Fatigue life evaluation of asphalt mixtures containing natural river sands and designed by bailey method

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Abstract. This study aims to investigate the efficiency of Bailey method of optimizing the fatigue life of asphalt mixtures when natural sand is included in the mix at two coarseness levels of aggregate gradations: Fine-Graded (FG) and Coarse-Graded (CG), with three mixes which varied with the percentage of the natural river sand, were prepared at each coarseness level, namely: Corse-Graded with Quarry Sand only (CG-QS), Corse-Graded with Natural Sands only (CG-NS), Corse-Graded with Quarry and Natural Sands (CG-QNS), Fine-Graded with Quarry Sand only (FG-QS), Fine-Graded with Natural Sands only (FG-NS), and Fine-Graded with Quarry and Natural Sands (CG-QNS). The portions of the natural sand either in CG-QNS and FG-QNS mixes were minimized as possible without violating the Bailey ratios. The Beam Fatigue (BF) test was used to evaluate the performance of each mixture at a strain level of 1000 micro strain. The sensitivities of the volumetric measures with N_f were evaluated. The study's findings indicate that the Number of Cycles to Failure (N_f) was generally decreasing with the increase of the natural sand in the mix at any strain levels. The Dust Proportion (DP) was the most significant volumetric. The Bailey gradation method successfully provided a similar gradation coarseness for CG-QNS compared to CG-QS, which resulted in comparable N_f and indicates a similar aggregate interlock.

Introduction and Background

Understanding the material characteristics that define the performance of the asphalt over the lifespan of the pavement is necessary for the design of asphalt pavements. The type of aggregate and its gradation have a considerable impact on the workability and performance of asphalt concrete pavements in use. Mineral aggregates make up 90–95% of the mixed weight [1]. In essence, the type of binder used as well as the shape, toughness, durability, and gradation of the aggregate is mainly accountable for the permanent deformation and cracking of asphalt mixtures. Additionally, excessive amounts of fine aggregate in rounded shapes are primarily diagnosed for early failures in asphalt concrete mixtures [2,3]. Pavement agencies prefer natural fine aggregates over crushed sand because they are more readily available, cost-effective, and workable when producing Hot Mix Asphalt (HMA). Contrarily, crushed fine aggregate must be quarried, processed, cleaned, and separated into distinct size fractions, all of which raise the price of making asphalt concrete. As a result, several experiments have been done to assess how well asphalt concrete performs when natural sands are added to the mix.

Most of these studies had inconsistent results, where the evaluation of the inclusion of natural sand was arbitrarily or without following a systematic procedure, and percentages of natural sands included in the mix were relatively high. This can be seen in a number of studies including [4, 5, 6, 7, 8, 9, 10]. The results of the aforementioned studies lack consistency since not much consideration was given to aggregates particles shapes, packing, and gradations. On the other hand,

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Ramli [11] and Park and Lee [12], Stuart and Mogawer [13], and Freeman and Kuo [14] suggested identifying poor quality sand from good quality to be used in the asphalt mix based on the combined effect of sand or fine aggregate texture, shape, gradation, and quantity which eventually affect the packing densities of sand. This signifies the necessity of following a systemic procedure to assess and design the aggregate structure for asphalt mixes. Bailey method is a systematic procedure that can evaluate and design blends of aggregates and provides a practical tool assisting the designer to ensure that the pavement obtains the required durability with the available aggregates. The method evaluates how the particles pack together to provide a good interlock between the particles. Bailey proposed three ratios were to evaluate the gradation of asphalt mixture. Two principles were considered in Bailey method to evaluate a mixture: the first one is aggregate packing which considers that aggregates cannot completely fill a certain volume. The second principle is defining coarse and fine aggregate. Coarse particles are essential to provide the aggregate interlock and deformation resistance and are defined as the particles retained on a pre-specified sieve size (primary control sieve) and fine aggregates are defined as particles that fill the voids between coarse aggregates. Bailey method has proven its superiority over any other aggregate gradation design and resulted in a better performance mix. This can be shown in studies conducted by Ghuzlan et al.[15]; Sivasubramaniam et al.[16]; Zhu et al.[17]; and Vavrik et al.[18]. There is a need for a more inclusive approach to evaluate the utilization of natural sands at different levels of gradation coarseness as well as studying the most influencing volumetric measure on the performance of the compacted asphalt mixtures.

To this end, all of the aforementioned studies indicate the necessity of evaluating the aggregate surface textures, packing, and gradation especially when natural sand is utilized in the mix. The Bailey method is the most reliable method to achieve an optimized gradation so far. Henceforth, the study aims to investigate the fatigue performance of asphalt mixtures designed by following Bailey method when natural sand is included in the mixture at different coarseness levels of aggregate gradations. Two levels of gradations were evaluated: Fine and coarse, and three mixes which varied with the percentage of the natural river sand were prepared at each coarseness level. The Beam Fatigue (BF) was used to evaluate the fatigue performance of the mixtures.

