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Performance evaluation of asphalt concrete mixes under varying replacement percentages of natural sand

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ABSTRACT

Frequently, load associated mode of failure, rutting and fatigue, are the main failure types found in some newly constructed roads within Baghdad, the capital of Iraq, and some suburban areas. The use of excessive amount of natural sand in asphalt concrete mixes which is attractive to local contractors could be one of the possible causes to the lack of strength properties of the mixes resulting in frustration in the pavement performance. In this study, the performance properties of asphalt concrete mixes with two natural sand types, desert and river sands, were evaluated. Moreover, five replacement rates of 0, 25, 50, 75, and 100% by weight of the fine aggregate finer than 4.75 *mm* were used. The performance properties including moisture susceptibility, resilient modulus, permanent deformation, and fatigue characteristics were evaluated using indirect tensile strength, uniaxial repeated loading and repeated flexural beam tests. Also, as a part of the research objective, the laboratory tests result were used to predict the performance using VESYS computer software. Results showed that mixes with high natural sand content (NSC) are more susceptible to moisture damage and rutting, lower resilient modulus and some improvement in fatigue resistance. Based on the obtained results, the necessity has rise to revise the current local specification for asphalt concrete which specifies the limits of natural sand content in the mixes of wearing and binder courses with 25% whereas for base course mixes no limit exist yet.

1. Introduction

Premature failures in asphalt pavements are considered as a major problem for pavement agencies. Mineral aggregates compose 90–95% of mixture weight and 75–85% of mixture volume. Accordingly, the type and gradation of aggregates significantly impacts the workability and performance of asphalt concrete pavements in use [22]. Premature failures are often attributed to the excess amount of round-shaped fine-aggregate used in the asphalt concrete mixes. Permanent deformation of asphalt concrete mixes is associated with the shape, gradation, durability and toughness of the aggregate [3,9,10,13,19,25,26]. Most of natural fine aggregates used in road construction are mined from river deposits, or glacial outwash. Oftentimes, mined fine aggregate is used without any further process in manufacturing the hot-mix asphalt (HMA). On the other hand, processed or crushed fine aggregate has been quarried, crushed, separated into distinct size fractions, and washed for the purpose of using in HMA. Due to the availability of natural fine aggregates, in addition to their competitive cost and workability, in comparison to crushed sand, they are preferred to be used by pavement agencies and private contractors in HMA mixes.

Physical properties such as fine aggregate angularity (FAA) was found to significantly impact the performance of asphalt concrete mixes [25]. Results showed that the resistance of HMA are directly proportional with FAA values. Several studies were conducted to explore the impact of fine aggregate properties on the performance of HMA mixes. The physical characteristics of fine aggregate (shape and surface texture) have been found to affect the asphalt mixture properties and its performance [14,21]. Kamaruddin et al. [12] and Yasreen [26] studied the effect of sand on performance of asphalt concrete mixture. The researchers focused on the performance of asphalt concrete mixes in terms of rutting and fatigue behavior. Two types of sand, quarry and mining sand, were used where the angularity of the sands was measured. Due to the type of aggregate formation, quarry sand was found to acquire higher FAA values in comparison to the mining sand. Wheel tracking test machine was used to measure rutting behavior on the asphalt mixture and it was conducted at 40°C. Fatigue beam test was performed to evaluate the fatigue behavior of the asphalt concrete mixes. Moreover, test results showed that specimens with quarry sand over-performed the specimens with mining sand

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in both rutting and fatigue tests.

Ahlrich [3] evaluated the utilization of substandard aggregate using rounded uncrushed course and fine aggregate. The study focused on impact of low quality aggregate on the rutting behavior under aircraft loads. The evaluation combines the effects of particle shape, texture and fine aggregate gradation on rutting characteristics of asphalt concrete mixes. The performance of these tests indicated that the rutting potential increased when the amount of natural-sand material was equal of greater than 20%. Zaniewski and Srinivasan [27] examined the relation between natural sand content and the rutting potential in asphalt concrete mixes. The study examined the impact of replacement of limestone aggregate finer than 4.75 *mm*with low and high replacement percentage of natural sand. Results showed that HMA mixes with 40% of natural sand exhibits higher rutting depths in comparison to mixes with 0% of natural sand content.

Mainly, most of the studies focus on improving the performance of asphalt concrete mixes using locally available materials to produce a sustainable and low cost newly constructed asphalt highway design within the asphalt transportation industry. Some researchers focused on using Recycled Concrete Aggregate (RCA) on the performance of asphalt mixes [11,15,20,23]. Other studies focused on the use of marble quarry waste Akbulut and Gurer [5] or granite sludge Akbulut et al. [6] in asphalt concrete mixes. On the other hand, sensitivity analysis of natural sand replacement to the total proportion of manufactured fine aggregate on the mechanistic behavior of HMA mixes was conducted [10]. The study utilized manufactured fines in 20, 40, 60% replacement of total fines finer than 5*mm*. Results demonstrated that the increase in manufactured fines content result in an improved densification properties, Marshall stability and dynamic modulus.

Since asphalt, as a binding material, is highly susceptible to temperature, there is an urgent need to limit the amount of round-shaped fine aggregate in the HMA in the hot and arid regions. The available specifications for asphalt concrete paving works limits the percentage of uncrushed fine aggregate finer than 4.75 *mm* to 25% for wearing and binder courses SCRB/R9 [24]; Municipality c [18], and MOC [16] states that the amount of natural sand in the HMA should not exceed 15% of the total weight of aggregate finer than 4.75 *mm*. However, none of the mentioned specifications limits the use of natural sand in the base course layer. Since the dominant types of sand in the regions of the aforementioned specifications are either river or desert sand, this study focuses on performance of asphalt concrete structure with two natural sand types, river and desert sands. Five replacement rates of 0–100% by 25% increment by weight of aggregate finer than 4.75 *mm* was used for base course mixes. The study evaluated the performance of HMA mixes in terms of moisture susceptibility, resilient modulus, permanent deformation, and fatigue characteristics. Finally, results acquired from the lab tests were used to evaluate rutting and fatigue behavior over a design period of 10 years using VESYS 5 W software.

