Relationship between aggregate packing characteristics and compactability of Hot-Mix Asphalt mixes

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ABSTRACT

Compaction of Hot-Mix Asphalt (HMA) is an essential process in the construction of asphalt pavement as it is critical to the performance of the road infrastructure. The compaction process enables the asphalt mixtures to achieve stability, provide resistance to deformation (rutting) against traffic loading, reduce permeability of the layer and improve its durability. One of the factors affecting compactability (or workability) of the HMA is its internal structure. The research work presented in this paper is aimed at investigating the influence of the internal structure of HMA based on aggregate gradation and packing characteristics on the compactability. Three coarse-graded HMA mixes were used to evaluate parameters that describe aggregate packing characteristics, including the gravel to sand ratio, gradation shape factor, as well as the traditional and revised rational Bailey ratios. HMA specimens were compacted using a Superpave Gyratory Compactor (SGC), and the data were analyzed to determine five parameters of HMA compactability. The HMA compactability parameters were then correlated to the aggregate packing parameters. Overall, the parameters of HMA compactability exhibited a strong correlation with the aggregate packing parameters. The outcomes of the study not only provide a better understanding of the influence of aggregate gradation and packing characteristics on HMA compactability, but also identify essential input parameters to be considered when developing models to simulate HMA compaction.

INTRODUCTION

Among many other factors, the performance of Hot-Mix Asphalt (HMA) pavements is highly dependent on adequate compaction. Inadequate HMA compaction may affect the fundamental properties including reduced stiffness, accelerated aging, reduced fatigue life, poor rut resistance, increased permeability, and increased moisture damage (Awed et al., 2015; Verhaeghe, et al., 2007; Walubita et al., 2016). On the other hand, over compaction of HMA mixes may result in bleeding and/or crushing of the aggregate particles that may negatively impact the pavement surface texture and skid resistance properties (Verhaeghe, et al., 2007; Walubita et al., 2016).

During compaction, HMA undergoes internal structural changes in response to the compaction effort, whereby the distance between aggregate particles reduces, resulting in decreased air voids (Masad et al, 1999; Walubita et al., 2012). The aggregate packing, binder volume and stiffness together with the air void distribution define the internal structure of the HMA, which in turn, plays a significant role on the mechanical and volumetric properties of HMA, as well as its ability to resist distresses (Chang and Meegoda, 1997; Masad et al, 1999; Micaelo et al, 2009). Compaction effort or energy needed to achieve a specific density or percentage air voids content is commonly known as compactability or workability of HMA mix. Recent research studies are focusing on the understanding of the influence of aggregate packing on the compactability of HMA. These researches include advanced techniques such as discrete element methods, image analysis and aggregate packing simulation (Micaelo, et al., 2009; Xu, et al., 2010; Walubita et al., 2012; Kutay et al., 2015).

The objective of the laboratory study presented in this paper was to investigate the influences of aggregate packing characteristics on the compactability of HMA mixes. Aggregate packing parameters were determined for three coarse-graded HMA mixes. HMA specimens were compacted using a Superpave Gyratory Compactor (SGC), and the compaction data were analyzed to determine five parameters of HMA compactability. Inherently, the second objective of the study was to contribute to the body of technical knowledge and provide a better understanding of how the aggregate gradation-packing characteristics affect compactability, as well as the identification of some essential input parameters to be considered when developing models to simulate HMA compaction.

The paper is organized and structured as follows; this introduction section is followed by an overview of aggregate gradation and packing characteristics, followed by a brief description of the compactability parameters. The laboratory study approach is then described, followed by analysis and discussions of the test results. Conclusions and recommendations a presented at the end of the paper.

AGGREGATE GRADATION AND PACKING CHARACTERISTICS

Maximum Density Line concept

Over the years, several studies have been carried out in the area of aggregate packing, and ideal aggregate gradations to achieve maximum density have been proposed. Fuller and Thompson (1907) presented Equation 1 for the maximum density curve. The *n* value in Equation 1 can provide an indication of the aggregate structure. The higher the *n* value, the coarser the aggregate gradation, and vice versa. It is recommended to avoid gradation curves that follow the maximum density line in order to increase the total voids in the mineral aggregates and allow sufficient asphalt-binder to provide adequate film thickness for adequate HMA durability.

$$P_i = \left(\frac{d_i}{D_{max}}\right)^n \qquad \text{Equation 1}$$

where Pi is the percentage of aggregate passing sieve size with diameter of di, D_{max} is the maximum size of aggregates, and n is a gradation shape factor.

