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The Effect of Dune Sands on Permanent Deformation Characteristics of Asphalt Mixtures

Mohammad Reza Moghaddam Nayyeri [a], Yunus Niazi [b], Morteza Jalili Qazizade [c]*, Abolfaza Mohammadzade[d]

a. M.Sc., Grad., Faculty of Civil Engineering, Ferdowsi University of Mashhad, Mashhad, Iran.
b. Assistant professor, Faculty of Civil Engineering, Ferdowsi University of Mashhad, Mashhad, Iran.
c. Ph.D. student, Faculty of Civil and Environmental Engineering, Tarbiat Modares University, Tehran, Iran.
d. Ph.D. student, Faculty of Civil Engineering, Ferdowsi University of Mashhad, Mashhad, Iran.
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ABSTRACT:

An attempt was made to determine the permanent characteristics of asphalt mixtures produced using dune sand. Most of the research studies to date have concentrated on sand asphalt characterization using dune sand, but only a few studies have been conducted using dune sand in hot mix asphalt. The objective of this research is to assess the replacement of fine aggregate materials in asphalt mixtures with dune sand and to evaluate its effect on the permanent deformation of the asphalt mixtures. Two types of dune sand were collected from eastern desert areas of Iran. The Marshall test, indirect tensile strength test, dynamic creep test and wheel track test were undertaken to study and compare the properties of asphalt mixtures containing two types of dune sand and crushed sand. The Marshall and indirect tensile strength test results for the three types of mixture were very similar. However, the results of the dynamic creep test and wheel track test exhibited greater rutting in mixes containing dune sand. Based on the results obtained, the asphalt mixture containing dune sand has only the potential for being used in low or medium volume roads.

Keyword: Dune Sand, Crushed Sand, Permanent Deformation, Rutting, Dynamic Creep Test, Wheel Track Test

1. Introduction

The high cost of road construction in desert areas and a lack of good-quality aggregate have always been major problems in arid areas (Al-Mudaiheem J. A., 1990). One of the solutions that has been suggested is to replace a proportion of the fine aggregate in asphalt mixtures with dune sand. Experimental work has also focused on studying the possibility of using dune sand powder (DSP) as a partial mass addition to Portland cement (Guettala S., Mezghiche B., 2011). Almost all of the reported research is regarding sand-asphalt mixtures using dune sand and there is no outstanding study about the use of dune sand in hot mix asphalt (HMA) (Al-Mudaiheem J. A., 1990, Al-Juraiban S. A. and Jimenz R. A., 1983).

**Corresponding Author, Tel: +98 9155213108*
E-mail address: morteza.jalili@modares.ac.ir

It is believed that in the desert environment, the principal form of failure of roads is rutting rather than fatigue cracking (Al-Juraiban S. A. and Jimenz R. A., 1983). Rutting, or permanent deformation, results from the accumulation of small amounts of unrecoverable strain caused by repeated loads applied to the pavement. Rutting is a problem that can take place in the subgrade, unbound base course or HMA (Janoo V. and Korhonen C., 1999, Pérez I and Gallego V., 2010). It is caused by a combination of densification (decrease in volume and subsequent increase in density) and shear deformation (plastic flow with no volume change) (Sousa J. B., Craus J. and Monismith C. L., 1991). Hofstra and Klomp observed that shear deformation was the primary asphalt concrete layer deformation rather than densification in their test-track studies. A greater amount of deformation was observed in the asphalt concrete layer near the loaded surface, as it gradually decreased at lower levels (Hofstra A. and Klomp A.J.G., 1972).

The weight and volume of aggregates used in asphalt mixtures are 90-95% of the mixture weight and 75-85% of mixture volume, respectively. The physical properties of aggregates on which the load bearing capacity of a pavement depends directly affects the properties of the mixture, the workability of a fresh mixture and the performance of a pavement (Topal A. and Sengoz B., 2005, Prowell B.D, et al., 2005). An asphalt mixture produced from angular aggregates (obtained by crushing) deformed to a minor extent and was more stable than a mixture with the same composition and grading but made from rounded aggregates (Uge P. and van de Loo P.J., 1974). Several research studies have shown that desert sand usually has a spherical and round shape (Al-Mudaiheem J.A., 1990, Pye K. and Tsoar H., 1990, Marks V.J. et al., 1990). On the other hand, an angular aggregate has more internal friction and more aggregate interlock (Marks V. J. et al., 1990).

Considering all the above-mentioned aspects, it would be useful to study the effect of dune sand on asphalt mixture properties, especially rutting properties in the desert environment.

2. Objectives

The objectives of this study can be summarized as follows:

- To measure and compare the index of the crushed sand and dune sand particle shapes and to investigate the effect of aggregate angularity on permanent deformation of HMA.
- To determine the aggregate mix proportion of HMA that contains dune sand.
- To evaluate the effects of dune sand on the properties of HMA and comparing it with HMA that only incorporates crushed sand.

