathbf{VMA}) + \boldsymbol{VMA}\right]}{\left[\left(\frac{\mathbf{PP}_{4.75}}{100}\right)(\boldsymbol{V_{TM}} - \mathbf{VMA}) + \boldsymbol{VMA}\right]} \tag{10}$$

where,

$\eta_{(4.75-2.36)}$ = Porosity of the fraction passing 4.75 mm sieve and retained on 2.36 mm sieve;

$PP_{2.36}$ = Percentage particles passing 2.36 mm sieve;

$PP_{4.75}$ = Percentage particles passing 4.75 mm sieve;

VMA = Voids in mineral aggregate; and

V_{TM} = Total volume of mix.

It is, therefore, possible to calculate the porosity for various RBRs. This would cover mostly the RBRs in the macro and meso range. In the DASR approach, the oversized aggregates are excluded as they tend to “drift” on top of the plugger (P) and interceptor (I) ranges and do not appear to contribute to the load-bearing aggregate skeleton. That implies the first two RBRs (Equation 1 and 2) may not provide good porosity reduction values.

It is anticipated that the combined ratios $\frac{I}{PN}$ and $\frac{C_f}{F_c}$ may be closer to the original concept of the DASR as they exclude the oversized and ends the locked in aggregate ranges in their ratios on the SCS. The SCS size is the typical divide between the DASR (macro size aggregates down to the SCS and fines, which include the Interstitial Content (IC) aggregate size range. Therefore, the equivalent range of the DASR expressed in terms of the RBRs sieve sizes expressed as a contiguous aggregate range would be stretching from NMPS to SCS. Such a CAP main skeleton load-bearing contiguous aggregate range can be described as expressed in equation 11 (See definitions in Fig. 3.1).

$$CAP = \frac{(\%\mathbf{PCS}-\%\mathbf{SCS})}{(\%\mathbf{NMPS}-\%\mathbf{PCS})} = \frac{\%\mathrm{CoarseofFine(CoF)}}{\%\mathbf{Pluggers}+\%\mathbf{Interceptors}} = \frac{Mesorangeaggregates}{\mathbf{Macrorangeaggregates}} \quad (11)$$

From equation 11, it is obvious that the DASR is the same as described by the CAP, but with the difference that the pseudo-DASR is now described in terms of the Bailey method control sieves and contiguous range aggregate fractions. Recommendations made by Green et al. [14] regarding DASR porosity ranges are translated to the CAP range as shown in Table 3.3. These porosity values can be used to indicate if a design mix aggregate grading may have strong or weak structural stiffness contributions. Only one Rational Bailey Ratio per macro, meso, and micro level of the typical grading curve is shown here for this benchmark purposes.

Table 3.3. Porosity benchmark ranges for selected RBRs.

RBR	Porosity range	
	Good structural stiffness and dense	Marginal structural stiffness and less dense
I/PN	40 to 49	50 to 65
C_f/F_c	40 to 49	50 to 65
CAP	38 to 48	48 to 52

4. Stiffness and rut resistance correlation with Rational Bailey ratios

4.1. Stiffness prediction with Rational Bailey ratios

Stiffness is an important structural indicator of asphalt mixes. Work done by Al-Mosawi et al. [1] built on previous prediction models and then included macro and messo levels RBRs in an updated prediction model to determine asphalt stiffness via Binder elastic modulus and VMA. This work indicated the meso level contiguous ratios (Cf/Fc and F/C) contribute significantly towards correlated stiffness and not just as suspected the larger aggregate skeleton portion represented by the original Bailey ratio (i.e. CA). Al-Mosawi et al. [1] correlation equation thus developed is shown in Equation 13, where “E” is the stiffness expressed in MPa. The R^2 value of this correlation study was 0.79, making it a reliable potential predictor of asphalt stiffness. The value of Equation 13 allows a design to be checked using the RBRs as a simple, early verification of actual stiffness.