Gravel to Sand Ratio (G/S)

Based on the Fuller's concept, Sanchez-Leal (2007) proposed a gravel-to-sand ratio (G/S) to explain the influence of aggregate gradation on HMA performance characteristics such as compactability (workability), rutting resistance, and permeability. For a given aggregate gradation, Equation 2 is used to determine the G/S ratio. It should be mentioned that in this study, the standard sieve sizes as defined by the South African National Standards (SANS) were used. Gradation analysis was conducted in accordance with the SANS 3001-AG1 (SABS, 2014). Using the SANS sieve sizes, the 4.75 mm sieve is replaced by 5 mm sieve. Consequently, 5 mm, instead of 4.75 mm, was used in Equation 2 for all the analyses conducted in this paper.

$$\frac{G}{S} = \frac{D_{max}^{n} - 4.75^{n}}{4.75^{n} - 0.075^{n}} \qquad \text{Equation 2}$$

where, D_{max} is the maximum size of aggregates, and n is a gradation shape factor.

The Bailey Method

Detailed background and the basic principles of the Bailey method can be found elsewhere (Vavrik et al., 2002). The Bailey method was originally developed as a tool for designing and adjusting aggregate proportions, taking into account the aggregate packing and its influence on the performance of HMA mixes. The method can also be used to evaluate aggregate packing characteristics of the aggregate gradation.

Aggregate gradation curve is the basis of the Bailey method, whereby certain control sieves are used to determine ratios that provide an indication of the aggregate packing efficiency. The first control sieve is the Nominal Maximum Particle Size (NMPS), which is commonly defined as one sieve larger than the first sieve that retains more than 10% of the overall aggregate blend (Asphalt Institute, 1996). Starting with the NMPS, other control sieve sizes are defined as illustrated in Figure 1. These control sieves include the Half Sieve (HS), defined as the sieve closest to a half of the NMPS; the Primary Control Sieve (PCS), defined as the sieve closet to 22 % of the NMPS; the Secondary Control Sieve (SCS), defined as the sieve closet to 22 % of the PCS, and the Tertiary Control Sieve (TCS), defined as the sieve closet to 22 % of the SCS.

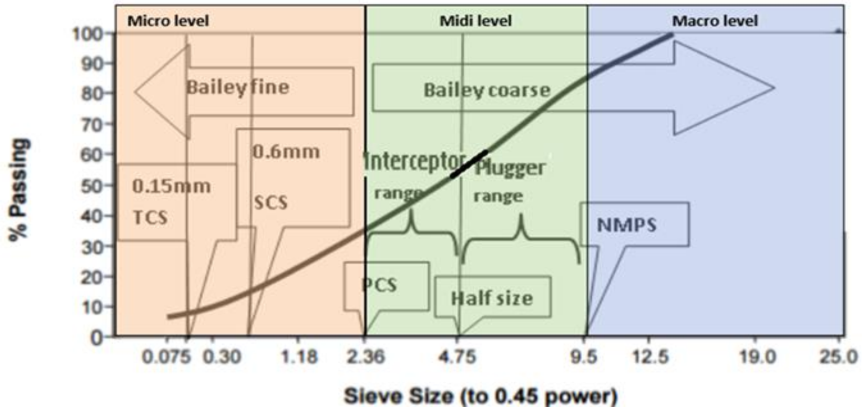


Figure 1. Illustration of Bailey Ratios (Horak and Cromhout, 2018)

In the Bailey method, the PCS defines coarse and fine aggregate fractions, whereby aggregate fractions larger than PCS are coarse aggregate and smaller than PCS are fines. The fines portion describes the Micro level of the entire aggregate skeleton, whereas the coarse portion is subdivided into Midi range and Macro range of aggregate fractions as illustrated in Figure 1. One of the fundamental principles of the Bailey method is that for a given aggregate gradation, the coarse aggregate particles create voids to be filled by fine aggregate particles.