3- Materials

3-1- Aggregate

The crushed aggregates were obtained from the Asphalt Nemooneh company plant on the Qoochan-Mashad highway in the Khorassan Province of Iran. This aggregate is produced by crushing the limestone rock and its properties are shown in Table 1. Regarding the aim of this research, which was to evaluate the effects of dune sand and natural sand on HMA, and also the requirements of the Iran Highway Asphalt Paving Code (IHAPC), which states that using natural sand in the surface course is forbidden but acceptable up to 25% in the binder course (IHAPC, 2002), the aggregate gradation of a 25 mm (1-in.) nominal maximum size binder course dense-graded mix (ASTM D3515) was selected. The gradation of the mix blend is also shown in Table 2.

3-2- Dune sands

In this research, five dune sand samples were collected from the eastern desert area of Iran. The particle size distribution of the sand was determined (ASTM C136). The results and grading curves are shown in Table 3 and Figure 1, respectively.

Considering the similarity in the samples' gradation, the coarsest and finest dune sands were selected for evaluation of their effects on the asphalt mixture. The decision was made to evaluate the effect of different particle sizes of dune sands in order to obtain the most meaningful results.

3-3- Asphalt

Asphalt cement of 60/70 penetration grade from the Isfahan refinery was used throughout this study, which is widely used for hot mixes in Iran. The physical properties of the asphalt cement are shown in Table 4.

4- Mix design

Mix design equations, which are shown in Table 5, have been developed to determine the aggregate mix proportion of the three mixtures based on aggregate gradation as displayed in Tables 2 and 3. The results of the equations for mixtures with dune sand are changed to fit within the Asphalt Institute grading tolerances.

Due to the similar gradation of the two selected types of dune sand, the mix blend designs shown in Table6 are the same. Three aggregate blends shown in Table7 are calculated based on the mix designs.

Table 1. Physical properties of crushed aggregate components

Property		AASHTO designation	Coarse gravel	Mid-Coarse gravel	Fine gravel	Crushed sand	Filler
Sand equivalent value %		T176				81	
Los Angeles abrasion %		T96	21				
Liquid limit		T89					N.G.
Plasticity index		T90					N.G.
Soundness by freezing and thawing		T103	0.4	0.5	1.3	1.3	
Soundness by Sodium Sulfate		T104	0.6	1.7	2	2	
Fractured particle %	One face		100	100	100		
	Two faces		100	100	100		

Table 2. Gradation of crushed aggregate components

Sieve size (mm)	Binder Course 25 (mm) nominal maximum size	Passing %				
		Coarse gravel(x)	Mid-Coarse gravel(y)	Fine gravel(z)	Crushed sand(m)	Filler(n)
25	100	100	100	100	100	100
19	90-100	92	100	100	100	100
9.5	56-80	1.9	92.7	100	100	100
4.75	35-65	0.1	21	92	100	100
2.36	23-49	0	2.2	30.4	98.2	100
0.3	5-19	0	0	0.5	23.7	96.5
0.075	2-8	0	0	0.2	5.6	68.6

Table 3. Gradation of dune sands

Sieve Size (mm)	Passing %				
	Type A (m_2)	Type B (m_1)	Type C	Type D	Type E
0.6	100	100	100	100	100
0.3	100	92.1	100	95	99.8
0.15	69.5	13.6	42.7	45.5	50
0.075	1.6	1	3.8	5.8	7

5- Test procedures

5-1-Index of aggregate particle shape and texture

The particle index is based on the concept that the shape, angularity and surface texture of a uniformly (single) sized aggregate affects not only the void ratio but also the rate at which the voids change when the aggregate is compacted in a standard mold (Janoo V., 1998).

The particle index test was undertaken on the crushed sand and selected dune sands to determine dune sand roundness. This test was to compare the effects of angular crushed sand and dune sand on the properties of hot mix asphalt in accordance with ASTM D3398.

All the fine aggregates were tested using standard mold D. The samples were washed on sieve NO.200 and dried in the oven at 110 ± 5 ˚C. They were then sieved into individual size fractions according to ASTM C136. Each of the individual size fractions was then compacted in a standard mold using 10 and 50 blows of the tamping rod. The voids and particle index for each size fraction were calculated using equations 1, 2 and 3. A higher index value implies a greater degree of aggregate angularity.

$$V_{10} = [1 - \frac{M_{10}}{G_{sb(dry)} \cdot V}] \times 100 \qquad (1)$$

$$V_{50} = [1 - \frac{M_{50}}{G_{sb(dry)} \cdot V}] \times 100 \qquad (2)$$

$$I_a = 1.25\, V_{10} - 0.25\, V_{50} - 32 \qquad (3)$$

Where:

V_{10}= voids in aggregate compacted at 10 drops per layer, %

V_{50}= voids in aggregate compacted at 50 drops per layer, %

M_{10}= average mass of the aggregate in the mold compacted at 10 drops per layer, g

M_{50}= average mass of the aggregate in the mold compacted at 50 drops per layer, g

S= bulk-dry specific gravity of the aggregate size fraction

V= volume of the cylindrical mold, ml

I_{a}= Particle index

5-2- Marshall test

The specimens for the Marshall Test were prepared by placing the mixture in a preheated Marshall mold and compacting it with 75 blows of a 10-lb compaction hammer on each side of the specimens. Forty-five specimens were made for the asphalt mixes using the two selected dune sands and conventional mix, with the asphalt cement content ranging from 3 to 5 percent by weight of the total mix in 0.5 percent increments. The samples were then tested for bulk specific gravity (ASTM D1188) and the percentage of air voids was also determined. The Marshall Stability and flow were determined at 60˚C following the procedures of ASTM D1559. The results of the Marshall Test have been shown in table 9. Figure 2 and figure 3 give the results of Marshall stability, respectively.