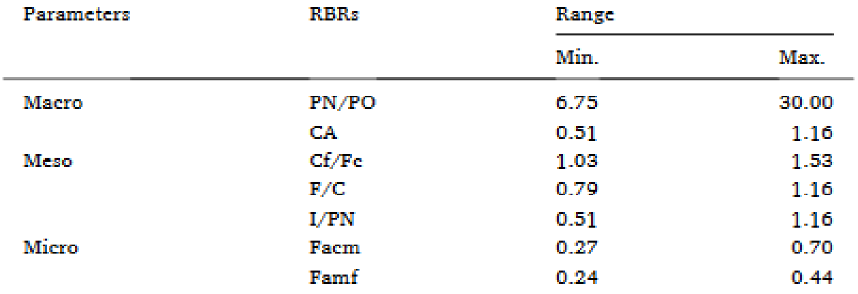
$$E=4412-245\ CA+337(C_f/F_c)+1784\ (F/C) \tag{13}$$

4.2. Rut prediction with Rational Bailey Ratios

In Al-Mosawi’s PhD thesis (2016), it was postulated that permanent strain (∊) could be predicted by linear regression analysis with a limited database of 13 asphalt mixes. Al-Mosawi [2] attempt to correlate RBRs with permanent strain resulted in equation 14. The RBRs are as defined in Table 4.1, and the R^2 value for the dataset was 0.79.

$$\epsilon=-8.51+0.713CA+25.58FA_c+0.205C_f/F_c \tag{14}$$

Table 4.1. Suggested Rational Bailey Ratio ranges for rut-resistant mixes.



Parameters	RBRs	Range	
		Min.	Max.
Macro	PN/PO	6.75	30.00
	CA	0.51	1.16
Meso	Cf/Fc	1.03	1.53
	F/C	0.79	1.16
	I/PN	0.51	1.16
Micro	Facm	0.27	0.70
	Famf	0.24	0.44

When Al-Mosawi [2] enlarged the data set and included Stone Mastic Asphalt and Porous Asphalt mixes to the original continuously graded asphalt mixes, the correlation previously established was not reliable anymore. Further work with Artificial Neural Network (ANN) and later adaptive neuro-fuzzy inference system (ANFIS) technique confirmed these RBRs identified in Equation 14 have a significant and more complex interaction to predict permanent strain (∊). Such more complex outputs and larger data sets certainly would allow machine learning techniques to use during design procedures to predict what rut propensity might be, but falls outside the simpler benchmark methodology approach pursued in this paper.

More recent work by Sebaaly et al. [32] has found a good correlation between dry Hamburg Wheel Tracking Test (HWTT) and RBRs when considering various RBRs and the result is shown in Equation 15. The R^2 value of Equation 15 was 0.64. Sebaaly et al. [32] commented that PN/PO does not have a high impact on the correlation, since the R^2 fit does not get significantly affected if this parameter is excluded from the calculations. Table 4.1 illustrates the RBRs ranges proposed by Sebaaly et al. [32] for the prediction of rut resistant mixes. These RBRs value ranges and Equation 15 can be used as a first-order benchmark check on continuously graded mixes.

$$\begin{aligned}&\mathbf{RD(dryHWT)}\\&= 11.94 + 0.003\frac{\mathbf{PN}}{\mathbf{PO}} + 16.9\mathbf{CA} - 17.81\frac{\mathbf{C_f}}{\mathbf{F_c}} + 32.50\frac{\mathbf{F}}{\mathbf{C}} - 29.37\frac{\mathbf{I}}{\mathbf{PN}} - 9.03\mathbf{FA_{cm}}\\&- 3.92\mathbf{FA_{mf}}\end{aligned} \tag{15}$$

5. Permeability potential

5.1. Rational Bailey ratios as permeability indicators

Horak et al. [19], [18] used the RBRs linked with porosity and BAP principles to the two phenomena observed in aggregate mixes, namely: The wall effect and the disruptor or loosening effect. Both aggregate packing phenomena are believed to be linked to the potential for interconnected voids which, in itself is a basic requirement for permeability linked to the flow of water in asphalt mixes [19], [18].