Based on the control sieves, the traditional Bailey method defines three gradation ratios to describe the packing characteristics of the Macro, Midi and Micro skeleton matrix levels, respectively: the Coarse Aggregate Ratio (CA Ratio), Fine Aggregate Coarse Ratio (FAc Ratio) and Fine Aggregate Fine Ratio (FA_f Ratio), which are determined using Equations 3 to 5, respectively. Recently, Horak et al., (2017) and Horak and Cromhout (2018) proposed some revised rational Bailey ratios, corresponding to the traditional Bailey ratios. The revised rational Bailey ratios incorporate aggregate packing efficiency that includes the concept of binary aggregate packing as described by Olard (2015). The basis of the Binary Aggregate Packing (BAP) analysis is the triangle diagram describing the “Wall effect” and the “Loosening effect” concepts, which influence the potential for the interconnectedness of voids. The BAP concept allows for the zooming into the voids at each of the Micro, Midi and Macro levels of aggregate packing. To this end, the revised rational Bailey ratios have been formulated as ratio of the coarse/fine aggregate fraction instead of fine/coarse used in the traditional Bailey ratios, and are determined using Equations 6 to 8 respectively.

$$CA\ Ratio = \frac{(\%\ passing\ HS - \%passing\ PCS}{100\% - \%\ passing\ HS} \qquad \text{Equation 3}$$

$$\mathrm{FA_c\ Ratio} = \frac{\%\ \mathrm{Passing\ SCS}}{\%\ \mathrm{Passing\ PCS}} \qquad \text{Equation 4}$$

$$\mathrm{FA_f\ Ratio} = \frac{\%\ \mathrm{Passing\ TCS}}{\%\ \mathrm{Passing\ SCS}} \qquad \text{Equation 5}$$

$$\mathrm{CA_r} = \frac{(\%\ 100 - \%\mathrm{HS})}{(\%\mathrm{HS} - \%\mathrm{PCS})} \qquad \text{Equation 6}$$

$$\frac{C}{F} = \frac{(\%\mathrm{NMPS} - \%\mathrm{PCS})}{\%\mathrm{PCS})} \qquad \text{Equation 7}$$

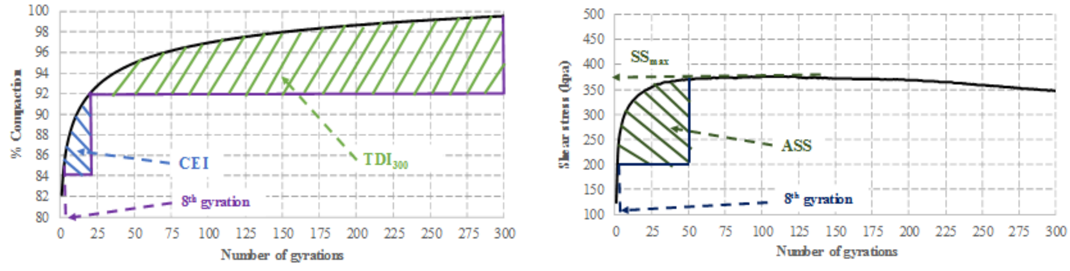
$$FA_{rmf} = \frac{(\%\mathrm{SCS} - \%\mathrm{TCS}\ )}{(\%\mathrm{TCS} - \%\mathrm{Filler})} \qquad \text{Equation 8}$$

HMA COMPACTABILITY

As defined before, compactability of HMA mix describes the energy needed to achieve a specific density or percentage air voids content. Over the years, serval approaches have been proposed to analyze HMA compaction data for particular compaction equipment to determine parameters that describe the compactability of HMA mixes (Bahia et al., 1998; Awed et al, 2015). Below is a list and brief description of the HMA compactability parameters that can be computed from a gyratory compactor basic output data. Figure 2 shows a graphical illustration of the compactability parameters.