Materials and Methods

This section describes the material properties used in producing the HMA specimens; including asphalt, aggregate, and the HMA mixture with all the tests and specifications used in characterizing these paving materials in accordance with the Superpave mix design procedure described in the Asphalt Institute (AI) MS-2 manual [19]. Six types of HMA mixes were utilized in this study, namely: Corse-Graded with Quarry Sand only (CG-QS), Corse-Graded with Natural Sands only (CG-NS), Corse-Graded with Quarry and Natural Sands (CG-QNS), Fine-Graded with Quarry Sand only (FG-QS), Fine-Graded with Natural Sands only (FG-NS), and Fine-Graded with Quarry and Natural Sands (CG-QNS). A traffic level of 0.3 to 3 million Equivalent Single Axle Load (ESAL) was chosen in this study to mimic the low level of traffic. The Nominal Maximum Aggregate Size (NMAS) for aggregate blends was chosen to be 12.5 mm. The Beam Fatigue (BF) test was conducted to evaluate the inclusion of the Natural Sand (NS) on the performance of the asphalt mixes.

Asphalt Binder. The asphalt binder used in this study had a penetration grade of 60/70. The asphalt binder was further tested to determine its performance grade (PG) and to ensure that it meets the Superpave performance requirements. Accordingly, by conducting several asphalt binder tests, it was found that the proper Superpave asphalt grade is PG 70–10. The results are summarized in Table 1.

Table 1. Results of asphalt binder test

Test	Test Method	Test Temp. (°C)	Parameter	Criterion	Results
Rotational Viscometer (RV)	[20]	135	Viscosity (Pa.s)	≤ 3	0.204
Dynamic Shear Rheometer (DSR; unaged)	[21]	64	G*/sin δ (kPa)	≥ 1	1.610
		70			0.772
Rolling Thin Film Oven (RTFO)	[22]	163	% Mass Loss	≤ 1	0.13
Direct Shear Rheometer (DSR; RTFO residue)	[21]	64	G*/sin δ (kPa)	≥ 2.2	2.452
		70			1.112
Pressure Aging Vessel (PAV)	[23]	100	-	-	-
Direct Shear Rheometer (DSR; PAV residue)	[21]	31	G*×sin δ (kPa)	≤ 5000	261.54
		34			172.79
Bending Beam Rheometer (BBR)	[24]	0	S(t) at t = 60s (Mpa)	≤ 300	7.62
			m value at t = 60s	≥ 0.3	0.502

Aggregate. Several aggregates stockpiles of crushed limestone were used in this study. The aggregate stockpiles were 12.5 mm Aggregate, 9.5 mm Aggregate, Quarry-made Sand (QS), and River Natural Sand (NS). Fig. 1 shows the gradations of each stockpile utilized to prepare the proposed mixtures. Table 1 illustrates the test procedures used to characterize the coarse and fine aggregates, respectively along with the experimental results of each test. Accordingly, the tests included flat and elongated particles for coarse aggregate, coarse aggregate angularity, fine aggregate angularity, and bulk-specific gravity. These properties are significant to provide a reliable aggregate interlock and proper compaction without braking and endure the traffic loading over the life span of the pavement. It is important to note that significant portions of each stockpile were taken, combined, and then sieved (i.e., fine and coarse) to measure the consensus properties of the aggregate. Table 2 shows the results of the aggregate properties.