2. Materials

The raw materials used in this study were asphalt cement, quartz aggregate as the course aggregates and three types of fine aggregate, crusher, river, and desert sand. Further, limestone dust was used as a mineral filler. The properties of these materials are given below.

2.1. Physical properties

Asphalt cement produced from Doura Oil Refinery of a performance grade PG 64–16 was used. The physical properties of the used asphalt cement are presented in Table 1. The specific gravity of coarse aggregate, fine aggregate, and filler, in addition to the mechanical properties of the coarse aggregate were conducted. The physical properties of the aggregates and the mineral filler are presented in Table 2.

FAA is considered as a crucial factor to differentiate between the types of fine aggregate. FAA can be determined through the percentage of voids in the sand sample. The higher the percentage of voids, the higher FAA value the aggregate acquire. From Table 2, it is clear that crusher sand has the highest FAA value in comparison to desert and river sand.

Table 1
Physical Properties of Asphalt Cement based on Performance Grade.

Binder	Parameter	Temperature Measured	Measured Parameters	Specification Requirements AASHTO M320-05
Original	Flash Point, C	–	298	230 C, min
	Viscosity at 135 C, Pa.s	–	0.487	3 Pa s, max
	DSR, G/sin at 10 rad/s, kPa	58	3.3522	1.00 kPa, min.
		64	2.020	
		70	0.889	
RTFO Aged	Mass Loss, %	–	0.654	1%, max
	DSR, G/sin at 10 rad/s, kPa	58	4.1596	2.2 kPa, min
		64	3.1483	
		70	1.9809*	
PAV Aged	DSR, G/sin at 10 rad/s, kPa	28	4684	5000 kPa, max
		25	6477	
	BBR, Creep Stiffness, mPa	−6	134	300 mPa, max

Table 2
Physical properties of aggregates and mineral filler.

Property	ASTM Design.	Test Results			SCRB Specification
Coarse Aggregate		Crushed Quartz			
Bulk Specific Gravity		2.632			
Apparent Specific Gravity		2.636			
Water Absorption, (%)	C 127	0.261			
Percent wear by Los Angeles abrasion, (%)	C 131	18			30 max.
Soundness Loss by Sodium Sulfate Solution, (%)	C 88	4.3			12 max.
Fractured Pieces, (%)	D 5821	97			90 min.
Fine Aggregate		Crusher	Desert	River	
Bulk Specific Gravity		2.581	2.564	2.542	
Apparent Specific Gravity		2.662	2.575	2.562	
Water Absorption, (%)	C 128	0.809	0.966	1.103	
Sand Equivalent, (%)	D 2419	59	49	45	45 min.
Clay Limps and Friable Particles, (%)	C 142	1.2	1.37	0.83	3 max.
Fine Aggregate Angularity (FAA), (%)	C 1252	48	41	38	
Filler		Lime Stone			
Specific Gravity		2.789			
Surface Area (m2/kg)		247			
Passing Sieve No. 200 (0.075 mm), (%)		98			

2.2. Chemical properties

Due to the importance of chemical composition of fine aggregate, X-ray fluorescence (XRF) test was conducted. Chemical composition test results are presented in Table 3. The chemical composition defines the behavioral characteristics of the fine aggregate particles within the HMA mix which is reflected on the performance of HMA mixes. For instance, SiO_2 compose 78.73% of the crusher sand, while it composes 19.74 and 44.81% of desert and river sands respectively. The high SiO_2 content in the sand can cause HMA stripping [2]. On the other hand, Al_2O_3, which contributes to the hardness of the sand particles, was found to be the highest in the river sand where is composes 6.01% of the total percentage, while it has lower values in both desert and crusher sands. Further, due to the small size of Fe_2O_3 particles, it contributes to the density of the HMA mixes. Fe_2O_3 content was found to be the highest in river sand, and the lowest in crusher sand where it composes 4.55 and 0.98% of the total

Table 3
Chemical composition of aggregates.

Chemical Composition	Crusher Sand	Desert Sand	River Sand	Filler (Lime Stone)
Loss	8.3	27.41	13.06	
SiO_2	78.73	19.74	44.81	10
Al_2O_3	1.66	4.26	6.01	6
Fe_2O_3	0.98	2.44	4.55	1
CaO	6.77	35.54	22.12	29
MgO	0.63	0.96	8.77	16
SO_3	2.3	9.39	0.25	0.12
L.O·I				37

percentages respectively.

3. Experimental tests

This section consists description for the conducted tests to mix design as well as the mechanical properties evaluation of the HMA mixes for wearing, binder, and base course under different Natural Sand Content (NSC) for both types, desert and river sands as a percentage of replacement from the crusher sand in the control mix. Following the mix design using Marshall method, Asphalt concrete mixes were prepared at their optimum asphalt content and then tested to evaluate moisture susceptibility using indirect tensile strength (ITS), resilient modulus (M_r) and permanent deformation using uniaxial repeated load test, and fatigue characteristics using repeated flexural beam tests.

3.1. Marshall mix design

The coarse and fine aggregates were sieved and recombined in the proper proportion to meet the wearing, binder and base course gradation requirement as specified in Ref. [24]. The final aggregate gradation and specification limit are presented in Table 4.