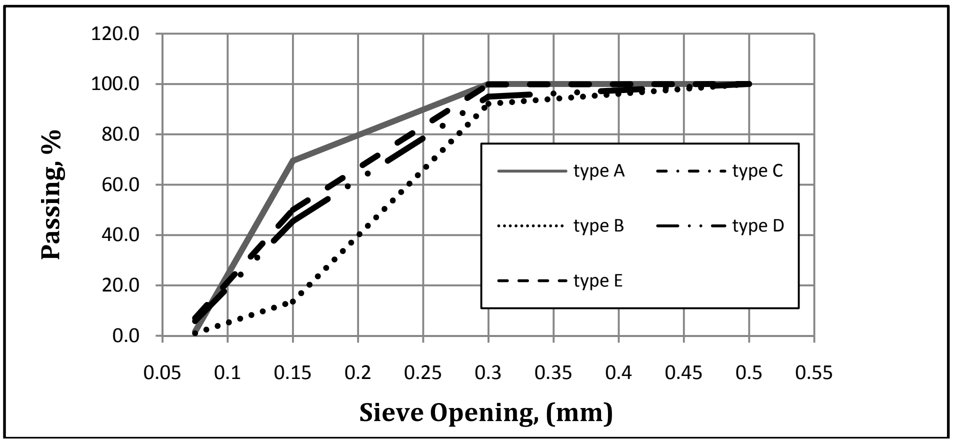

Figure 1. Gradation of different dune sands

Table 4. Physical properties of asphalt cement

Property	ASTM designation	Result	IHAPC specification	
			Min.	Max.
Penetration (0.1 mm) @ 25˚C (100 g, 5 seconds)	D5	64	60	70
Softening point (˚C)	D36	51	49	56
Kinematic Viscosity, cst (135˚C)	D2170	318	>200	-
Specific gravity	D70	1.013	-	-

Table 5. Mix design equations

Type of mixture	Equations	Results of equation
Equation of mixture with crushed sand	$1.9x + 92.7y + 100z + 100m + 100n = 100 \times 68$ $0.1x + 21y + 92z + 100m + 100n = 100 \times 50$ $0 + 2.2y + 30.4z + 98.2m + 100n = 100 \times 36$ $0 + 0 + 0.02z + 5.6m + 68.6n = 100 \times 5$ $x + y + z + m + n = 100$	$x = 30.93$ $y = 22.66$ $z = 14.98$ $m = 26.71$ $n = 4.71$
Equation of mixture with dune sand type B	$1.9x + 92.7y + 100z + 100m_1 + 100n = 100 \times 68$ $0.1x + 21y + 92z + 100m_1 + 100n = 100 \times 50$ $0 + 2.2y + 30.4z + 100m_1 + 100n = 100 \times 36$ $0 + 0 + 0.2z + 1m_1 + 68.6n = 100 \times 5$ $x + y + z + m_1 + n = 100$	$x = 30.94$ $y = 22.57$ $z = 15.79$ $m_1 = 24.02$ $n = 6.68$
Equation of mixture with dune sand type A	$1.9x + 92.7y + 100z + 100m_2 + 100n = 100 \times 68$ $0.1x + 21y + 92z + 100m_2 + 100n = 100 \times 50$ $0 + 2.2y + 30.4z + 100m_2 + 100n = 100 \times 36$ $0 + 0 + 0.2z + 1.6m_2 + 68.6n = 100 \times 5$ $x + y + z + m_2 + n = 100$	$x = 30.94$ $y = 22.57$ $z = 15.79$ $m_2 = 23.81$ $n = 6.9$

Table 6. Aggregate mix proportion

Type	Coarse gravel	Mid-Coarse gravel	Fine gravel	Crushed sand	Filler
Conventional mixture	31	23	15	26	5
Mixture with dune sand (Type A & B)	30	13	40	10	7

Table 7. Aggregate gradation of the three asphalt mixtures

Sieve size (mm)	Grading Tolerances	Passing %			
		Binder course 25 (mm) nominal maximum Size	Conventional mixture	Mixture with type A Dune sand	Mixture with type B Dune sand
25	±8	100	100	100	100
19	±8	90-100	95	96	96
9.5	±7	56-80	68	70	70
4.75	±7	35-65	50	57	57
2.36	±6	23-49	36	30	30
0.3	±5	5-19	11	15	15
0.075	±3	2-8	5	5	5