The original models by Sadasivim and Khosla (2006) and Denneman et al. [9] on specific aggregate fractions and ranges influencing permeability in asphalt mixes gave weak empirical correlations with actual permeability measurement. These data sets were reworked by Horak et al. [16], [18] to correlate RBRs with the probability of permeability occurring in the asphalt mixes. The RBRs showing the best probability to influence permeability potential are listed in Table 5.1.

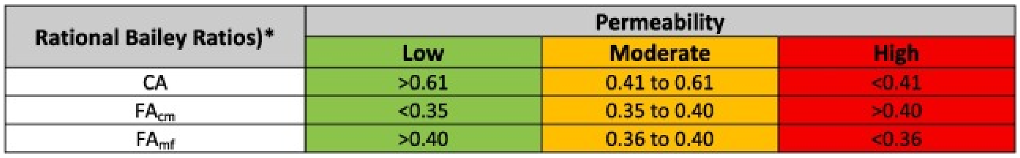
Table 5.1. Rational Bailey Ratios and likelihood to influence permeability.

Skeleton level	Rational Bailey Ratios	Likelihood to influence interconnected voids
Macro	PN/PO	Less likely
	CA	Likely
Meso or Midi	I/PN	Less likely
	Cf/Fc	Less likely
	F/C	Less likely
Micro	FAcm	More likely
	FAmf	More likely

This better likelihood of influencing permeability tends to be in the meso and more so in the micro range RBRs. In the asphalt mix design process, once the macro and meso level skeleton had been formed, providing the needed structural stiffness framework the voids in between need to be filled by the micro-level aggregates. In this ideal grading description, the rule of thumb developed is *"The voids are (now) in the fines*!". These voids can be limited in individual size while connectivity will be governed by primarily the characteristics of the micro range of the grading envelope adhering to the void filling principles described by the Bailey method. Their benchmark indications are colour coded along the idea of RAG (Red for high permeability, Amber for moderate or fair and Green for low permeability impact) to enable their use in a first-level benchmark application. From this, it is clear that the micro-level ratios are more likely to influence permeability than messo and macro levels ratios. The original Bailey ratio, CA, is the only ratio in the macro level that shows such potential to influence permeability.

Only the RBRs identified in Table 5.1 are benchmarked with the typical RAG benchmarking in Table 5.2. In this case, RAG stands for the colour Red "severe or significant", the colour Amber "medium or warning", and the colour Green "low to insignificant" influence on permeability. These ranges can be used as indicative in a first level benchmarking to indicate possible permeability issues with asphalt mixes, and with experience, it can be improved as the size of the database increases.

Table 5.2. Average Rational Bailey Ratios for reworked data sets for low and high permeability mixes (Adjusted from Horak et al., 2017b in 2021).



Rational Bailey Ratios)*	Permeability		
	Low	Moderate	High
CA	>0.61	0.41 to 0.61	<0.41
FA_{cm}	<0.35	0.35 to 0.40	>0.40
FA_{mf}	>0.40	0.36 to 0.40	<0.36

5.2. Use of large international permeability studies using air voids

Horak et al. [9], Blaau et al. [3] and Cromhout [6] indicated that the research by Norambeuna-Contreras et al. (2013) enables the development of a universal relationship between hydraulic conductivity or the coefficient of permeability (k in cm/s) and void content for a variety of HMA types (Fine, Dense, up to Open and even Porous asphalt). Nor Bailey method neither DASR principles were applied, and therefore, no reference is made to them in this study by Norambeuna-Contreras et al. (2013). The mix designs used in this large international database study did follow Superpave guidelines with NMPS for a variety of mix types ranging from 19 mm to 9.5 mm. The study statistically described the spread of void content and the variability of void interconnectedness. Measurements from laboratory testing, field testing, and published work were included in the study. The relationship is shown in equation 16.