- **Compaction energy index (CEI)** defined as the area under the densification curve from the 8th gyration to 92% compaction (Bahia et al., 1998), as illustrated in Figure 2a. HMA mixes with lower CEI values are desirably less difficult to compact.
- **Traffic densification index (TDI),** defined as the area under the densification curve from 92% to 98% compaction (Awed et al, 2015). It should be pointed out that in practice, certain mixes cannot easily be compacted to 98%. Therefore, a new traffic densification index was proposed. The new index is defined as the area under the densification curve from 92% to 300 gradations (i.e., **$\mathbf{TDI_{300}}$**), as illustrated in Figure 2a. Generally, the smaller the TDI_{300}, the more difficult it is to compact the HMA mix.
- **Maximum shear stress ($\mathbf{SS_{max}}$),** defined as the maximum shear stress during the gyratory compaction as illustrated in Figure 2b. Like TDI_{300}, this is also new parameter proposed in this study. The higher the SS_{max}, the more difficult it is to compact the HMA mix.
- **Area under the shear stress curve (ASS),** defined the area under shear stress from the 8th gyration to the maximum shear stress as illustrated in Figure 2b. This is also a new parameter proposed in this study. Similar to SS_{max}, the higher the ASS, the more difficult it is to compact the HMA mix.
- **Compaction slope (CS),** which is the rate of compaction determined by using Equation 3 (Wang et al, 2000).

$$CS = \frac{\%\,compaction\ at\ N_{max} - \%\,compaction\ at\ N_{initial}}{\log(N_{max}) - \log(N_{initail})} \qquad \text{Equation 9}$$



(a) CEI and TDI_{300}

(b) SSmax and ASS

Figure 2. Conceptual Illustration of Compactability Parameters.

LABORATORY STUDY APPROACH

Aggregate and Asphalt Binder

Dolerite aggregates, which are routinely used in the production of HMA mixes, were sourced from a commercial asphalt plant in Gauteng province, South Africa. The aggregates consisted of 22.5 mm, 13.2 mm, 9.5 mm and 6.7 mm NMPS aggregate fractions, as well as crusher dust, mine sand and filler. Penetration-grade (35/50) asphalt-binder, which is equivalent to PG 64-16 as per the draft South African Performance Grade (PG) bitumen specification, was sourced from the same commercial asphalt plant. This binder, which conforms to the South African specification (SABS, 2016) was used to manufacture the HMA samples.

HMA Mix Design

The HMA mix design was also sourced from the same commercial asphalt plant in Gauteng province, South Africa. The HMA was a coarse-graded (stone-skeleton), with 20 mm NMPS, and is used routinely in the production of good-performing HMA mixes. The optimum asphalt-binder content was 4.3 %, and the design number of gyrations (N_{design}) is 125. In order to investigate the influence of aggregate gradation and packing characteristics on the compactability of HMA mixes, additional two gradation curves were designed. The gradation curves were designed to fall within the specified gradation envelopes according to the South African standard specifications for road and bridge works (COLTO, 1998) and resulting in three distinct coarser, medium, and finer gradation curves as illustrated in Figure 3.

