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ORIGINAL PAPER

Experimental study on the utilization of dune sands as a construction material in the area between Jeddah and Mecca, Western Saudi Arabia

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Abstract Due to the arid continental climatic conditions, about 37 % of Saudi Arabia is covered by desert sands. These sands are mostly dynamic and cause environmental problems. However, these huge quantities of dune sands are considered important natural resources of fine aggregate construction materials. The studied dune sands are predominantly coarse, medium and fine sands with average percentages of 2.4, 19.97 and 76.28 %, respectively, with scarce percents of silt and clay-size particles (around 1 %). The fineness modulus (FM) values of these sands vary from 0.98 to 1.02. Therefore, it is necessary to improve their gradation and textural characters by adding well-graded, crushed fine aggregates to produce an acceptable level of gradation. Mineralogically, the studied dune sands are mainly composed of quartz (88 %), feldspars (9 %) and a negligible amount of carbonates (2.2 %). The workability and compressive strength values of both cement mortar and concrete of the studied dune sands were found to decrease abruptly at dune sand contents >50 %. Finally, the studied dune sands are acceptable as fine aggregates for both concrete and mortar when they do not exceed 50 % of the total volume of fine aggregates at a constant mix ratio of 2:1:3 (water:cement:fine aggregates) and 1:2:4:6 (water:cement:fine aggregates: coarse aggregates), respectively, for cement mortar and concrete.

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Introduction

Because of the dry continental climatic conditions, nearly one-third of Saudi Arabia is covered by active dune fields, representing the largest continuous body of aeolian sand on earth (800,000 km^2 of 2.3 million km^2, USGS 1963; Garzanti et al. 2013). Mostly, these sands are concentrated in the eastern provinces and Arabian Shield. Generally, the sand dunes of Saudi Arabia are restricted to the Arabian Shield and its wadi courses, which cut through Precambrian igneous and metamorphic rocks (Al-Harthi 2002). These sand dunes are growing, migrating and causing problems for the expansion of cities, roads, and power and communication lines. In the studied area, owing to the migration of dune sands, serious geo-environmental risks have developed for urban areas and road construction (Figs. 1, 2, 3).

The western regions of Saudi Arabia are characterized by a rareness of fine natural aggregate resources. At the same time, these desert areas involve construction activities that require many aggregates. Because of the remoteness of the construction sites from aggregate production quarries in these areas, transporting aggregates is expensive and uneconomical. In addition, engineers face the difficulties of a more restricted choice of materials in these regions (Amjad 1989; Al-Harthi 2002; Al-Fredan 2008).

Therefore, these sand dunes are considered a vital source of fine aggregates for use in construction material for producing concrete, mortar and pavement material. Fine aggregate usually constitutes about one-third of the total volume of concrete aggregates, where it fills the space