To determine the optimum asphalt content (OAC) for the HMA mixes with various percentage of NSC, a complete mix design was conducted according to Marshall mix method as outlined in ASTM D6926 using 75 blows per face of the Marshall compactor. Three specimens were prepared for each asphalt cement content and OAC was obtained as the average asphalt cement contents yields the maximum stability, maximum unit weight, minimum voids in mineral aggregates, and 4% air voids [4].

3.2. Indirect tensile test

To evaluate the moisture susceptibility of HMA mixes, the procedure described in ASTM D 4867 was adopted. For each type of mix, six Marshall specimens were compacted to an air void level ranges between 6% and 8%. The specimens were divided into two subsets, control and treated subsets. While the control specimens were tested in temperature of 25^{o}C in indirect tension test, the other subsets were subjected to one cycle of freezing and thawing, 16 h in −18 ±2^{o}C then 24 h in 60 ±1^{o}C. Then the specimens were tested under the same conditions of the untreated subsets. During the indirect tension test, specimen is loaded along the diameter and the splitting force is recorded. The test parameters are calculated as follow:

$$ITS = \frac{2P}{\pi h D} \tag{1}$$

$$TSR = \frac{C \cdot ITS}{UC \cdot ITS} \tag{2}$$

where P is the splitting load in N; h is the specimen height, mm; D is the specimen diameter, mm; $C \cdot ITS$ is the conditioned indirect tensile stress, MPa; and $UC \cdot ITS$ is the unconditioned indirect tensile stress, MPa.

3.3. Uniaxial repeated load test

The uniaxial repeated loading tests were conducted for cylindrical specimens, 101.6 *mm* (4 inch) in diameter and 203.2 *mm* (8 inch) in height, using the pneumatic repeated load system. In these tests, repetitive compressive loading with a stress level of 20 *psi* was applied in the form of rectangular wave with a constant loading frequency of 1 Hz (0.1 s load duration and 0.9 s rest period) and the axial permanent deformation was measured under the different loading repetitions. The uniaxial repeated loading tests were conducted at 20^{o}C (68^{o}F) for the resilient modulus determionation and 40^{o}C (104^{o}F) to acquire permanent deformation properties. The specimen preparation method for this test can be found elsewhere [7] The permanent strain (ε_p) is calculated by applying the following equation:

$$\varepsilon_p = \frac{p_d \times 10^6}{h} \tag{3}$$

where ε_p is the axial permanent microstrain, p_d is the axial permanent deformation and h is the specimen height. Also, throughout this test the resilient deflection is measured at the load repetition of 50–100, and the resilient strain (ε_r) as well as resilient modulus (M_r) are calculated as follows:

$$\varepsilon_r = \frac{p_d \times 10^6}{h} \tag{4}$$

$$M_r = \frac{\sigma}{\varepsilon_r} \tag{5}$$

where ε_r is the axial resilient microstrain, r_d is the axial resilient deflection, h is the specimen height, M_r is the resilient modulus and σ is the repeated axial stress.

3.4. Flexural beam fatigue test

Within this study, third-point flexural fatigue bending test was adopted to evaluate the fatigue performance of asphalt concrete mixtures

Table 4
Aggregate gradation.

Sieve Size		Wearing Course		Binder Course		Base Course	
		Selected Grade, (% Passing)	SCRB/R9 Limits	Selected Grade, (% Passing)	SCRB/R9 Limits	Selected Grade, (% Passing)	SCRB/R9 Limits
1 1/2”	37.5 mm	–	–	–	–	100	100
1”	25 mm	–	–	100	100	95	90–100
3/4”	19 mm	100	100	93	90–100	80	76–90
1/2”	12.5 mm	95	90–100	78	70–90	65	56–80
3/8”	9.5 mm	85	76–90	67	56–80	55	48–74
No.4	4.75 mm	68	44–74	45	35–65	40	29–59
No.8	2.36 mm	32	28–58	27	23–49	22	19–45
No.50	0.3 mm	9	5–21	9	5–19	7	5–17
No.200	0.075	7	4–10	6	3–9	5	2–8

using the pneumatic repeated load system, this test was performed in stress controlled mode with flexural stress level varying from 5 to 30% of ultimate indirect tensile strength applied at the frequency of 2 Hz with 0.1 s loading and 0.4 s unloading times in rectangular waveform shape. All tests were conducted as specified in SHRP standards at 20^{o}C (20^{o}F) on beam specimens 76 mm (3 in) x 76 mm (3 in) x 381 mm (15 in) prepared according to the method described in Refs. [8]. In the fatigue test, the initial tensile strain of each test has been determined at the 50th repetition by using Equation (6) shown below and the initial strain was plotted versus the number of repetition to failure on log scales, collapse of the beam was defined as failure, the plot can be approximated by a straight line and has the form shown below in Equation (7).

$$\varepsilon_t = \frac{\sigma}{E_S} = \frac{12h\Delta}{3L^2 - 4a^2} \tag{6}$$

$$N_f = k_1(\varepsilon_t)^{-k_2} \tag{7}$$

where ε_t is the initial tensile strain; σ is the extreme flexural stress; E_S is the stiffness modulus based on center deflection; h is the height of the beam; Δ is the dynamic deflection at the center of the beam; L is the length of span between supports; a is the distance from support to the load point ($L/3$); N_f is the number of repetitions to failure; k_1 is the fatigue constant value of N_f when $\varepsilon_t = 1$ and k_2 is the inverse slope of the straight line in the logarithmic relationship.