$$-ln(k) = 45.97\left(\frac{1}{A_{vc}}\right) + 1.82 \tag{16}$$

where,

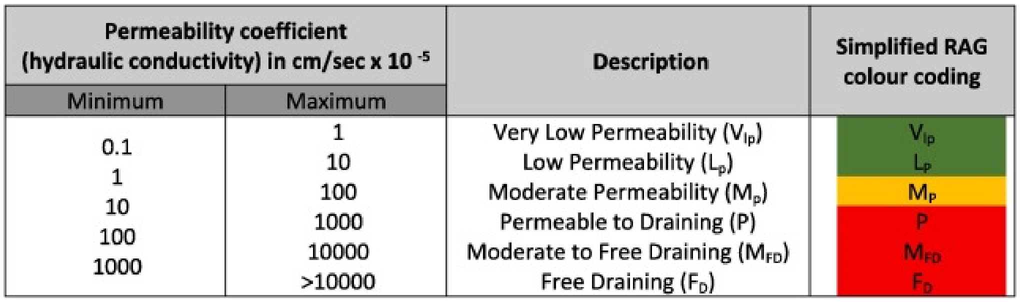
Ln = Natural logarithm;

k = Coefficient of permeability; and,

Avc = the air void content.

Norambeuna-Contreras et al. (2013) indicated that the benchmarked ranges of hydraulic conductivity (permeability) are best described as shown in Table 5.3 with a simplified RAG benchmark colour coded scale added.

Table 5.3. Permeability coefficient (hydraulic conductivity) ranges.



Permeability coefficient (hydraulic conductivity) in cm/sec x 10^{-5}		Description	Simplified RAG colour coding
Minimum	Maximum		
0.1	1	Very Low Permeability (V_{lp})	🟩 V_{lp}
1	10	Low Permeability (L_p)	🟩 L_p
10	100	Moderate Permeability (M_p)	🟨 M_P
100	1000	Permeable to Draining (P)	🟥 P
1000	10000	Moderate to Free Draining (M_{FD})	🟥 M_{FD}
	>10000	Free Draining (F_D)	🟥 F_D

The empirical relationship developed by Vardanega and Waters (2011 and 2015) and Vardenega et al. (2008, 2011 and 2017) qualify as a truly "universal" permeability potential indicator. A vast collection of actual data sets of known permeable and less permeable mixes were used by Vardenega and Waters (2015) to provide their correlation relationship. The more recent research by Vardenega et al. (2017) also includes the Norumbeura-Contreras et al. (2013) database, therefore making it a very big international database inclusive of data using various means determining permeability in the laboratory and field.

Vardanega and Waters (2015 and 2017) succeeded to predict asphalt permeability using a more descriptive parameter, representative pore size (RPS), which strongly links to interconnected voids. The RPS value is related to the air voids in the compacted mix and effective particle size. Vardanega and Waters (2015 and 2017) and Feng et al. [10] developed Equation 17 that may be used to calculate indicative values of permeability of asphalt layers and mixes.

$$\mathbf{k} = \frac{46}{100}(\mathbf{R_P})^{3.70} \tag{17}$$

where,

K = permeability (mm/s);

$R_p = (2/3)*[AV(\%)/100]*[D_{75}(mm)]$;

AV(%) = percentage air voids; and,

D_{75} = the effective particle size which is the sieve aperture (mm) through which 75% of the granular material in the mix would pass.

Feng et al. [11] expanded the original and later Vardenega et al. (2015 and 2017) database to develop an improved empirical model. The empirical relation is based on an even larger database of permeability tests with various laboratory and field test equipment. In this more recent study, a new prediction model comprising of both air voids and grading entropy is presented which improved the prediction model even further. Typically, the empirical model or equation was also improved and is still using the representative effective particle size which was changed to the D_{60} value. This smaller effective particle size (D_{60} versus D_{75}) relates even better to the previously mentioned mantra: "*The voids are now in the fines!*"

The intention is to propose the use of these RBRs and regression correlation calculations (Equations 16 and 17) as early warning indicators of potential for permeability in the mixes. It is suggested these equations should be used on laboratory produced briquettes during the design phase on mixes that had already proved to be strong and stiff. Horak et al. [18] demonstrated the use of these benchmarking ranges with forensic investigations on laboratory produced briquettes during the mix design process and if indicated they may be permeable they also were confirmed by actual permeability observed and tested via cores from the road in the field.