Table 8. Physical properties of dune sand

Property	ASTM Designation	Type of sand		
		Crushed	Type A	Type B
Bulk specific gravity	C 128	2.664	2.65	2.652
Apparent specific gravity	C 128	2.714	2.668	2.667
Water absorption %	C 128	0.69	0.27	0.23
Particle index	D 3398	14.5	9.52	8.72

Table 9. Marshall test results

Type of mixture	AC Content (%)	Stability (KN)	Flow (0.01 mm)	Unit Weight	Air Voids (%)	Optimum AC (%)
Conventional	3	15.1	228	2.378	8.04	4
	3.5	15.4	240	2.41	6.02	
	4	15.4	255	2.451	3.7	
	4.5	13.66	340	2.446	3.11	
	5	12.4	346	2.424	3.25	
With type A dune sand	3	10	207	2.407	6.14	4.1
	3.5	10.8	237	2.421	4.82	
	4	15.6	290	2.437	3.47	
	4.5	12.1	330	2.461	1.76	
	5	11.1	337	2.459	1.1	
With type B dune sand	3	15.3	270	2.424	5.72	3.8
	3.5	15.7	303	2.447	4.05	
	4	12.9	320	2.45	3.19	
	4.5	12.7	323	2.451	2.4	
	5	11.1	373	2.442	2.03	

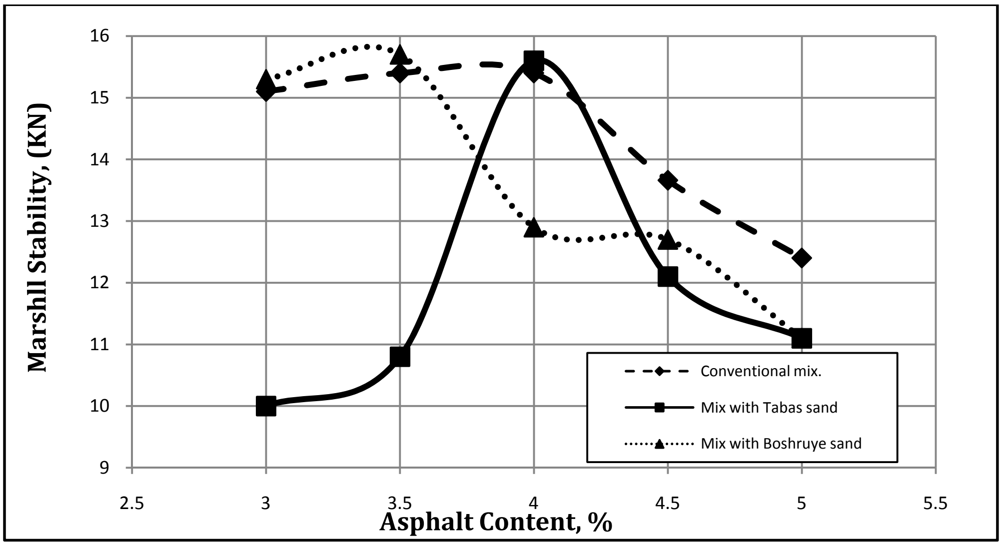

Figure 2. Marshall Stability of different asphalt mixtures

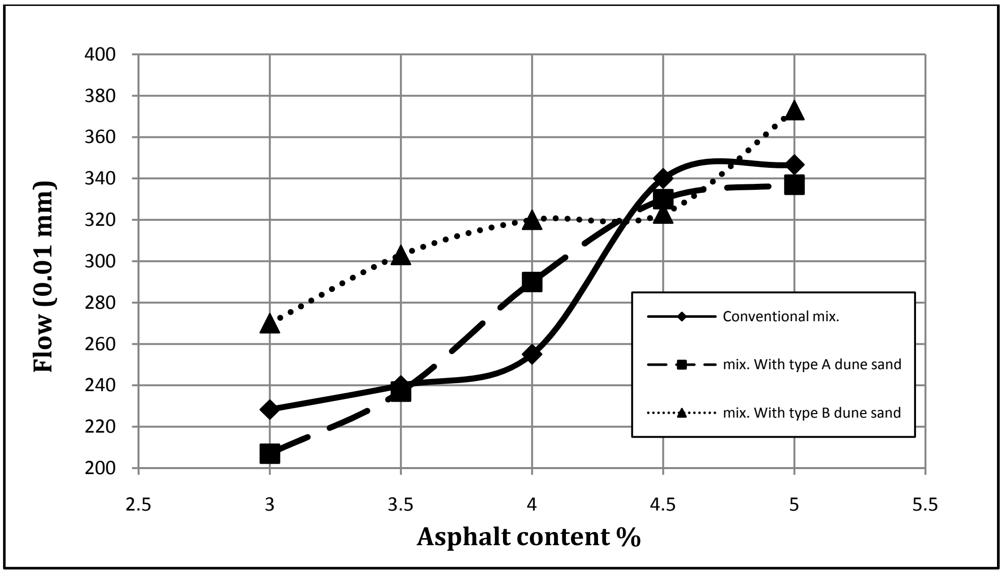

Figure 3. Marshall Flow of different asphalt mixtures

5-3- Indirect tensile test

The indirect tensile strength test was used to determine the tensile properties of the asphalt mixture, which can be further related to the cracking properties of the pavement (Anagnos J. N. and Kennedy T. W., 1972). The IDT test involves loading a cylindrical specimen with vertical compressive loads, which generates a relatively uniform tensile stress along the vertical diametrical plane. Failure usually occurs by splitting along this loaded plane (AtkanAksoy et al., 2005, Kok B. V., Yilmaz M., 2009).