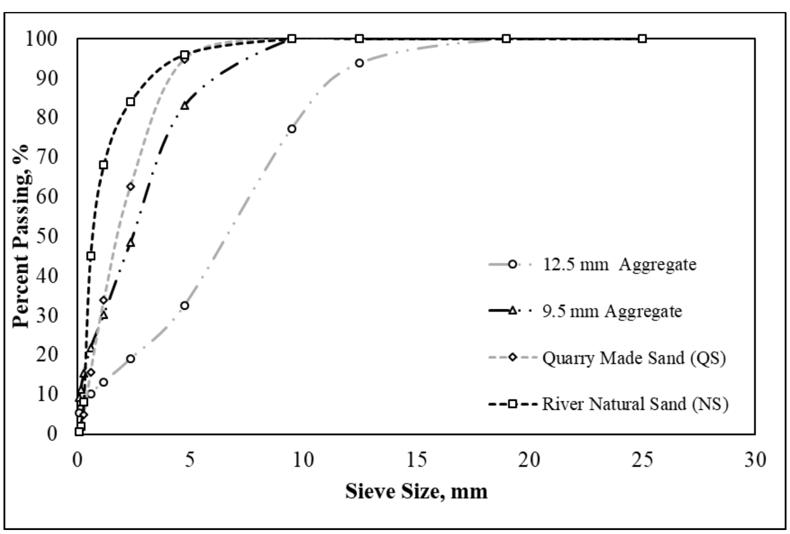

Figure 1. Aggregate stockpiles gradations

Table 2. Aggregate consensus properties

Property	Coarse aggregate		Fine aggregate				Superpave acceptable range (0.3 – 3 million ESALs)	Test method
	12.5 mm	9.5 mm	QS	NS	12.5 mm	9.5 mm		
Flat and elongated,%	3	2	-	-	-	-	-	[25]
Coarse aggregate angularity, %	92/97	94/98	-	-	-	-	≥50/-	[26]
Fine aggregate angularity, %	-	-	43	40	42		≥40	[27]
Bulk Specific Gravity	2.684	2.681	2.679	2.652	2.789	2.686	-	[28]

As shown in Vavrik et al. [18], there are three control sieves in Bailey gradation used to determine the optimized blend, namely: Primary Control Sieve (PCS) that separates the coarse aggregate portion from the fine portion, Secondary Control Sieve (SCS) that splits the fine part from the previous equation (passing the PCS) into two further fractions, and then Tertiary Control Sieve (TCS) where the materials passing SCS are further spliced with the Tertiary Control Sieve (TCS). The calculations of PCS, SCS, and TCS are shown below in Eq. 1, 2, and 3, respectively.

$$PCS = NMAS \times 0.22 \quad (1)$$
$$TCS = PCS \times 0.22 \quad (2)$$
$$SCS = TCS \times 0.22 \quad (3)$$

This method also suggests three ratios to evaluate the aggregate blend (Vavrik et al., 2002). They are used to understand and analyze the structure of the aggregate gradation. Accordingly, aggregates in the blend are classified into three portions, the coarse portion which retained on the PCS, the coarser part of fine aggregates which passes the PCS and retained on the SCS, and the finer part of fine aggregates which passes through the SCS and retained on the TCS. Based on these definitions, Bailey suggested three ratios; Coarse Aggregate Ratio (CA), Fine Aggregate Coarse Ratio (FA_c), and Fine Aggregate Fine Ratio (FA_f). In essence, the CA Ratio obtains the interlock between coarse particles by introducing a Half Sieve (HS), which is simply half of the NMAS. The particles with sizes between HS and PCS are called interceptors.

Changing the percentages of interceptors affects the VMA of the mixture because they cannot fill the voids between the larger particles. Voids will also be found between the particles of the coarser part of the fine proportion, and the finer parts of the fine proportion will fill these voids. The ratio of these fractions is described by FA_c. Finally, FA_f ratio is significant for understanding some mixture properties such as binder content and volume of voids, because it is concerned with the very finest material content (including filler) in the mixture.

Vavrik et al. [18] suggest different ranges of CA, FA_c, and FA_f based on the coarseness of gradation (fine or coarse) and NMAS. Coarse-graded the follows Bailey guidelines generally provide higher resistance to deformation when compared to fine-graded mixes [16]. In fine mixes, the fine aggregate has to be noticeably strong in order to compensate for the absence of the larger aggregate portions to resist different types of deformation. In dense-graded mixtures, the gradation coarseness is defined by the position of the gradation line with reference to the maximum density line. According to AASHTO M323 [29] and Khasawneh and Alsheyab [30], when the gradation line mostly lies above the maximum density line and above PCS, the gradation is defined as fine-graded. In contrast, when the gradation line mostly lies below the density line and below PCS, the gradation is defined as coarse-graded. The calculations of CA, FA_c, and FA_f are shown below in

Eq.4, 5, and 6, respectively. Table 3 shows the sieves and formulas used for the calculations of the Bailey ratio for NMAS 12.5 mm as reported in Vavrik et al. [18]. Note for fine-graded mixtures the calculations and the sieves included in Bailey ratios calculations are slightly modified as reported in Vavrik et al. [18] as if PCS is considered the NMAS for the fine-graded mixtures.

$$CA = \frac{\text{\%Passing HS - \%Passing PCS}}{\text{100-\%Passing HS}} \tag{4}$$

$$FA_c = \frac{\text{\%Passing SCS}}{\text{\%Passing PCS}} \tag{5}$$

$$FA_f = \frac{\text{\%Passing TCS}}{\text{\%Passing SCS}} \tag{6}$$

Table 4. Sieves and formulas used in Baily ratio calculation for NMAS 12.5 mm

Gradation Coarseness	**Ratio**		
	CA	**FA_c**	**FA_f**
Coarse-graded	$\frac{(6.25\text{ mm} - 2.36\text{ mm})}{(100\% - 6.25\text{ mm})}$	$\frac{0.60\text{ mm}}{2.36\text{ mm}}$	$\frac{0.150\text{ mm}}{0.60\text{ mm}}$
Fine-graded	$\frac{(1.18\text{ mm} - 0.60\text{ mm})}{(100\% - 1.18\text{ mm})}$	$\frac{0.150\text{ mm}}{0.60\text{ mm}}$	N/A