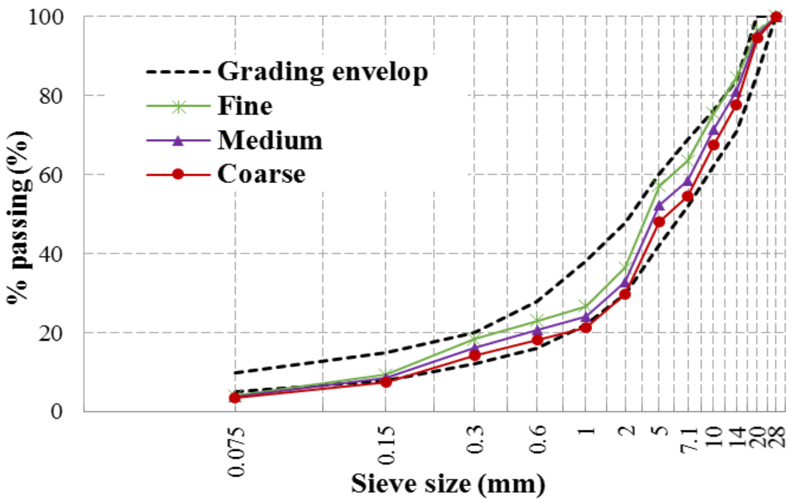


Figure 3. Aggregate gradation

HMA Mixing and Compaction

The mixing and compaction of the HMA specimens were done according to the South African Council for Scientific and Industrial Research (CSIR)'s test protocols for testing asphalt mixes in South Africa (Anochie-Boateng et al., 2010). The calculated masses of individual aggregate fractions were blended in accordance with the design gradation and pre-heated to the required mixing temperature (160 °C). The required amount of pre-heated asphalt-binder and the pre-heated blended aggregate were placed into a pre-heated mechanical mixer, and mixed until a uniform mixture was obtained (approximately 15 minutes). After mixing, the loose HMA material was placed into an oven set at compaction temperature (145 C) for four hours to simulate short-term ageing. (Anochie-Boateng et al., 2010).

Following the ageing simulation, HMA specimens were compacted using the SERVOPAC gyratory compactor. The mould diameter was 150 mm, and all the HMA specimens were compacted to 300 gyrations. For each of the three gradations, three replicates of HMA specimens were compacted. Figure 4a is a picture of the SERVOPAC gyratory compactor used in this study, with a typical compacted HMA specimen. Figures 4b and 4c show plots of the typical compaction output data (i.e., HMA specimen height and shear stress) from the SERVOPAC gyratory compactor, which are the basic used data for the analysis presented in this paper.

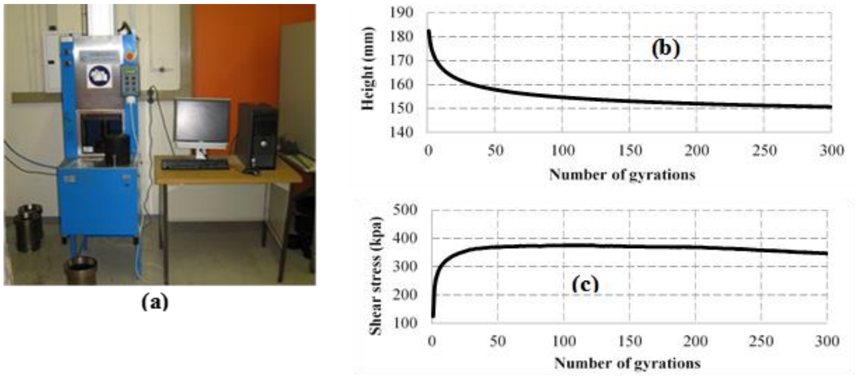


Figure 4. SERVOPAC gyratory compactor and typical output data.

Volumetric Analysis of Compacted HMA Specimens

The maximum void-less density (MVD) was determined on the loose HMA material according SANS 3001-AS11 (SABS, 2011a), whereas the bulk density (BD) of the compacted specimens was determined according to SANS 3001-AS10 (SABS, 2011b). Both the MVD and BD are key input data during the processing of the gyratory compaction data to determine the compaction densification curve. The gyratory output data (i.e., specimen diameter and height after each gyration) was used to calculate the theoretical density, which was then used to determine the actual density after each gyration using Equation 10 (Anochie-Boateng et al., 2010).

$$Actual\ density = Calculated\ density \times \frac{Measured\ density}{Calculated\ density\ 300\ gyrations} \qquad \text{Equation 10}$$

RESULTS AND DISCUSSIONS

Aggregate Gradation and Packing Parameters

Table 1 presents the aggregate gradation parameters and Bailey ratios for the three gradation structures investigated in this study. The coarser the aggregate gradation, the higher the G/S and *n* values, indicating that both, the G/S and *n* parameters can effectively differentiate the aggregate gradation structures. With respect to the traditional Bailey ratios, the results indicate that all the three ratios increase as the gradation structure becomes finer. Contrary to the traditional Bailey ratios, the revised rational ratios decrease as the aggregate gradation becomes finer. This trend was expected, as the revised rational ratios have been formulated in an inverse format (i.e., coarse/fine), in line with the binary aggregate fraction packing principles.

Table 1. Aggregate Gradation Parameters and Bailey Ratios.