6. Compactability and workability

6.1. Introduction to compactability parameters

Asphalt mix design often focuses on aspects like being rut resistant, while the actual constructability may be problematic due to the harshness of the mixes proposed. The more recent work on compactability linked with RBRs by Komba [22] and Komba et al. [7], based on the gyratory compactor to compact asphalt mixes, is summarised here to indicate the potential use via further benchmark analysis of constructability aspects linked with the RBRs. The use and availability of the gyratory compactor in asphalt laboratories in South Africa make this a very useful tool to investigate the compactability of asphalt mixes. The compactability of each HMA mix was evaluated by analysing the gyratory compaction data to determine compactability parameters, which indicate the mix resistance to the compaction energy. The determined compactability parameters included:

- locking point (LP),

- compaction energy index (CEI),

- traffic densification index (TDI_{300}),

- compaction slope (CS), and

- the area under shear stress (ASS_{max}).

A more detailed description of these indices or parameters are not explored in this paper, but the Komba PhD thesis (2021) gives a detailed description. However, basic descriptions of these parameters are given first to enable the actual aim to correlate these with the RBRs to facilitate benchmarking analysis of the constructability aspect of asphalt mix designs. The CEI and TDI_{300} compactability parameters are conceptually illustrated in Fig. 6.1a, and the ASSmax parameter is illustrated in Fig. 6.1b. Equation 18 is used to determine CS, using parameters illustrated in Fig. 6.1c, and the locking point definition is illustrated in Fig. 6.1d.

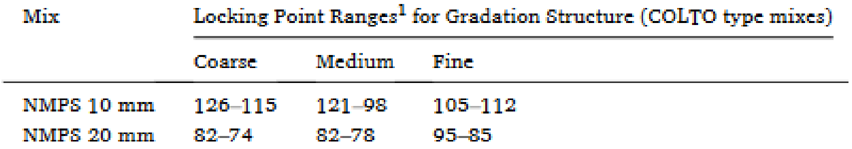
Each of these compactability parameters is briefly discussed, and the ranges proposed are based on the limited data range produced by Komba [22]. It should be seen as an initial indicator and such ranges can be adjusted as more data for different mix types become available.

6.2. Locking point

The number of gyration at which the HMA mix resists further compaction is referred to as the locking point (LP) and is related to the compactability or workability of the HMA mix. The locking point definition adopted by Komba [22] is the first gyration of the three consecutive gyrations that yield the same HMA specimen height where these gyrations follow the two sets of gyrations that have the same height (see Fig. 6.1d).

In Table 6.1, the ranges for LP are interpreted from the Komba [22] test range values to indicate potential ranges. As indicated, these ranges are based on limited data, and further research and implementation data should help update these guiding ranges in the future.

Table 6.1. Proposed Locking Point ranges of typical mix types.



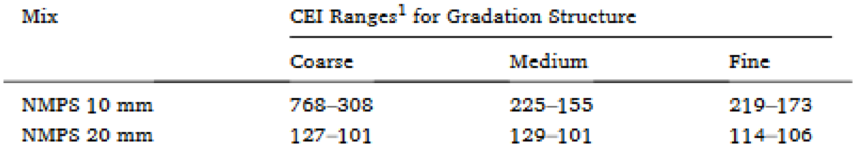
Mix	Locking Point Ranges[1] for Gradation Structure (COLTO type mixes)		
	Coarse	Medium	Fine
NMPS 10 mm	126–115	121–98	105–112
NMPS 20 mm	82–74	82–78	95–85

Note 1. These ranges are based on the average plus or minus one standard deviation of the Komba data (2021).