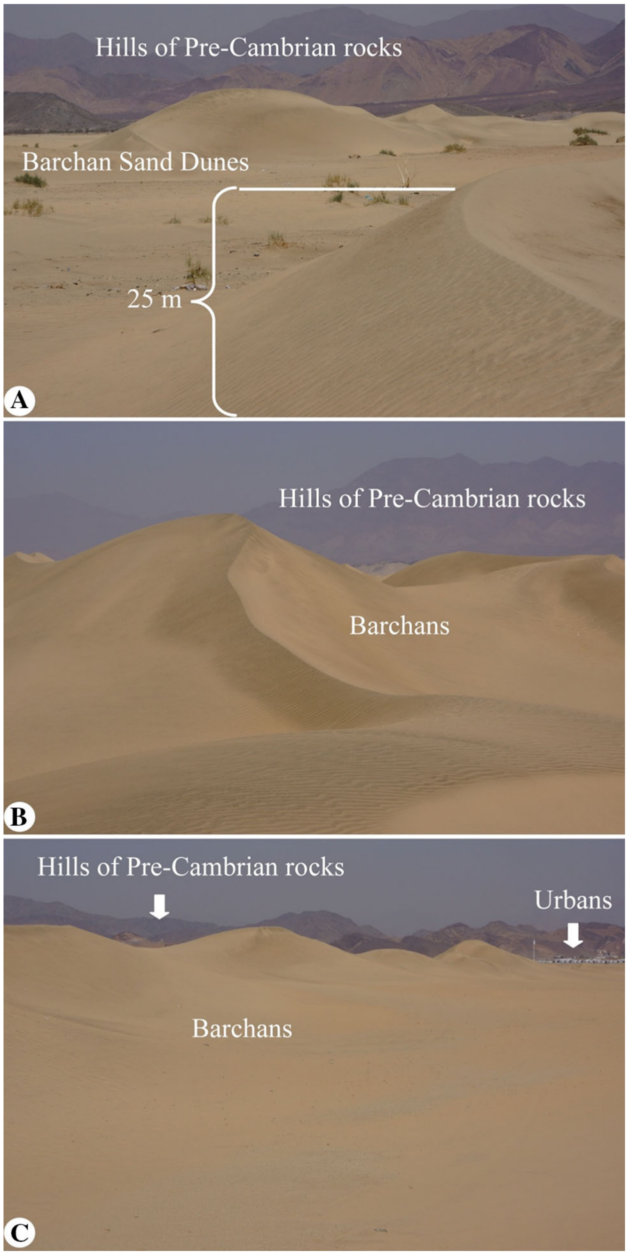


Fig. 1 Field photographs of barchan sand dunes in the studied area

between coarse aggregates. Also, fine aggregate (sands) makes up the main bulk of masonry mortar; therefore, it has a significant effect on the properties of the product in both the fresh and hardened state. Moreover, fine aggregates play a vital role in providing the fineness and cohesion of concrete.

We reviewed similar research published in the last decades (e.g., Khan 1982; Al-Sanad and Bindra 1984; Al-Sanad et al. 1993; Al-Abdul Wahhab and Asi 1997; Al-Harthy et al. 2007; Alhozaimy et al. 2012; Abu Seif 2013a, b; Elipe and López-Querol 2014), which was applied to evaluate dune sands as a construction material, pavement aggregate and replacement soil layer. The mechanical properties of these mixes (concrete and mortar) are affected by the strength of the dune sand-cement-aggregate bond and by various factors such as the texture and chemical stability of these components. This work presents the results of extensive field and laboratory tests carried out to assess dune sands with respect to their use as concrete and mortar fine aggregates.

Location and geological setting

The study area is located between latitudes 21°21′ and 21°33′ N and longitudes 39°30′ and 39°42′ E (Fig. 4) and covers the area between Jeddah and Mecca cities. This area is considered one of the most important, strategic, promising and investment-attracting parts of the Kingdom of Saudi Arabia. This area is expected to have major development projects in the near future. The construction of these projects requires huge quantities of fine aggregates, a major component of concrete, mortar and sandy brick mixes. Extracting such aggregates from the surrounding sand dunes is not only economically important because of their close proximity but also capable of gradually reducing the environmental problems caused by active sand dunes. Accordingly, studying these dune sands is vital for future development in this area.

Materials and methods

Detailed field investigations were conducted to evaluate the environmental risks of the sand dunes in the study area. In the present study, 15 samples were collected from 5 sites. The samples were collected along a profile across the movement direction of a given sand dune. The studied dune sands were subjected to evaluation tests, e.g., physical, mineralogical, chemical and mechanical.

The physical tests included sieve analysis, specific gravity, absorption, fineness modulus and sand equivalency. Sieve analysis and fineness modulus tests were conducted in accordance with ASTM C33 (1999). The sand equivalent values were determined in accordance with ASTM D2419-95 (1998). The specific gravity and absorption tests were carried out in accordance with ASTM C128 (1993). Table 1 presents the grain size characteristics and some physical properties of these dune sands. Additionally, the textural characteristics (forms and roundness degree) were counted and are listed in Table 2. The different forms of the studied aggregates (dune and crushed aggregates) were counted using a binocular microscope, whereas the roundness degree was determined for 100 quartz grains using the Powers' visual chart (1953).