4. Results and discussion

4.1. Marshall properties

Marshall properties with varying NSC at the OAC for the base course are shown in Fig. 1. The results showed that mixes with NSC up to 50% possess the same OAC as those mixes with crusher sand. On the other hand, further increment in NSC resulted in a higher OAC. While the OAC for the mixes with 0% NSC are 3.6, 4.3 and 4.6 for the wearing, binder and base course respecitvely, the OAC was found to be 3.9, 4.6 and 4.9% for 100% of NSC for the courses. The increase in OAC is attributed to the higher surface area of natural sand as compared to that of crusher sand. It can be noticed from Fig. 1 that OAC for both types of natural sand, desert and river sands, acquire the same OAC for the same NSC percentages.

In general, the results revealed that Marshall stability decreased as the NSC increase. The deterioration rate varies with the type of sand and its content. In case of desert sand, results showed a decrease in the stability by 0.19 kN/25% for base course mixes. While a higher deterioration in stability was noticed in cases where river sand was used as a NSC. The deterioration in stability was noticed to be 0.350 kN/25%. Further, Marshall flow results showed similar trend to stability behavior of the HMA specimens. This behavior could be attributed to the low FAA values of river and desert sands in comparison to crusher sand. The low FAA value associated with natural sand results in less angular particles, and smaller rough surface texture which results in a lower bonding between the aggregate particles and asphalt cement which results in reduction in Marshall stability Topal and Sengoz [25] and negatively impact the

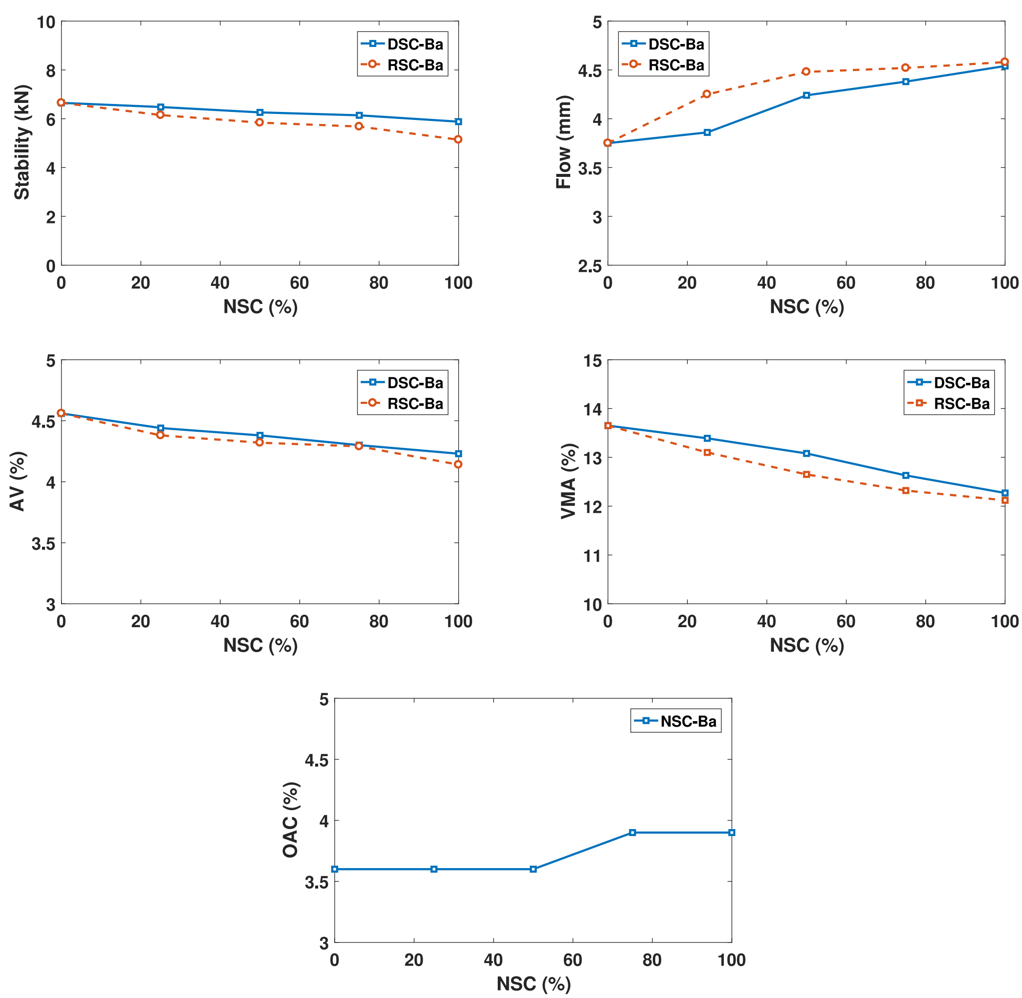


Fig. 1. Effect of natural sand content on Marshall properties for Base Course.

properties and performance of HMA mixes [14]. Regardless of the mix type, the average Marshall flow value was noticed to be increased by 22% and 25% when the crusher sand was entirely replaced by the desert and river sand respectively. Eventually, the OAC for each NSC was used to prepare the HMA specimens for all specimens used in the tests for wearing, binder, and base courses.

4.2. Moisture susceptibility

Based on the results presented in Table 5 and exhibited in Fig. 2, its obvious that the HMA mixes with natural sand is more susceptible to moisture damage than those with crusher sand, The average tensile strength ratio (TSR) for the HMA mixes with 100% desert and river sand was lower than those with crusher sand by 21 and 24%, respectively. Also, It's interesting to note that the unconditioned indirect tensile strength (UCITS) approximately linearly proportional to the NSC with constants of proportionality of −38.5 kPa and −42.4 kPa per 10% increase in desert and river sand content, respectively. The matter which revealed that the HMA mixes with river sand is more sensitive to stripping behavior than that containing desert sand. Reminding that the minimum acceptable limit for the TSR is 80%, it's clear that mixes with up to 25% NSC could satisfy the specification limit; further increase in NSC resulted in drop in TSR value out of specification minimum requirement. This findings confirms that the moisture induced damage is enhanced using high NSC, the matter which could be attributed to the low angularity (low FAA) for this type of fine aggregate in comparison with the crusher sand resulting in reduced interlock between the particles from one side and adhesion between the aggregate and the asphalt cement from the other side.