6.3. Compaction energy index (CEI) and traffic densification Index(TDI)

These two compaction indices (CEI and TDI) are combined as illustrated on the gyratory compaction densification graph shown in Fig. 6.1a. Note the common reference point between CEI and TDi is the 92% density point. The proposed ranges of CEI is shown in Table 6.2 and that for TDI in Table 6.3. The key characteristic of the densification curve, as depicted in Fig. 6.1a, is that at the initial stage of the compaction process, the HMA material is still in a loose state. Hence, the degree of compaction increased rapidly with an increase in the number of gyrations. Once the HMA sample has achieved a certain level of densification, a further increase in the number of gyrations results in a relatively small addition in the degree of compaction.Table 6.4

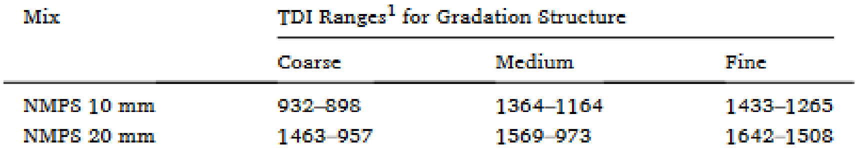
Table 6.2. Proposed Compaction Energy Index ranges of typical mix types.



Mix	CEI Ranges[1] for Gradation Structure		
	Coarse	Medium	Fine
NMPS 10 mm	768–308	225–155	219–173
NMPS 20 mm	127–101	129–101	114–106

Note 1. These ranges are based on the average plus or minus one standard deviation of the Komba data (2021).

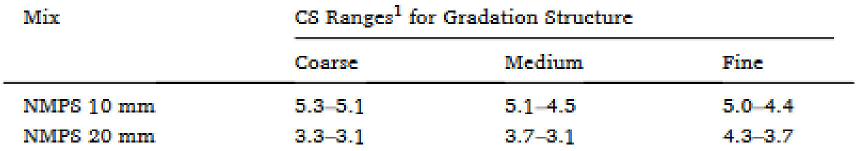
Table 6.3. Proposed Traffic Compaction Index (TDI_{300}) ranges of typical mix types.



Mix	TDI Ranges[1] for Gradation Structure		
	Coarse	Medium	Fine
NMPS 10 mm	932–898	1364–1164	1433–1265
NMPS 20 mm	1463–957	1569–973	1642–1508

Note 1. These ranges are based on the average plus or minus one standard deviation of the Komba data (2021).

Table 6.4. Proposed Compaction Slope (CS) ranges of typical mix types.



Mix	CS Ranges[1] for Gradation Structure		
	Coarse	Medium	Fine
NMPS 10 mm	5.3–5.1	5.1–4.5	5.0–4.4
NMPS 20 mm	3.3–3.1	3.7–3.1	4.3–3.7

Note 1. These ranges are based on the average plus or minus one standard deviation of the Komba data (2021).

6.4. Compaction slope (CS)

The gyratory compaction densification curve of each HMA sample can be used to determine the compaction slope (CS) described by Equation 18. Fig. 6.1c illustrates the determination of the parameter required to compute the compaction slope. The proposed CS ranges established are shown in Table 6.4.

$$CS = \frac{\%compactionatN_{max} - \%compactionatN_{initial}}{log(N_{max}) - log(N_{initail})} \qquad (18)$$

where,

$N_{initial}$ is the number of gyrations at initial compaction; and

N_{max} is the number of gyrations at maximum compaction.

6.5. Area under the shear stress curve (ASS_{max})

The new compaction parameter developed by Komba [22] is the area under shear stress (ASS_{max}) from the 8th gyration to the gyration where maximum shear stress is achieved, and an example is illustrated in Fig. 6.1b. Generally, the higher the ASS_{max}, the more difficult it is to compact the HMA mix. The proposed ranges in ASSmax is shown in Table 6.5. This parameter has high Coefficients of Variability in the data observed and is not rated as a reliable indicator at present.

Table 6.5. Proposed Area under the Shear Stress (ASS_{max}) ranges of typical mix types.