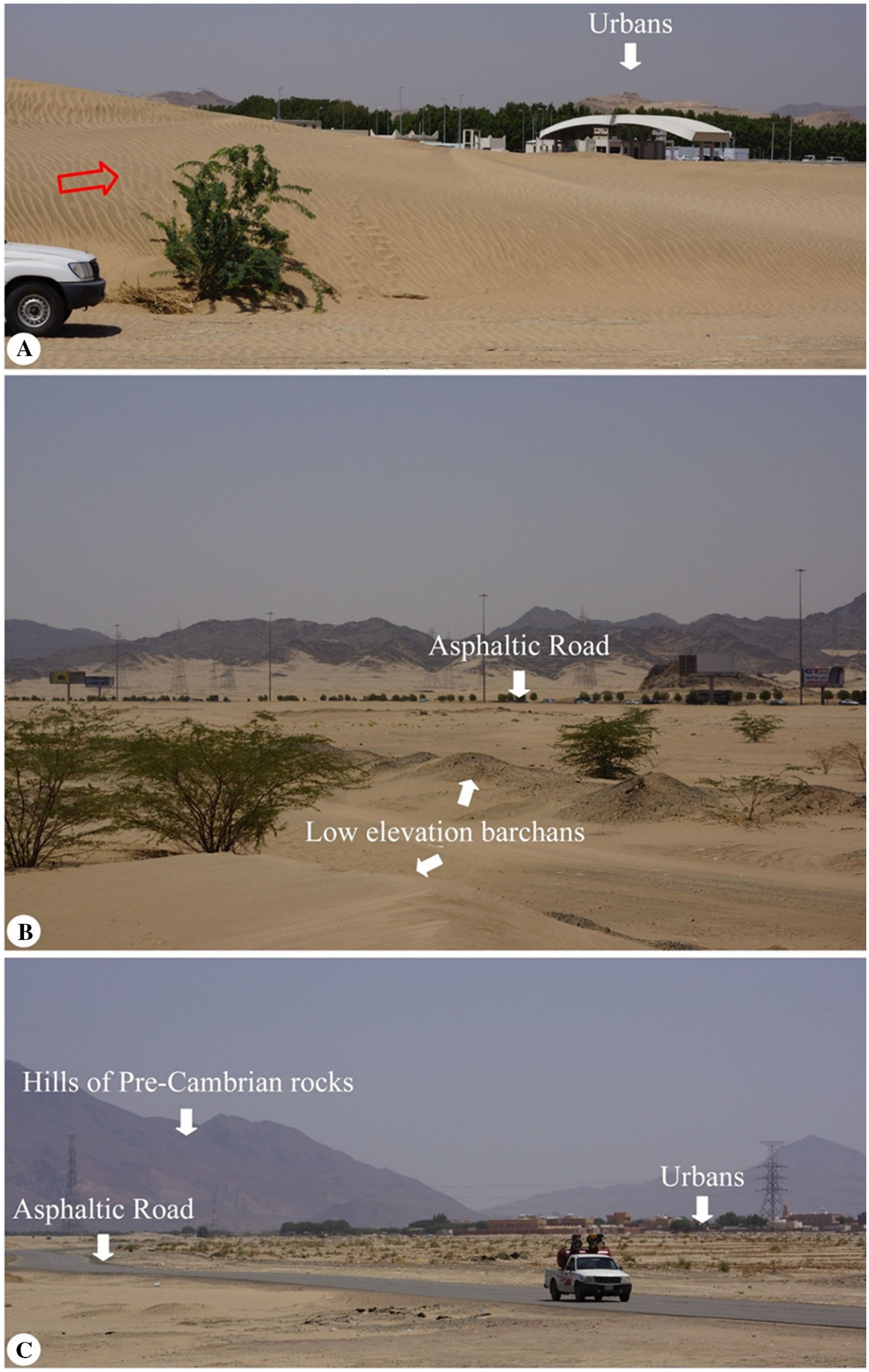


Fig. 2 Field photographs of barchan sand dunes showing (**a**) migration of sand dunes toward urbans areas and (**b** and **c**) the destructive effect of sand dunes along asphalt roads in the studied area

Approximately 100 g of each dune sand sample was covered with water and soaked for 3 h to allow the grains to disaggregate. Then, they were dried and about 10 g was mixed with epoxy and allowed to harden, forming artificial sandstones. Thin sections were prepared for microscopic investigations. The mineralogical composition of dune sands was estimated using petrographical analysis supported by x-ray diffraction (XRD). The chemical analysis of the dune sand bulk samples was performed to determine the chemical compounds. The results of both mineralogical composition and chemical analysis are listed in Table 3.