	Gradation Parameter/Bailey ratio	*Aggregate Gradation Structure*		
		Coarse	*Medium*	*Fine*
Gradation Parameters	*G/S*	1.29	1.12	1.01
	n	0.55	0.49	0.44
Traditional Bailey Ratios	*CA Ratio*	0.592	0.673	0.748
	FAc Ratio	0.442	0.460	0.468
	FAf Ratio	0.669	0.680	0.687
Revised Rational Bailey Ratios	CAr	1.688	1.487	1.336
	C/F	0.963	0.829	0.686
	FArmf	0.651	0.611	0.584

Parameters of HMA Compatability

Three replicates of HMA specimens were compacted for each of the three gradations, and the compaction data was analyzed to obtain five parameters (CEI, TDI_{300}, SS_{max}, ASS and CS) of HMA compactability. Sample statistics including mean, standard deviation (STD) and coefficient of variation (CoV) are included in the results presented in Table 2. With the exception of the ASS statistic, the CoV values are generally low (ranging from 0.5 to 14.9%), indicating that the measured compactability parameters are repeatable and exhibit low variability. In the subsequent section, the compactability parameters are correlated with aggregate packing parameters.

Table 2. Summary of Parameters of HMA Compactability.

Parameter	*Coarse*			*Medium*			*Fine*		
	Mean	*STD*	*CoV(%)*	*Mean*	*STD*	*CoV(%)*	*Mean*	*STD*	*CoV(%)*
CEI	112	12.1	10.9	113	12.8	11.3	108	3.3	3.0
TDI_{300}	1813	224.6	12.4	1866	277.9	14.9	2153	66.6	3.1
SS_{max}	389	2.1	0.5	382	7.0	1.8	369	5.5	1.5
ASS	396	93.8	21.1	328	21.8	5.6	309	43.7	23.3
CS	5.2	0.2	3.0	5.5	0.3	6.2	6.2	0.3	5.3

Parametric Correlations

The aggregate packing parameters were correlated with the average compactability parameters. Table 3 presents a summary of the correlation coefficient (r), as well as the coefficients of determination (R^2). The positive r values indicate a positive linear correlation or relationship, whereas, negative r values indicate a negative linear correlation. Overall, the TDI_{300}, SS_{max}, ASS and CS parameters show stronger correlations with the aggregate gradation parameters and the Bailey ratios ($r > |0.88|$). However, the correlations for CEI were found to be relatively weaker to medium (r ranging from |0.53| to |0.72|).

Table 3. Correlation Coefficients (R) and Coefficients of Determination (R^2).

Parameter	*CEI*		TDI_{30}		SS_{max}		*ASS*		*CS*	
	r	R^2	r	R^2	r	R^2	r	R^2	r	R^2
G/S	0.62	0.39	-0.88	0.78	0.97	0.93	0.98	0.96	-0.93	0.87
n	0.69	0.47	-0.92	0.84	0.98	0.97	0.96	0.92	-0.96	0.92
CA Ratio	-0.69	0.48	0.92	0.85	-0.99	0.97	-0.96	0.91	0.96	0.92
FAc Ratio	-0.53	0.28	0.82	0.68	-0.93	0.87	-1.00	0.99	0.88	0.78
FAf Ratio	-0.62	0.39	0.88	0.78	-0.97	0.93	-0.98	0.96	0.93	0.87
CAr	0.64	0.41	-0.89	0.80	0.97	0.95	0.97	0.95	-0.94	0.88
C/F	0.72	0.52	-0.94	0.88	0.99	0.98	0.94	0.89	-0.97	0.94
FArmf	0.62	0.38	-0.88	0.77	0.96	0.93	0.98	0.96	-0.93	0.86

Figure 5 show the graphical illustration of the correlation trends between the aggregate gradation parameters (i.e., G/S and n) and compactability parameters. The SS_{max} and ASS compactability parameters show a positive correlation with both the G/S and n, indicating that for the gradation structures investigated, the coarser gradation exhibits higher shear resistance. On the other hand, the TDI_{300}, and CS parameters show a negative correlation with the G/S and n parameters, but also indicating the coarser the gradation, the more difficult it is to compact. The CEI showed a relatively weaker positive correlation. This could be due to the fact that 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. Hence, influence of the aggregate gradation is still insignificant. With respect to the slope (rate of change), relationships with the *n* parameter exhibits a steeper slope than with the G/S parameter. This is primarily due to the differences in the range of the grading parameter values (i.e., *n* values range from 0.44 for finer gradation to 0.55 for coarser gradation, whereas G/S values range from 1.01 for finer gradation to 1.29 for coarser gradation.