Mix	ASS_{max} Ranges[1] for Gradation Structure		
	Coarse	Medium	Fine
NMPS 10 mm	4967–3491	4311–2537	4202–2820
NMPS 20 mm	5293–2833	4268–1916	4788–522

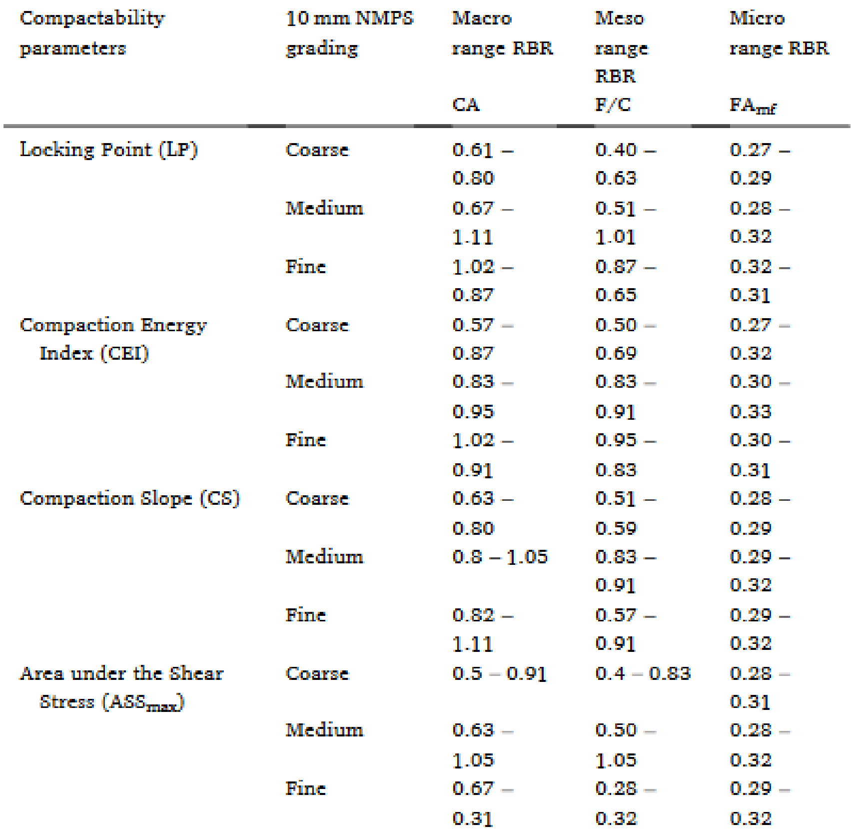
Note 1. These ranges are based on the average plus or minus one standard deviation of the Komba data (2021).

6.6. Rational Bailey ratios correlation with compaction parameters

The inverse of Rational Bailey Ratios (RBRs) was used by Komba [22] due to better linkage with BAP principles and knowledge. These inverse RBRs were correlated with the HMA compactability parameters discussed above [22]. To this end, the average HMA compactability parameters (LP, CEI, TDI_{300}, CS and ASSmax) of each of the coarse, medium and fine-graded HMA mixes were correlated to their inverse RBRs (CAr, C/F and FArmf). The results were reported for 10 NMPS mixes (mostly surfacing mixes) and 20 NMPS mixes (mostly asphalt base type mixes).

The study by Komba [22] and Komba et al. [21] found a strong correlation between gradation parameters and RBRs with HMA compactability parameters LP, TDI_{300}, SS_{max}, and CS with correlation coefficient (r) ranging from |0.88| to |1.00|). Correlations with CEI were found to be relatively weaker to medium (r ranging from |0.53| to |0.72|). This could be because the CEI is determined in the early stage of the compaction process (i.e., from 8th gyration to 92% compaction), while the HMA mix is still in a loose state at which the influence of the aggregate gradation structure is not prominent; The newly defined traffic densification index (TDI_{300}) proposed in the study showed a strong correlation (r ranging from |0.93| to |0.99|) with the packing parameters. Additionally, two shear stress-based HMA compactability parameters (SSmax and ASS) proposed by Komba [22] were also found to correlate very well with the aggregate gradation parameters and the RBRs. The selected RBRs represents the macro, meso, and micro aggregate fraction ranges. It had already been stated that this study represents a limited data set, but the stated correlation coefficients warrant RBR ranges that correlate with the compactability parameters shown in Table 6.6. Only the values for the 10 mm NMPS mixes are shown in Table 6.6, as it is the most commonly used asphalt mixes for surfacing in South Africa. Similar to the previous ranges presented in Table 6.1 to Table 6.5, the intention is to be used as an indicator of compactability in a benchmark fashion. Furthermore, as the database is enlarged, these ranges will also be reviewed and updated.