A comprehensive procedure for designing and identifying the optimized blend from different stockpiles can be found elsewhere in Vavrik et al. (2002). Accordingly, the loose and rodded unit weights of the aggregate stockpiles need to be determined in order to obtain the proportions from each stockpile to finally determine the mix design blend for Bailey gradations. The results of unit weights are summarized in Table 5.

Table 5. Summary of stockpiles unit weights

Unit weight	**Stockpiles**				**Test Method**
	12 mm	9.5 mm	Quarry Sands (QS)	Natural Sand (NS)	
Loose	1.683	1.635	1.533	1.495	[31]
Rodded	1.811	1.706	1.692	1.594	

By using the unit weights summarized in Table 4 and following the procedure in Vavrik et al. [18]. The proportions that contributed to obtaining the final blend of Baily gradations are shown in Table 6. The results of calculated Bailey ratios for each gradation are shown in Table 7.

All of the gradations were designed and evaluated to meet the Bailey ratios constraints and requirements as shown in Vavrik et al [18]. Accordingly, six gradations were evaluated in this study, namely Corse-Graded with Quarry Sand only (CG-QS), Corse-Graded with Natural Sands only (CG-NS), Corse-Graded with Quarry and Natural Sands (CG-QNS), Fine-Graded with Quarry Sand only (FG-QS), Fine-Graded with Natural Sands only (FG-NS), and Fine-Graded with Quarry and Natural Sands (CG-QNS). The portions of NS either in CG-QNS and FG-QNS mixes were minimized as possible without violating the Bailey ratios.

Fig. 2 shows the gradations lines of the six mixes used in the study. Concerning course-graded mixes, it can be seen that CG-QS and CG-QNS gradation lines are not significantly different. In CG-QNS, the inclusion of NS decreased the need for QS significantly, slightly changed the proportions taken from each stockpile, and finally decreased the portion of the total sands in the mix. Also, Bailey ratios are somewhat similar for both CG-QS and CG-QNS. Moreover, the CG-NS was the finest compared to either CG-QS or CG-QNS. On the other hand, for fine-graded mixes, it can be seen that the differences between FG-QS, FG-QNS, and FG-NS gradation lines are more evident. Accordingly, FG-NS was the finest followed by FG-QNS, and FG-QS, respectively. It can be seen that the inclusion of NS slightly increased the portion of the total sands for either FG-QNS or FG-NS. Also, the difference in Bailey ratios is higher in fine-graded gradations when compared to coarse-graded ones. It is important to mention that the proportions taken from each stockpile are highly dependent on the gradation of each stockpile and constrained by Bailey ratios, and it may be challenging to design a gradation curve unless the constraints are met or meet a certain or specified Baily ratio.

Table 6. Summary of the proportions taken from each stockpile

Gradations	**Stockpiles**			
	12 mm	**9.5 mm**	**Quarry Sands (QS)**	**Natural Sand (NS)**
CG	60.3	25.1	14.6	0.0
CG-QNS	64.4	26.6	6.7	2.3
CG-NS	56.3	33.2	0	10.5
FG	7.7	68.1	24.2	0.0
FG-QNS	9.5	65.4	13.5	11.6
CG-NS	5.4	72.2	0	22.4