"A higher tensile strength means asphalt pavement can tolerate higher strains before failing (i.e. cracking)" (Goh S. W., et al., 2011).

This test is simple and Marshall Specimens can be used. Surface irregularities do not seriously affect the results and the coefficient of the variation of the test results is low (Sureyya Tayfur et al., 2007). The indirect tensile strength test samples were prepared with the same method as described in 5.2, and for each group three samples were prepared. This test was performed at 25°c. The loading rate was 50 mm/min deformation rate. The load at failure was determined and the tensile strength of specimens was determined by the equation No. (4):

$$S_t = (2 \times P_{ult}) / (\pi \times d \times t) \quad (4)$$

Where S_t is the tensile strength of specimens, P_{ult} is the ultimate applied load required to failure of the specimens, t is the thickness of the specimens and d is the diameter of the specimens. Figure 4 shows the results of the indirect tensile strength tests on the specimens.

5-4- Dynamic Creep Test Procedure

The dynamic creep test applies a repeated pulsed uniaxial stress to an asphalt specimen and measures the resulting deformations in the same direction using linear variable differential transducers (LVDTs). For the dynamic creep test according to BS DD226, 15 cylindrical specimens that had a 150 mm × 100 mm diameter were prepared. The dynamic creep test was conducted by applying a dynamic stress of 100 KPa for 1 hour at 30˚C. The Universal Testing Machine (UTM-14P) (Fig.5) was used for this purpose. After capping the two sides of the specimen, it was placed in the loading machine under a conditioning stress of 10 KPa for 600s. Then, the conditioning stress was removed and a stress of 100 Pa was applied for 1800 cycles with 1 second loading and 1 second rest period and the axial deformation was measured during the creep test using LVDTs.

5-5- Wheel track test

The wheel track test simulates the deformation process caused by moving loads under special conditions.

"In the laboratory a wheel-tracking device simulates a vehicle to evaluate permanent deformation of the slab by rut depth. Rut depth is regarded as an appropriate indicator for comparing the susceptibility of mixtures to permanent deformation" (HalitÖzen, 2011).

The wheel tracking machine is designed so as to enable the test specimen to be moved backwards and forwards in its cradle under the loaded wheel in a fixed horizontal plane. The center of the contact area of the tire shall describe a simple harmonic motion with respect to the center of the top surface of the test specimen, with a wheel load of 520±5 N, a frequency of 21±2 load cycles per 60s and a total travel distance of 230±5 mm (Niazi and Qazizadeh, 2009).

In this study, the wheel track test was performed using the Wessex dry wheel tracker. In the dry wheel tracker as shown in Figure 10, a loaded wheel is run over an asphalt sample in a sealed and insulated cabinet. The device applies a 520N vertical force through a 150 mm width steel wheel with a 12.5 mm thick rubber contact surface. A computer program controls the operation of the machine and records rut depth, temperature and elapsed time during the test. The computer interface allows the user to plot rut depth versus time via displacement instrumentation on each loaded wheel.

For the wheel track test according to BS 598, part 110:1996, nine specimens with a slab dimension of 300×300×50 mm were prepared. The test specimens were kept at 45˚C for 4 hours.

The rate of loading was 31 cycles per minute and the total distance of travel was 230 ± 5 mm. Loading was performed inside a heat-regulated cabinet, the temperature of which was controlled with input from thermocouples mounted in holes drilled on the tops of the test specimens. The test was continued until the samples experienced a 15 mm rut depth or for 45 minutes, whichever occurred sooner.

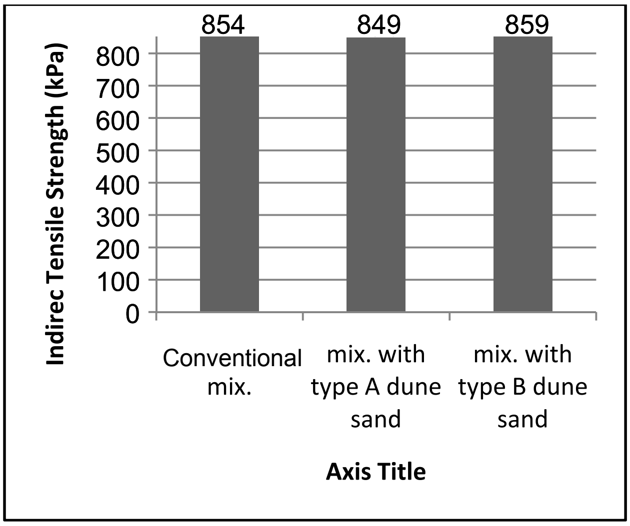

Figure 4. Indirect tensile strength of samples

Figure 5. Creep testing experimental setup

6- Results of tests and discussion

6-1- Particle Index

The crushed sand and two selected dune sands were tested for specific gravity of fine aggregate (ASTM C128). Regarding the results shown in Table 8, it is clear that crushed sand has higher aggregate indices; it is more angular than dune sand and the particle index of the two selected dune sands was almost the same.