Table 6.6. RBR ranges correlating with compactability parameter ranges for 10 mm NMP mixes.



Compactability parameters	10 mm NMPS grading	Macro range RBR CA	Meso range RBR F/C	Micro range RBR FA_{mf}
Locking Point (LP)	Coarse	0.61 – 0.80	0.40 – 0.63	0.27 – 0.29
	Medium	0.67 – 1.11	0.51 – 1.01	0.28 – 0.32
	Fine	1.02 – 0.87	0.87 – 0.65	0.32 – 0.31
Compaction Energy Index (CEI)	Coarse	0.57 – 0.87	0.50 – 0.69	0.27 – 0.32
	Medium	0.83 – 0.95	0.83 – 0.91	0.30 – 0.33
	Fine	1.02 – 0.91	0.95 – 0.83	0.30 – 0.31
Compaction Slope (CS)	Coarse	0.63 – 0.80	0.51 – 0.59	0.28 – 0.29
	Medium	0.8 – 1.05	0.83 – 0.91	0.29 – 0.32
	Fine	0.82 – 1.11	0.57 – 0.91	0.29 – 0.32
Area under the Shear Stress (ASS_{max})	Coarse	0.5 – 0.91	0.4 – 0.83	0.28 – 0.31
	Medium	0.63 – 1.05	0.50 – 1.05	0.28 – 0.32
	Fine	0.67 – 0.31	0.28 – 0.32	0.29 – 0.32

7. Conclusion

There are various discrete models of aggregate grading that evaluate the aggregate packing as a tool for asphalt mix design evaluation. The basis of these evaluations is linked to various definitions and descriptions of the standard aggregate grading. It is acknowledged that such an analysis using grading information is simplified and ignore the known impact of other factors of influence such as shape, texture, binder content, type and film thickness. The Bailey method definition of sieve sizes and known aggregate size on a typical asphalt aggregate grading curve forms the basis of the description of various parameters used. The basis of the Bailey method relies on the fundamental ratio of the size of space between aggregates to give further credibility to a universal description of the various aggregate sizes and control sieves on the grading curve. The contiguous aggregate size principle allows porosity calculation of binary or a range of contiguous aggregates. The grading curve description with various RBRs meets the contiguous principle. The calculation of porosity as a basic principle is possible with such contiguous aggregate ranges in such aggregate ratios defined in the RBRs. Porosity is known to be directly linked to density as well as voids in the asphalt mix and therefore also permeability. Density is a known measurable parameter that is linked with other engineering parameters such as desired design objectives, namely; asphalt stiffness and rut resistance.

It was shown that these RBRs can be linked to newly defined indices or parameters for asphalt mix compaction and density. It can also be linked to rut resistance and mix stiffness. The interconnected voids can be linked to two physical phenomena resisting porosity reduction, namely the wall effect and the disruptor or loosening effect. Both of these effects contribute to permeability potential and can be monitored by the porosity calculation made possible by the application of the contiguous principle. The impact on porosity, density, rut resistance and stiffness can be monitored via the basic RBRs either as a binary aggregate range or longer contiguous aggregate ranges. The Dominant Aggregate Size Range-Interstitial Content (DASR-IC) method typically determines this crucial aggregate range for a whole aggregate grading with the exclusion of the oversize aggregates and the Interstitial Content. The aggregate range correlating with the DASR-IC range for lowest porosity is described as the Contiguous Aggregate Packing ratio using the simplified Bailey method described aggregate grading curve as a basis.

Despite the simplicity of this approach using basic aggregate grading curve descriptions, it could be demonstrated how RBRs can be used to describe benchmark ranges for various asphalt mix properties. The benchmark technique makes use of the published ranges of various indices of good performing asphalt mixes. In the case of permeability, benchmarking the RAG principle is used where the colour red signifies severe condition, the colour amber signifies a warning condition, and the colour green signifies sound condition. It is believed that this benchmark analysis approach based on current peer-reviewed research publications can greatly enhance the asphalt mix design process.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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