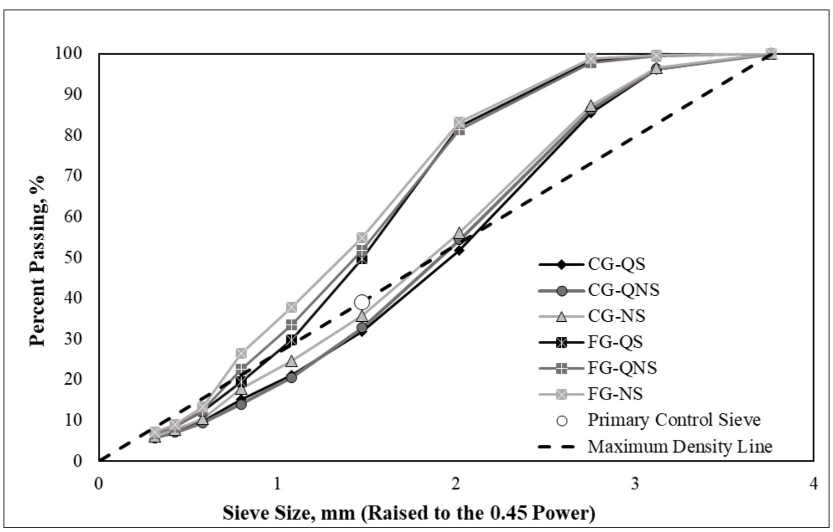

Figure 2. Bailey aggregate blend gradation

Table 7. Summary of calculated Bailey ratios

Gradations		Ratios		
		CA	**FA_c**	**FA_f**
Coase-gradaed	CG	0.54	0.47	0.50
	CG-QNS	0.54	0.42	0.50
	CG-NS	0.57	0.50	0.43
Constraint		0.5-0.65	0.35-0.5	0.35-0.5
Fine-graded	FG	0.60	0.44	-
	FG-QNS	0.62	0.37	-
	FG-NS	0.63	0.35	-
Constraint		0.6-1	0.35-0.5	-

Determination of the Volumetric Properties. The determination of the Optimum Asphalt Content (OAC) was carried out following the procedure described in MS-2 (Asphalt Institute, 2014). Accordingly, the mixing and the compaction temperatures were 161 °C and 152 °C, respectively. Loose test specimens were conditioned for 2 h after mixing at the specified compaction temperature (152 °C) to ensure mixture aging, then eventually the loose mixtures were compacted at a gyration number (Ndesign) of 75 gyrations to produce the compacted test specimens having a total mixture air voids percent (VTM) of 4% and having the desired volumetric properties of each mixture as recommended by Superpave specifications.

The 75 gyrations are intended to simulate the low traffic level which is equivalent to 0.3 to 3 million ESALs. Table 7 shows the Superpave average volumetric measures of the compacted test specimens for each mix. As can be concluded from both Table 8, the compacted test specimens' volumetric measures have met the Superpave volumetric criteria. The calculations of the volumetric measures are shown in Eq. 7 to 10. More details regarding the calculations of the volumetric measures can be found elsewhere [19, 32]. On average, coarse-graded mixes had higher OAC when compared to fine-graded. That is, more asphalt is needed to be absorbed by the larger aggregate particles to reach the same VTM as fine mixes (4%). However, larger air volumes (V_a) were formed, and lower asphalt portions covering the surface of the aggregate (V_{be}) were needed to reach a VTM of 4% for coarse-graded mixes due to lower surface area of the aggregate.

The DP is inversely proportional to the V_{be}, and therefore, the coarse-graded mixes had lower results of DP. The values of VMA and VFA are dependent on both V_a and V_{be}, and the trends of VMA and VFA of all mixes are challenging to identify. Concerning the coarse-graded mixes, the CG-NS had the highest OAC, highest V_{be}, and lowest V_a. The V_a values were very similar for both CG-QS and CG-QNS mixes, but OAC for CG-QS is slightly higher than CG-QNC which may be attributed to the fact that both gradations lines of CG-QS and CG-QNS were very similar. Concerning the fine-graded level, the FG-NS mix had the highest values OAC and V_{be} as well as the lowest V_a followed by FG-QNS, and FG-QS, respectively.

It is challenging to identify a specific trend for HMA volumetrics. However, the combination of NS and QS at the coarse-graded level reduced the V_{be} when compared to mixes that had completely either NS or QS in the mix. However, this was not noticed at the fine-graded level where it is clearly shown that the replacement of QS by NS always results in a higher aggregate surface area, lower OAC, lower V_a and higher V_{be}.

$$VTM = \frac{V_a}{\text{Total mix volume}} \text{ x } 100 \qquad (7)$$

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$$VMA = \frac{V_a+V_{be}}{\text{Total mix volume}} \times 100 \quad (8)$$

$$VFA = \frac{VMA-VTM}{VMA} \times 100 \quad (9)$$

$$DP = \frac{\text{Percent passing sieve No. 200 x Total mix volume}}{V_{be}} \quad (10)$$

Table 8. Summary of the volumetric properties

Volumetric Property	Mix Type						Constraint (0.3-3 million ESALs)
	Coarse-graded			Fine-graded			
	CG-QS	CG-QNS	CG-NS	FG-QS	FG-QNS	FG-NS	
OAC,%	4.36	4.30	4.44	4.18	4.21	4.31	-
VTM, %	4	4	4	4	4	4	4
VMA, %	15.3	15.1	15.0	15.0	15.2	14.6	14
VFA, %	73.9	73.5	73.3	73.3	73.7	72.6	70-80
DP	0.61	0.64	0.69	0.77	0.81	0.85	0.6-1.2
V_a, cm^3	83.91	83.89	82.96	82.82	80.61	79.82	-
V_{be}, cm^3	214.7	215.2	217.5	216.22	220.31	225.72	-