4.3. Resilient modulus and permanent deformation

The resilient modulus (M_r) results presented in Fig. 3, shows that NSC in the HMA mixes influence the elastic response of the HMA specimens. The low resilient modulus values are associated with the high content of natural sand. The average M_r , for the mixes with 100% of NSC, in both types desert and river sands, was found to be lower than those of crusher sand by 19% and 24% respectively.

Table 5
Effect of natural sand content on moisture susceptibility.

NSC, (%)		0	25	50	75	100
Desert	**UC.ITS, KPa**	938	863	814	620	578
	TSR, %	82.1	81.8	74.7	70.1	64.3
River	**UC.ITS, KPa**	938	808	743	596	513
	TSR, %	82.1	80.3	69.4	68.1	62

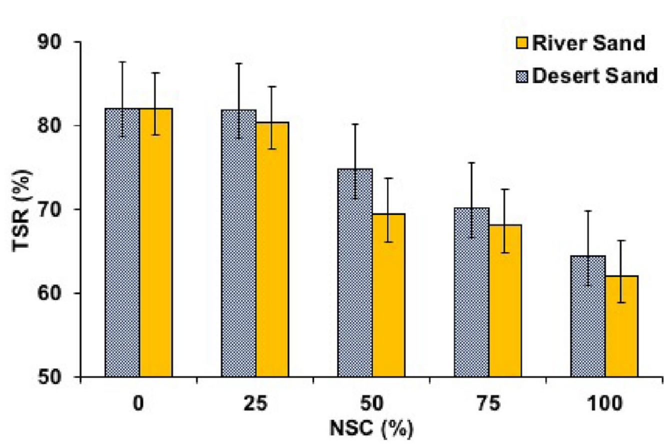


Fig. 2. Effect of NSC on tensile strength ratio.

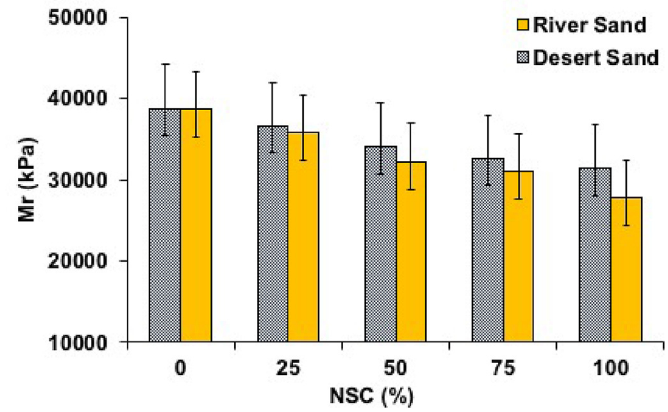


Fig. 3. Effect of NSC on the resilient modulus.

In addition, it can be noticed that the reduction in M_r values is negatively proportioned with the NSC. Moreover, mixes with river sand content acquired lower M_r values in comparison for mixes with desert sand content. The reduction of M_r values are attributed to the fine aggregate shape, where the angularity of crusher sand particles provide better interlock with the asphalt cement in comparison to the natural sand. Accordingly, lower resiliency of strain resulted from the particles sliding under compressive stress is recorded in case of crusher sand.

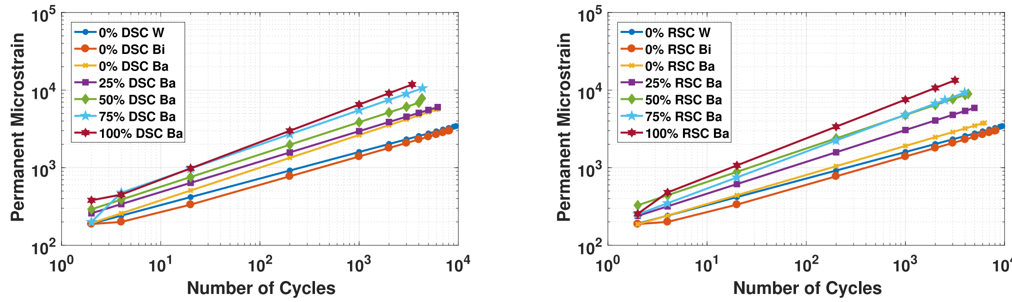
To acquire the permanent deformation parameters, intercept and slope, the uniaxial repeated load test was continued until failure of specimens. Permanent deformation parameters were calculated from the plots of deformation versus number of load repetition after representing them in log-log scale [17]. Permanent deformation test results exhibited in Fig. 4 and Table 6 demonstrates that the highest permanent strain is associated with HMA mixes with high NSC. Results show that mixes with crusher sand acquired the lowest permanent deformation values followed by mixes with desert sand, and river sand respectively. Although the discrepancy is a silent feature in the intercept values; however the intercept average results for the wearing, binder and base course mixes for mixes with desert and river sands are higher than those of mixes with crusher sand by 45.3 and 61.3% respectively.

In Fig. 4 (a), % DSC W refers to the percentage of Desert Sand Content (DSC) in the wearing course; % DSC Bi refers to percentage of DSC in the binder course; % DSC Ba refers to the percentage of DSC in the base course. The same naming scheme applies for Fig. 4 (b). However, River Sand Content (RSC) was used instead of the DSC.