The correlation trends for the traditional and the revised Bailey ratios are presented in Figure 6 and Figure 7, respectively. Contrary to the gradation parameters (*n* and G/S), the traditional Bailey ratios exhibited opposite correlation trends. This was expected because the traditional Bailey ratios were formulated in an inverse form (i.e. fine/coarse). For the revised rational Bailey ratios, as expected the correlation trends are similar to the gradation parameters (G/S and *n*), but opposite with the traditional Bailey ratios. Similar to the gradation parameters, the rate of change of the compactability parameters structure is determined by the range of the Bailey ratios.

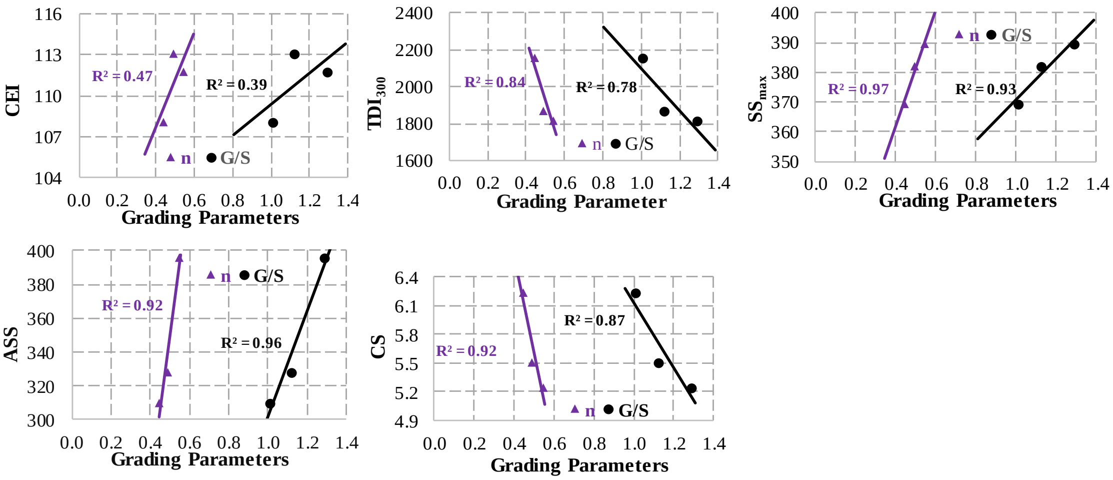


Figure 5. Gradation and Compactability Parameters Correlations.