Beam Fatigue Test. Three-point flexural fatigue bending test was conducted to evaluate the fatigue performance of asphalt mixtures. By using the pneumatic repeated load system, the test was performed in strain-controlled mode with a flexural strain level of 1000 micro strain. The type of loading was haversine where the ultimate indirect tensile strength was applied at the frequency 10 Hz with 0.1 s loading and 0.9 s unloading times. All tests were conducted at 25°C on beam specimens of 76 mm (3 in) x 76 mm (3 in) x 381 mm (15 in) prepared according to the method described in AASHTO T 321 [33]. In the fatigue test, the initial Elastic Modulus (E_i) has been determined at the 200th repetition by using Eq. 11 shown below, and the E_i was plotted versus the number of repetitions to failure. The collapse of the beam was defined as a failure when E_i reaches the half indicating the Numbers of Cycles to Failure (N_f), and the plot can be approximated by a straight line and has the form shown below in Eq. 12.

$$\varepsilon = \frac{\sigma}{E} = \frac{12h\Delta}{3L^2-b^2} \quad (11)$$

$$N_f = k_1(E)^{-k_2} \quad (12)$$

Where ε is the tensile strain; σ is the flexural stress; E is the stiffness modulus based on center deflection; h is the height of the beam; Δ is the deflection at the center of the beam; L is the length of span between fixed supports; b is the distance from support to the load point (L/3); N_f is the numbers of cycles to failure; k_1 and k_2 are regression coefficients. The N_f is generally explained by the values of k_1 and k_2. k_1 is a constant directly related to N_f. On the other hand, k_2 represents the deterioration rate of the beam. That is, when k_1 value increases or k_2 value decreases, the N_f value increases indicating a longer life (more fatigue resistant) of the asphalt concrete.

Results and Discussion

Tables 9 and 10 show the results of the BF results for CG mixtures and FG mixtures, respectively. It can be seen from both tables that the increase of NS content in mixtures always results in lower k_1 and E_i as well as a higher k_2 which resulted in lower N_f overall. Moreover, the CG mixtures resulted in higher N_f when compared to FG mixtures with an average increase of 104%. This is due to the improved aggregate interlock in CG mixtures caused by the presence of the coarse aggregate.

The CG-QNS had a comparable Nf with CG-QS with a percentage difference of 0.1% which indicates the proficiency of Bailey method of creating similar gradations and similar aggregate interlock at the coarse gradation level. However, the FG-QNS didn't have a comparable Nf with FG-QS where the percentage difference was 18%. This could be attributed to the absence of the course aggregate which creates a considerable interlock in the aggregate structure and improves the stability of the asphalt concrete. That is, Bailey method is effective if used only in a coarse mix design.

Table 9. BF Results of CG mixtures

Property	Mixture Type					
	CG-QS		CG-QNS		CG-NS	
	Sample 1	Sample 2	Sample 1	Sample 2	Sample 1	Sample 2
k_1	2319.15 x 10^{20}	2310.14 x 10^{20}	2301.13 x 10^{20}	2305.64 x 10^{20}	2111.85 x 10^{20}	1922.57 x 10^{20}
k_2	6.616	6.619	6.622	6.621	6.656	6.689
E_i, MPa	1409.2	1404.3	1399.4	1401.85	1380.55	1361.7
N_f	33386	33362	33338	33350	27485	21632
$N_{f\ average}$	33374		33344		24559	

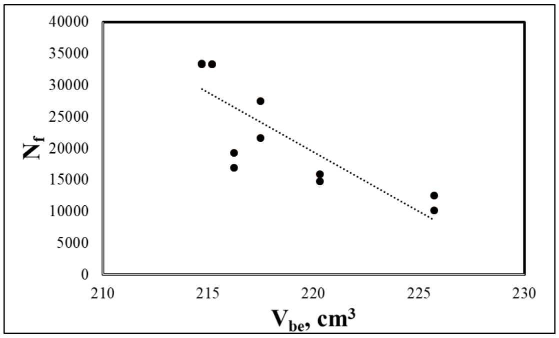
Table 10. BF Results of FG mixtures

Property	Mixture Type					
	FG-QS		FG-QNS		FG-NS	
	Sample 1	Sample 2	Sample 1	Sample 2	Sample 1	Sample 2
k_1	1769.82 x 10^{20}	1846.2 x 10^{20}	1675.48 x 10^{20}	1722.65 x 10^{20}	1218.50 x 10^{20}	1446.99 x 10^{20}
k_2	6.771	6.73	6.793	6.782	6.810	6.8015
E_i, MPa	1287.5	1324.6	1276.7	1282.1	1259.8	1268.25
N_f	16922	19277	14824	15873	10181	12503
$N_{f\ average}$	18100		15349		11342	