Moreover, results indicate that permanent deformation accumulation parameter, slope, for mixes with desert sand is higher than those of crusher sand by 27.6%, while mixes with river sand content acquired a higher slope value, by 3%, than mixes with desert sand. Results acquired from these tests comply with the results acquired in Kamaruddin et al. [12]; Yasreen et al. [26], Ahlrich [3]; Zaniewski and Srinivasan [27] where the results showed that HMA with manufactured fine aggregates possess lower rutting potentials in comparison with mixes with higher percentage of uncrushed fine aggregates finer than 4.75 *mm*.

4.4. Flexural fatigue

The fatigue coefficient k_1 and the exponent k_2 are characteristics used to predict and evaluate the fatigue life. For instance, if two materials have the same value of k_1, the a higher value of k_2 indicates a potential for longer fatigue life. On the other hand, a lower k_1 value represents a shorter fatigue life when k_2 is the same, resulting in parallel curves. The k_2 data presented in Table 7 suggest that the fatigue performance is improved when the crusher sand is replaced by natural sand. The average fatigue exponent k_2 is increase by 19.7 and 22.9% when the crusher sand was entirely replaced by desert and river sand, respectively. On the other hand k_1 values showed a reversed trend in comparison t k_2, where



(a) DSC (b) RSC

Fig. 4. Effect of NSC on permanent deformation parameters.

Table 6
Permanent deformation parameters.

		Wearing Course				
NSC, (%)		0				
Intercept		150				
Slope		0.342				
		Binder Course				
Intercept		112				
Slope		0.365				
		Base Course				
NSC, (%)		0	25	50	75	100
Desert Sand	Intercept	144	160	160	170	230
	Slope	0.374	0.410	0.431	0.476	0.499
River Sand	Intercept	144	180	243	180	240
	Slope	0.374	0.410	0.431	0.476	0.499

Table 7
Fatigue parameters.

		Wearing Course				
NSC, (%)		0				
K1		1505.87E-08				
K2		3.639				
		Binder Course				
K1		2.12E-08				
K2		3.526				
		Base Course				
NSC, (%)		0	25	50	75	100
Desert Sand	K1	1.09E-08	5.44E-08	2.32E-08	1.65E-09	7.72E-09
	K2	3.394	3.526	3.639	3.903	3.903
River Sand	K1	1.09E-08	1.17E-09	2.32E-09	5.76E-09	2.72E-09
	K2	3.394	3.639	3.764	3.978	4.331

$k_2$decrease by increase in NSC.

The average k_1 value for the mixes with 100% crusher sand was (3.2E-8) whereas for those mixes with 100% NSC it was (5.2E-9). Also, it is worth to notice from the k_2 data, that the expected performance of river sand against the fatigue life is better than that of desert sand. The better fatigue characteristics for the mixes with NSC could be attributed to the higher flow values provided by this type of fine aggregate which indicate a higher flexibility in comparison to those with crusher sand.

4.5. Performance prediction using VESYS 5 W

In order to predict the pavement performance during the analysis period, VESYS software was used. With the presence of several permanent deformation models, VESYS is considered as a promising rutting estimation model to be used to estimate the rutting performance of pavement structures [28]. VESYS is a probabilistic and mechanistic flexible pavement computer program. Two rutting models are embedded within the program, layer rutting and system rutting models. VESYS rutting model is based on the laboratory permanent deformation law that expresses the permanent strain per each loading pulse in the asphalt concrete specimen as follows:

$$\frac{\Delta\varepsilon_p(N)}{\varepsilon} = \mu N^{-\alpha} \tag{8}$$

where $\Delta_p(N)$ is the vertical permanent strain at load repetition, N; ε is the peak haversine load strain for a load pulse of duration of 0.1 *sec* measured on the 200^{th} repetition; and μ, α are the material properties based on stress state, temperature, etc. Moreover, the VESYS layer rutting model estimates the permanent deformation as the product of the elastic compression in each finite layer and the permanent deformation law associated with the elastic compression of the same layer. The layer rutting model can be expressed as follows:

$$R_D = \int_{N1}^{N2} U_s + \frac{e_t}{e_s}\mu_{sub}N^{-\alpha_{sub}} + \sum^{550} i = 1 \int_{N1}^{N2} \left(U_i^+ - U_i^-\right)\mu_i N^{-\alpha_i} \tag{9}$$

where U_s^+ is the deflection at top the subgrade due to single axle load; U_i^+, U_i^- is the deflection at top and bottom of finite layer *i* due to axle group; e_t is the strain at top of subgrade due to the axle group; e_s is the strain at top of subgrade due to a single axle; μ_{sub}, α_{sub} is the permanent deformation parameters of the subgrade; and μ_i, α_i is the permanent deformation parameters of layer *i*. On the other hand, the system rutting model treats the pavement structure as one unit. The model calculates and equivalent permanent deformation parameters, μ_{sys} and α_{sys} through least squared regression analysis. Correspondingly, the surface rut depth is calculated as follows:

$$R_D = \int_{N1}^{N2} U\mu_{sys}N^{-\alpha_{sys}dN} \tag{10}$$

where *U* is pavement surface deflection. For the purpose of this study, pavement structure geometry and the material properties, M_r and Poisson ratio *v* are illustrated in Fig. 5. The traffic load consists of application of 3.65×10^6 equivalent single axle loads (ESAL) during the analysis period of 10 years, each year 365×10^3, with tire inflation pressure of 551 *kPa* (80 psi) and contact radius of 11.49 *mm* (4.35 *in*). The input parameters for the rutting are α and μ. α is the rate of decrease in permanent deformation as the number of load applications increases (1-slope), and μ represents the constant of proportionality between permanent and resilient (elastic) strain $((intercept \times slope)/resilient \quad strain)$. The values of α and μ of the top three asphalt concrete layers are presented earlier in Table 6. For the granular subbase and subgrade courses, μ is fixed as zero to obtain zero rutting for these layers. Regarding the input parameters for the fatigue cracking, k_1 and k_2, the input values for the software are presented previously in Table 7.