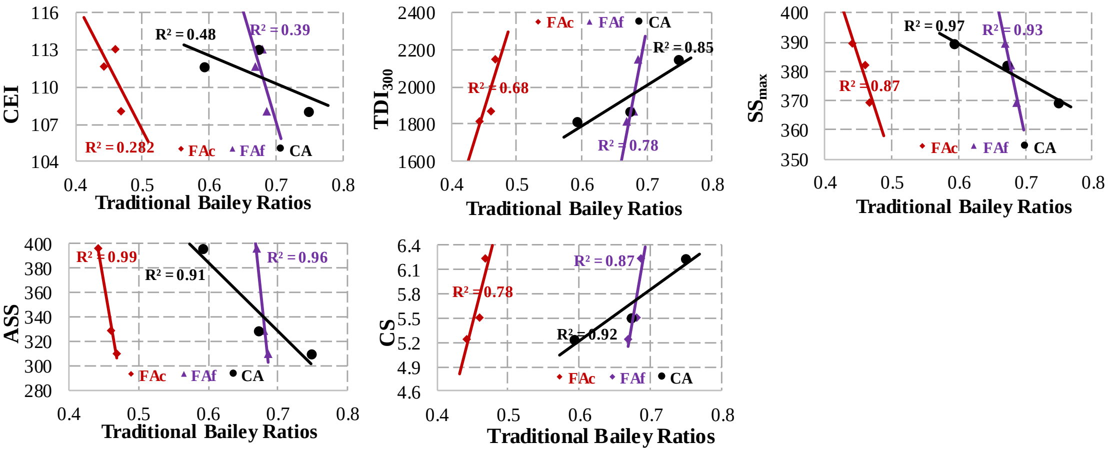


Figure 6. Traditional Bailey Ratios and Compactability Parameters Correlations

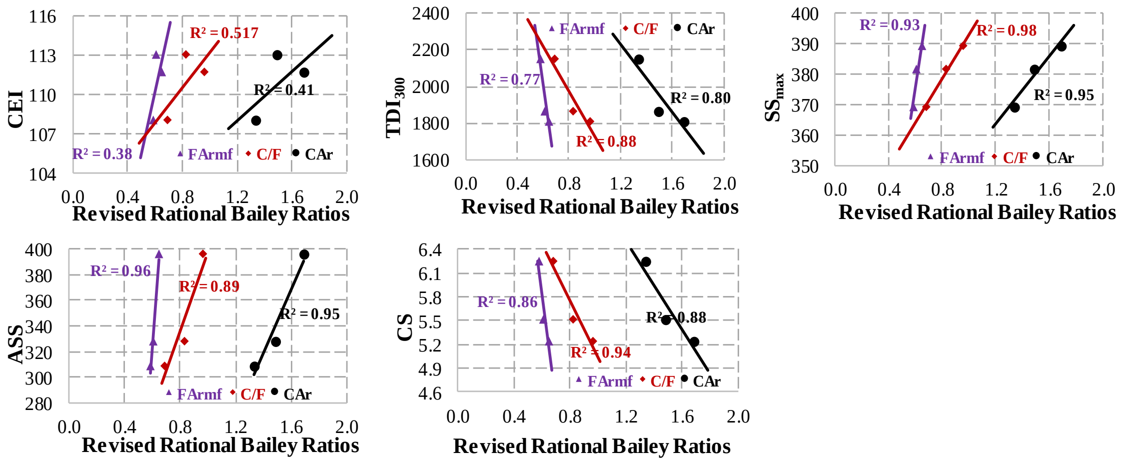


Figure 7. Rational Bailey Ratios and Compactability Parameters Correlations

CONCLUSION AND RECOMMENDATIONS

This paper investigated the influence of aggregate packing characteristics on HMA compactability. Two gradation parameters (G/S and *n*), three traditional (CA, FA*c* and FA_f) and revised rational (CA_r, C/F and FA_{rmf}) Bailey ratios were correlated with five different HMA mix compactability parameters (CEI, TDI_{300}, SS_{max}, ASS and CS). Based on the results and discussions contained in this paper, the following conclusions are drawn and recommendations made.

- The gradation parameters and the Bailey ratios showed a strong correlation with parameters TDI_{300}, SS_{max}, ASS and CS of HMA compactability (r > |0.88|). However, correlations for CEI were found to be relatively weaker to medium (r ranging from |0.53| to |0.72|). This could be due to the fact that 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;
- A new traffic densification index (TDI_{300}) proposed in the study showed a good correlation (r ranging from |0.93| to |0.99|) with the packing parameters and
- Additionally, two shear stress-based HMA compactability parameters (SS_{max} and ASS) proposed in this study were also found to correlate very well with the aggregate gradation parameters and the Bailey ratios.

Overall, this study demonstrated that the aggregate gradation structure, play a significant role in the compactability of an HMA mix, and this should be considered carefully when selecting a combination of individual aggregate fractions during the HMA design and production. The findings of this study suggest that for a specific gradation structure, the coarser the gradation structure, the higher the energy required to compact the resulting HMA.

As study focused on coarse gradation structure, future work should include more HMA mixes and other types of gradation structures to validate the findings. The influence of other attributes such as aggregate type and shape properties, also need be investigated. Although limited to three aggregate gradations, the study demonstrated that aggregate gradation parameters and Bailey ratios that can easily be computed from the basic gradation curve, may be very useful in terms of predicting the compactability of HMA mixes, without the need for the additional laboratory or field testing. Furthermore, the aggregate gradation parameters and Bailey ratios have the potential to be used as input parameters when developing models to simulate HMA compaction.

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