6-2- Marshall Test

Table 9 shows the results for samples that were tested under the Marshall test. It can be observed from Figure 2 that the Marshall stability of the three mixes with optimum asphalt content is approximately the same and that replacing part of the fine aggregate with dune sand does not decrease the Marshall stability. As shown in Figure 3, the flow trend is similar in all of the three specimens, although using the dune sand decreases the void of compacted specimens.

6-3- Indirect Tensile Strength Test

Figure 4 shows the average tensile strengths of the mixes. The results indicate that the use of dune sand does not cause an important change in tensile strength of mixes, which shows a mixture containing these additives has almost the same values of tensile strength at failure for the indirect tensile strength under static loading.

6-4- Dynamic Creep Test

As shown in Figures 6 and 7, the conventional mix exhibits the least permanent deformation, accumulated strain and resilient deformation. The mixture with type B dune sand has the highest permanent deformation. These results can be related to the fact that the highest particle index is attributed to the conventional mix and the type B dune sand has the lowest particle index.

On the other hand, as shown in Figures 8 and 9, the sand angularity increases the resilient modulus and creep stiffness, which are important factors in resisting pavement deformation. Therefore, type B and type A dune sand, which have the most roundness, respectively, exhibit the least resistance against permanent deformation and greater rutting.

6-5- Wheel Track Test

Figure 10 shows the rut depth versus time for the wheel track specimens and the average rut depths are shown in Figure 11. The bar chart in Figure 11 shows the test results of the rutting experiment and compares the rut depths of the three asphalt mixes. As shown in Figure 11, the conventional asphalt mix and the asphalt mix containing type B dune sand have the least and the greatest rut depth, respectively. Meanwhile the crushed sand and type B dune sand have the highest and the lowest particle index. So, therefore, the type B and type A dune sand, which are the roundest shaped sand types, have the least resistance to rutting. As compared to conventional mixes, a 30-35 % increase in the permanent deformation of asphalt mixes made with dune sand was observed.