Rutting in flexible pavements develops gradually with increasing numbers of load applications. It is caused by a combination of densifi-

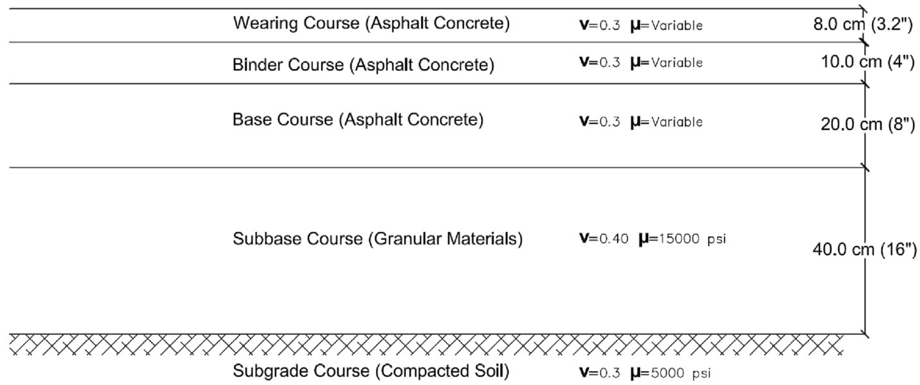


Fig. 5. The proposed geometry of the pavement structure.

cation (decrease in volume and, hence, increase in density) and shear deformation. According to AASHTO [1] rutting is classified according to its severity, into three levels; low (0–13 *mm*), medium (13–25 *mm*) and severe (more than 25 *mm*). Analysis results presented in Fig. 6 show that pavement section with 100% NSC (either desert or river) possessed severe rutting in early stage of design life, approximately within 2 year for sections with river sand as a NSC, and 3 year with desert sand as NSC. However, pavement sections with up to 50% DSC maintains low rut depth level till the end of design life of 10 years. Moreover, sections with 75% and 100% of DSC, by the end of design life, acquires medium and high rut levels respectively. However, structures with 25% and 50% RSC maintained medium rut depth by the end of design life, while structures with higher RSC acquired a high rut depth at the end of the design life. Accordingly, it could be inferred from the results presented in Fig. 6 that DSC has less impact on the performance of the pavement structures in comparison to RSC. Correspondingly, to maintain low rut levels at the end of design life, DSC can be used with a replacement percentage up to 50% from the total NSC finer than 4.75%. While in RSC case, the low rut level could not be maintained if the RSC exceeds the 25%.

The total rut depth results at the end of the design life are presented in Fig. 7 The results clearly show that the rut depth decreases as the NSC increases. In addition, rutting depths acquired from sections with river sand were higher than sections with desert sand.

In return to the local specification SCRB/R9 [24] which does not specify the allowable limit of NSC in base course mixes, VESYS 5 W output shows that base course contribution in the rut depth are 2.4 *mm* and 6.02 *mm* in case of using 25% of desert and river sand respectively. However, the impact of NSC on the total rut depth will be significant at 50% of RSC where the total rut depth 10.4 *mm* higher than the total rut depth acquired with 50% DSC.

To expand the analysis, fatigue cracking results were extracted from the VESYS 5 W software is presented in term of the crack index (CI) value. CI is a dimensionless parameter that provides an estimate for the amount of fatigue cracking in the pavement surface. A value less than 1 indicates the initiation of fatigue cracking at the bottom of lowest asphalt concrete layer. While values between 1 and 1.5 indicates slight fatigue cracking in the pavement surface. Whereas a value between 1.5 and 2.5 represents moderate fatigue cracking and a value between 2.5 and 3.5 indicates severe surface cracking. The CI values at the end of design life are presented in Fig. 8. Fig. 8 shows that the CI values decrease with the increase in the NSC. Correspondingly, asphalt concrete layers with river sand perform better than the mixes with desert sand. The overview of the results revealed that the use of crusher sand increases the fatigue cracking at the end of design life, however, the fatigue cracking was found to be in moderate level.

From the results presented earlier, and to maintain a low rut level and moderate fatigue cracking in the asphalt concrete structure at the end of

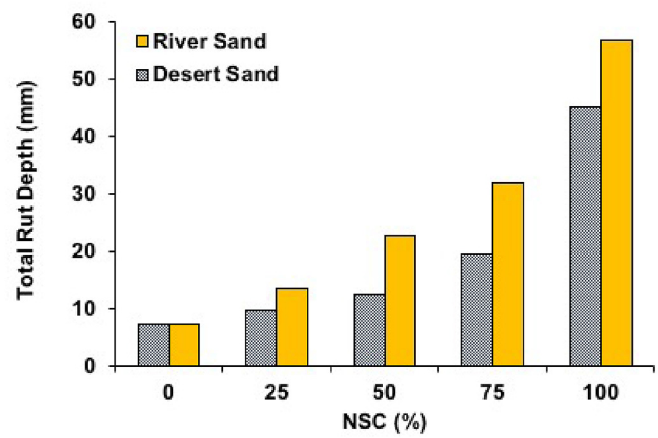
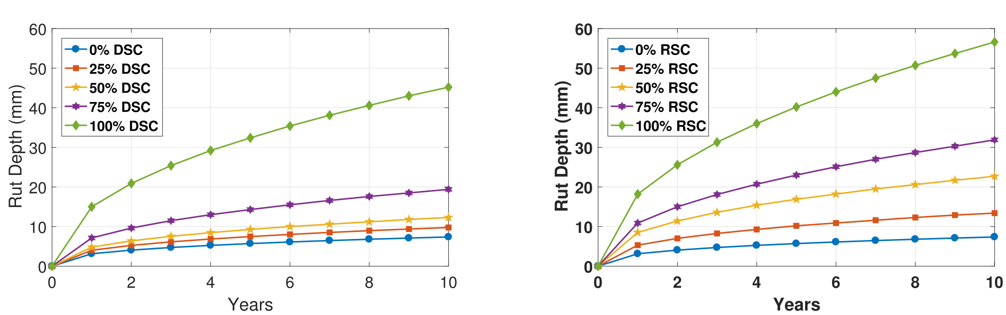