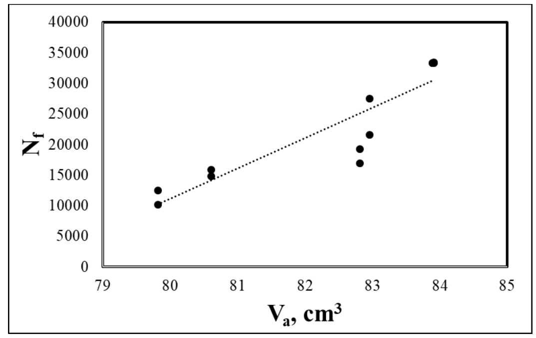
Statistical Assessment. The volumetric properties of a compacted mixture are important criteria by which the quality of an asphalt mixture is evaluated. Volumetrics historically provided a reliable indication of the mixture's probable performance during its service life. It is important to note that all of the asphalt mix volumetrics are mathematically interrelated. However, they may differ in their significance and corresponding sensitivities to the performance tests.

An attempt was made in the current study to identify the significance and the sensitivity (importance) of different volumetrics including DP, VFA, VMA, Va, and Vbe to each performance test output. Fig. 3 shows the trend lines of a number of volumetric measures with Nf including Va, Vbe, VMA, VFA, and DP. It can be seen that Nf was inversely related to both Vbe and DP. In contrast, Nf had a direct relationship Va, VMA nad VFA. Moreover, the data points dispersion is lower Va, Vbe, and DP indicating an improved relationship with Nf.

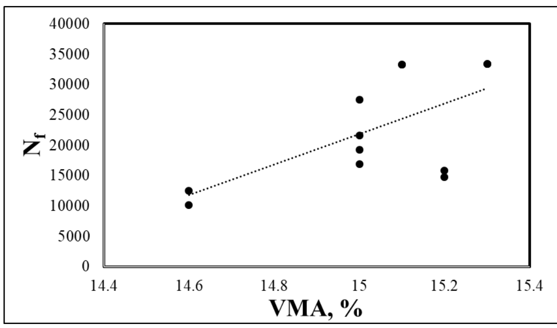
Fig.4 show the sensitivities and the significance of each volumetric explained by the tornado chart. The importance of each volumetric measure is based on the correlation coefficient (r), and the significance of each volumetric measure is based on the p-value at a risk level of 0.05. In other words, the higher the correlation, the higher the sensitivity and the higher the significance. As can be seen from Figure 4, all volumetric measures were significant at a risk level of 0.05 (p-value $\leq$ 0.05), but varied in importance or sensitivities. That is, although the correlation values were close due to the mathematical interrelationships between them, these mathematical relations have minor differences that lead to different correlations with the output of any performance test. Eq. 7 to 10 again show the calculations of the volumetric measures. In essence, DP was the most sensitive (important) to N_f followed by V_a, V_{be}, VMA, and VFA, respectively. This is because DP results in more distinctive values when compared to other volumetrics and the parameters used to calculate are mainly shared and included in the calculations of all volumetric measures.



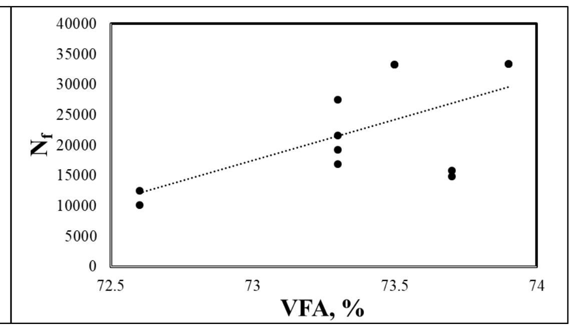
(a) V_{be}



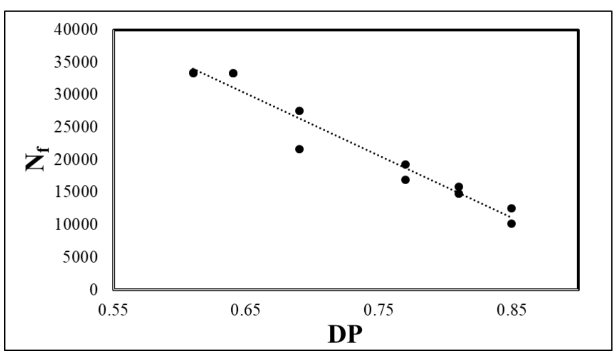
(b) V_a



(c) VMA



(b) VFA



(e) DP

Figure 3. Volumetric measures relationship with N_f: (a) $V_{be,}$ (b) $V_{a,}$ (c) VMA, (d) VFA, and (e) DP