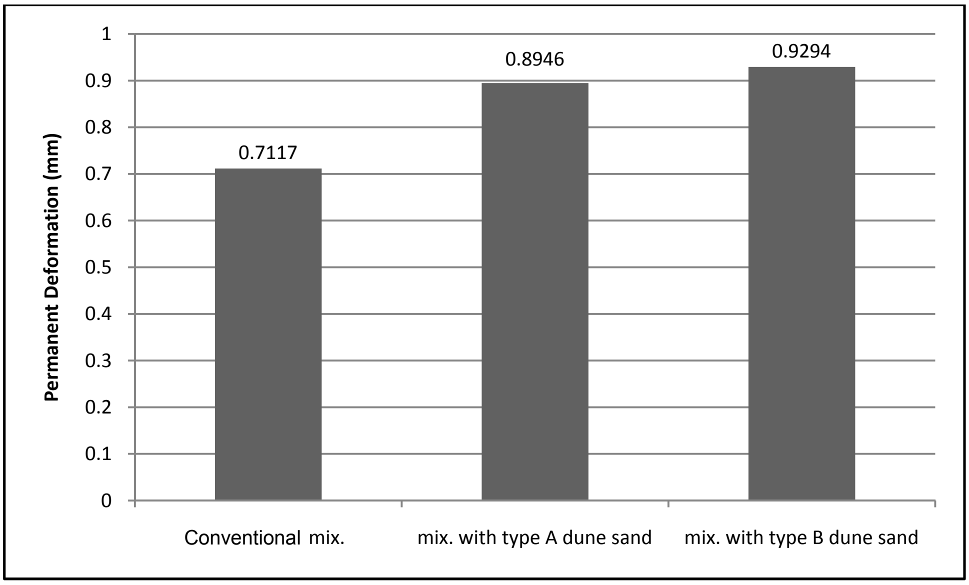

Figure 6. Permanent deformation of different asphalt mixtures

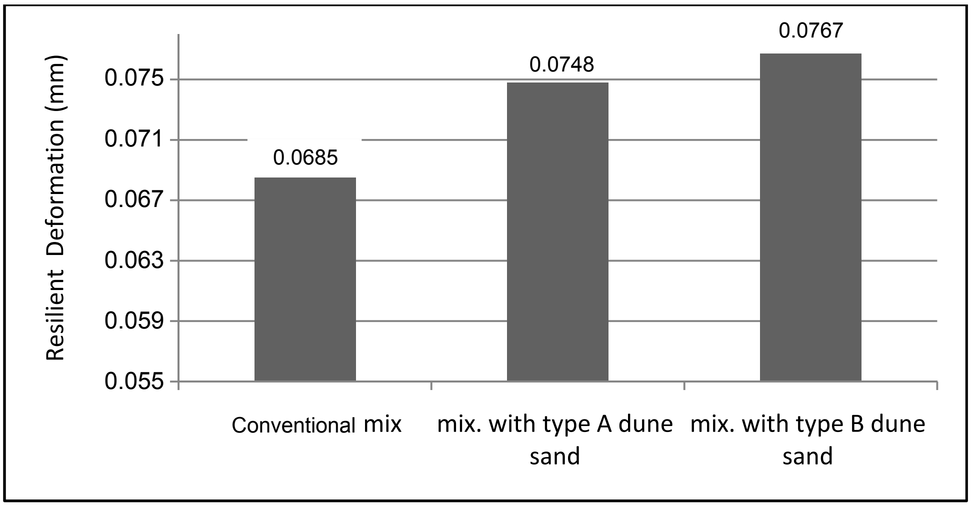

Figure 7. Resilient deformation of different asphalt mixtures

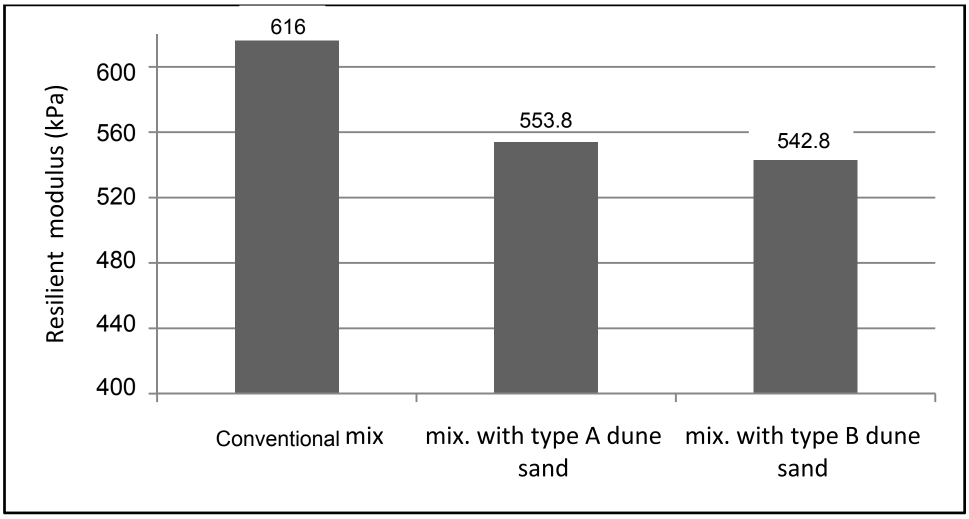

Figure 8. Resilient modulus of different asphalt mixtures

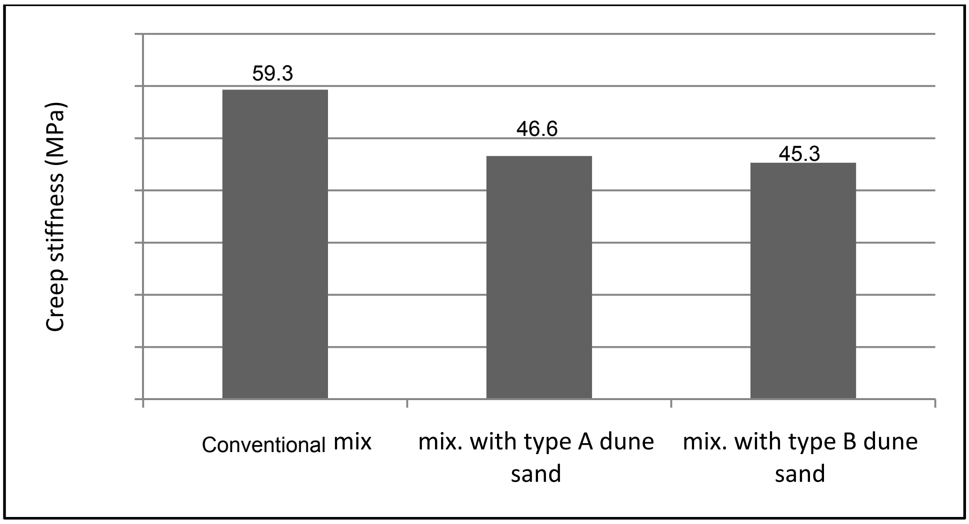

Figure 9. Creep stiffness of different asphalt mixtures

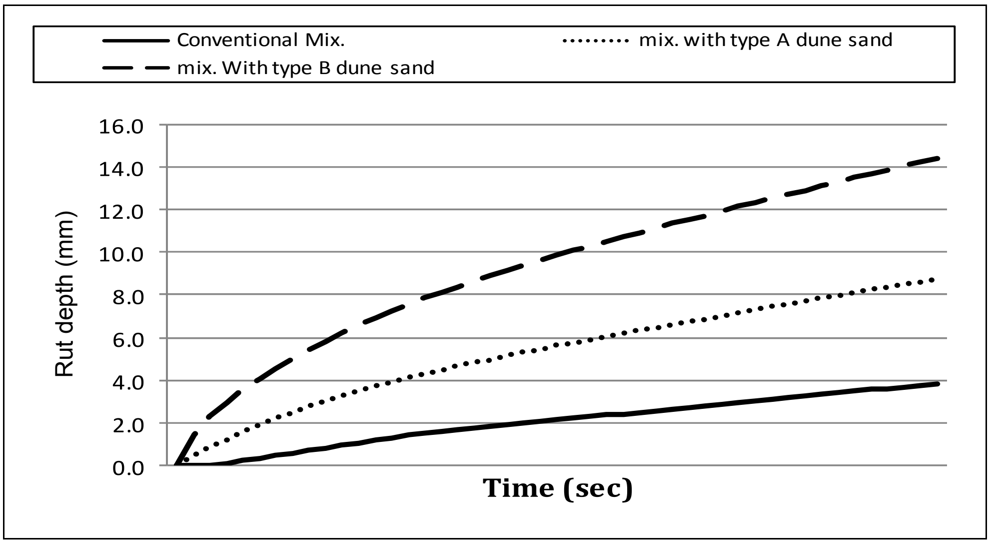

Figure 10. Rut depth versus time of loading for different asphalt mixtures

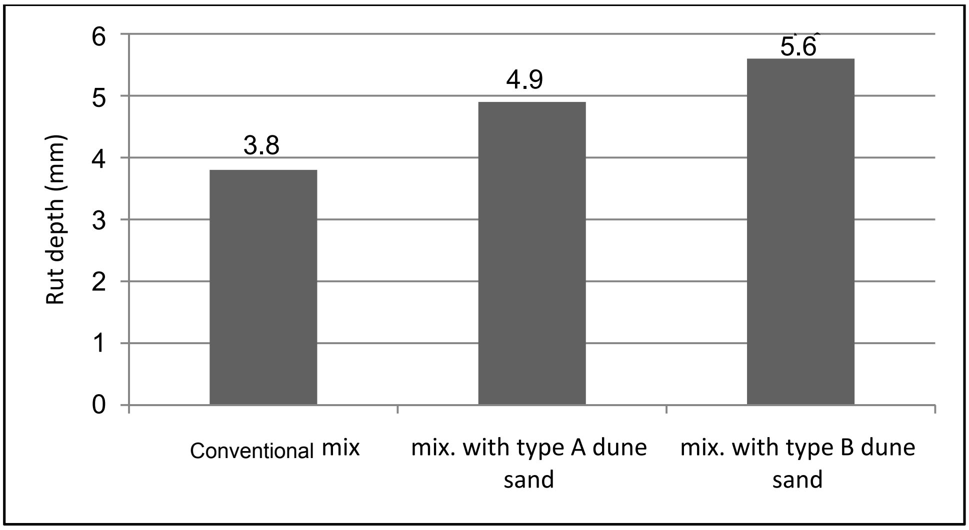

Figure 11. Average rut depth of the different asphalt mixtures

7- Conclusions

1. Replacing part of the fine aggregates by dune sand does not cause an important change in Marshall Parameters.
2. Using dune sand does not cause a considerable change in tensile strength of mixes.
3. The results of the dynamic creep test show that the use of dune sand resulted in an increased rut depth. The conventional mix and the mix containing type B dune sand exhibited the least and the most permanent deformation respectively, while the crushed sand and type B dune sand have the highest and the lowest particle index, respectively. On the other hand, the type B dune sand mix has the lowest resilient modulus and creep stiffness, which are the criteria for resistance to permanent deformation.
4. The results of the wheel track test shows that the conventional mix and the mix consisting of type B dune sand have the most and least permanent deformation, respectively.
5. Comparing the dynamic creep with the wheel track test shows approximately similar trends. Therefore, the wheel track test could be replaced by the dynamic creep test for a basic test of rutting.

6. Replacing part of the fine crushed aggregates by dune sand increases rutting up to 30-35%, but decreases the resilient modulus. Therefore dune sand should only be used as an aggregate in low-traffic roads.

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Notation

V_{10}: voids in aggregate compacted at 10 drops per layer% ,
V_{50}: voids in aggregate compacted at 50 drops per layer% ,
M_{10}: average mass of the aggregate in the mold compacted at 10 drops per layer, g
M_{50}: average mass of the aggregate in the mold compacted at 50 drops per layer, g
S: bulk-dry specific gravity of the aggregate size fraction
V: volume of the cylindrical mold
I_a: particle index
S : tensile strength of specimens
P : ultimate applied load required to fail specimens
t : thickness of the specimens
d : diameter of the specimens.

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