Fig. 7. Predicted rut depth for different NSC at the end of design life.



(a) DSC (b) RSC

Fig. 6. The predicted rut depth over design life for mixes with different NSC.

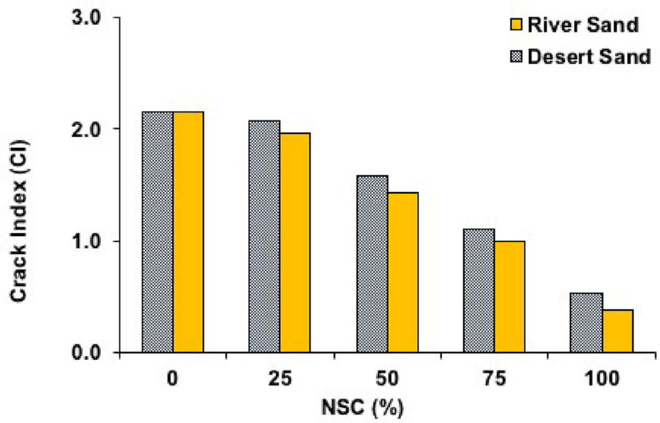


Fig. 8. Predicted crack index for different NSC at the end of design life.

design life, it could be recommended that the NSC in terms of DSC should not exceed 50% and RSC should not exceed 25% of the total fine aggregate finer than 4.75*mm*.

The performance-based results acquired from the VESYS 5w which is based on the input data obtained from the laboratory tests for the different sand types, crusher, desert, and river sands, and replacement% indicate that the rutting resistance is enhanced when the natural sand is entirely replaced by the crusher sand. On the other hand, the fatigue cracking showed an improved performance with the increase of NSC. Therefore it can be concluded that the use of 100% of crusher sand in the hot climate regions could be beneficial in reducing the rutting. However, the incorporation of natural sand could improve the fatigue resistance in the cold climate regions.

5. Conclusion

This paper presents a performance-based analysis for the impact of NSC on the performance of asphalt concrete mixes. In addition to cover the gap in the literature review, this paper focused on analyzing a region-based permanent deformation issues associated with the use of natural sands, as fine aggregate, in HMA mixes. The research studies the impact of NSC, using two types of locally available sands, river and desert sands, on rutting, fatigue, and cracking performance in hot climate regions like Iraq. Further, the research extends the laboratory-based analysis to evaluate the performance of asphalt concrete mixes over a proposed design life of 10 years using VESYS pavement performance analysis software.

Laboratory tests showed that mixes with NSC acquires lower Marshall stability values as the percentage of NSC increases. In addition, it was found that, volumetric mix properties, AV and VMA are negatively proportional with the NSC. On the other hand, it was found that HMA mixes with NSC were more susceptible to moisture damage than those with crusher sand only. The average TSR values for mixes with 100% desert and river sand were lower than those with crusher sand by 21 and 24% respectively. These values are attributed to the higher content of SiO_2 in the river sand in comparison to desert sand.

Further, permanent deformation accumulation rate and slope were evaluated. Results revealed that slope was significantly affected by the NSC where the average slope values for the mixes with 100% desert and river sand were higher than those of crusher sand by 27.6% and 30.6% respectively.

To extend the laboratory tests and analysis, VESYS 5 W software was used to estimate the rut depth over a design life of 10 years. Software analysis output showed that pavement structures with asphalt concrete layers that contain 100% NSC possess severe rut depth within the first 3 years of the design life, whereas the pavement with 100% crusher sand showed low rut depth at the end of design life of 10 years. However, the pavement structure acquired a higher rut depths in case of river sand in comparison with structure where desert sand is used as NSC.

Moreover, fatigue cracking results, in terms of CI, showed a decrease in the CI value as the NSC increase, revealing a better fatigue resistance for mixes with higher NSC. Correspondingly, it could be concluded that the pavement structures with the asphalt concrete layers containing NSC performs better, in terms of fatigue cracking, than mixes with crusher sand. Further, mixes with river sand performs better than mixes with desert sand as a natural sand content. The aforementioned behavior is attributed, mainly, to the FAA of the fine aggregate in its different types. From the results presented earlier, and to balance the rutting behavior with the fatigue performance, it could be recommended that DSC should not exceed 50% of aggregate finer than 4.75*mm*, while RSC should not exceed 25% for the same gradation of aggregates.

Declaration of competing interest

Note: The authors declare that there is no conflict of interest regarding the publication of this paper.

CRediT authorship contribution statement

Amjad H. Albayati: Conceptualization, Methodology, Writing - review & editing. **Harith Abdulsattar:** Investigation, Resources, Data curation, Writing - original draft.

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