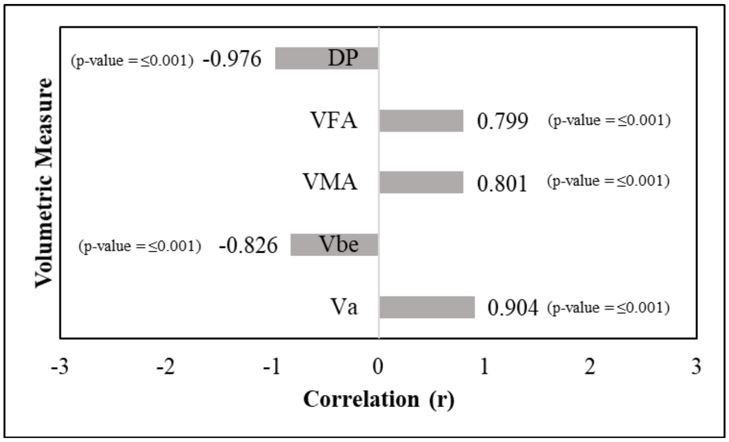


Figure 4. Volumetric measures sensitivities and significance

To this end, it is shown that N_f is highly dependent on aggregate structure that is correspondent to the volumetric measures which, in turn, had a significant influence on N_f. Therefore, it would be advantageous to generate statistical relationships between the volumetric measures and N_f. Khasawneh et al. [34] showed that curve-fitting regression can improve prediction and provide more reliable results than linear regression. The non-linear curve fitting regression analysis was carried out. To run the nonlinear analysis, curve fitting software is needed to select the best fit for each predictor from a pool of existing functions. MATLAB R2022a and CurveExpert Professional 2.7 are powerful software and easy to use for this purpose. Multiple functions are fitted with data and the best-fit function can be chosen based on the Coefficient of Determination (R^2) value. Accordingly, Table 10 shows the relationships between V_{be} and each performance test output. The R^2 values are also provided in the table. It can be noticed R^2 values are consistent with the correlation values shown in Figure 4. That is, the DP model had the highest R^2 followed by V_a, V_{be}, VMA, and VFA, respectively. That is, the DP was the best predictor for N_f since DP results in more distinctive values when compared to other volumetrics and the parameters used to calculate is mainly shared and included in the calculations of all volumetric measures.

Table 10. Statistical relationships of different volumetric measures with N_f

Volumetric Measure	Model	R^2
DP	N_f=219.7- 6923.4 ln(DP)	0.956
V_{be}	$N_f = (-2.194 \times 10^{-7} + 1.0292 \times 10^{-9} V_{be})^{-\frac{1}{1.93}}$	0.817
V_a	$N_f = (8.36 \times 10^{-7} - 1.0187 \times 10^{-8} V_a)^{-\frac{1}{1.782}}$	0.930
VMA	$N_f = 1.12135 \times 10^{12}\ e^{-\frac{266.7}{VMA}}$	0.425
VFA	N_f=- 4206864 + 984603 ln(VFA)	0.418

Conclusions

1. The fine-graded mixes have lower optimum asphalt content compared to coarse-graded ones. That is the surface area for fine-graded mixes are higher than coarse-graded, and this resulted in less need for asphalt to reach the same air voids level of 4%.
2. Increasing NS content in the mixture reduced the optimum asphalt content, since the presence of the natural sand fills the voids between angular aggregate (fine and coarse).

3. DP, V_a and V_{be} result in more distinctive values than VTM, VMA, DP and VFA and are mainly included in the calculations of all volumetric measures. However, DP had more distinctive values than V_a and V_{be}.
4. The increase of NS content in mixtures always results in lower k_1 and E_i as well as a higher k_2 which resulted in lower N_f overall.
5. The CG mixtures resulted in higher N_f when compared to FG mixtures with an average increase of 104% due to the enhanced aggregate interlock when the coarser aggregate are used in the mixture.
6. The CG-QNS had a comparable N_f with CG-QS with a percentage difference of 0.1% which indicates the proficiency of Bailey method of creating similar gradations and similar aggregate interlock.
7. The FG-QNS didn't have a comparable N_f with FG-QS where the percentage difference was 18%.
8. The volumetric measures including VMA, DP, VFA, V_a and V_{be} were significant to the performance indices. However, DP was the most significant and sensitive followed by V_a, V_{be}, VMA, and VFA, respectively.
9. Bailey method is effective if used only in a coarse mix design. That is, the absence of the course aggregate creates a considerable interlock in the aggregate structure and improves the stability of the asphalt concrete.

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