Fig. 3 Field panoramic photograph shows vast flat areas covered by aeolian sand sheets

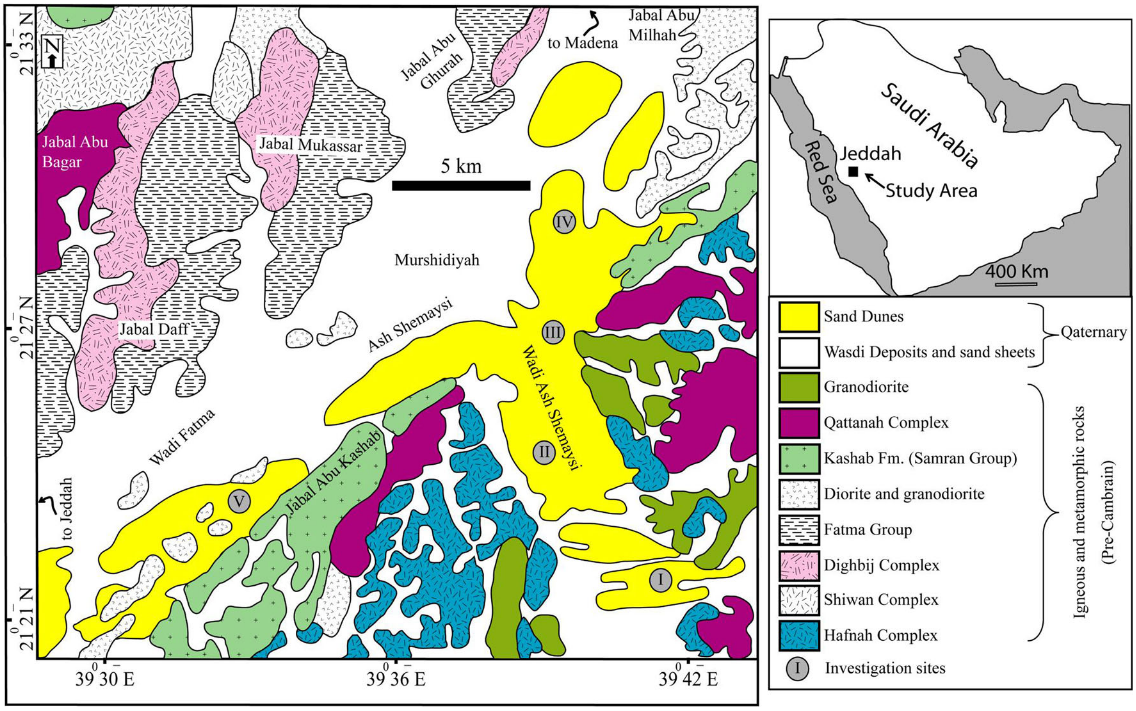


Fig. 4 Geological map of the studied area (modified from Moore and Al-Reaili 1989)

In order to evaluate the effect of dune sands on the concrete and mortar properties, various dune sand mixes varying from 10 to 100 % of the total content of fine aggregates were used instead of crushed aggregates. The crushed aggregates used in these tests were taken from a nearby granodiorite crusher in north Jeddah, near Breman Bridge (21°55′ N, 39°17′ E).

The weight design of concrete and mortar mixes and dune sand ratio used are listed in Table 4. The cement used in this work was Ordinary Portland Cement (OPC) from Qassim Cement Co. (Saudi Arabian Standards Organization, no. SSA-143/1979). Slump and compressive strength tests, f_{cu} (28 days), were carried out on 150 × 300-mm specimens in accordance with ASTM C469 (1994). The concrete samples were free steel types. The results of the slump and shear tests are listed in Table 5.

Results and discussion

Grain grading

From a sedimentological point of view, the grain size analysis of dune sands was used to deduce their depositional environment characteristics. Dune sands are usually characterized by well sorted, rounded grains and cubic forms. From the geotechnical point of view, the grain size distribution of both fine and coarse aggregates has a significant influence on the mechanics of both hardened and fresh concrete and mortar. The main goal of fine aggregate proportioning and sizing was to maximize the aggregate volume in the concrete and minimize the cement paste volume.

Notably, the grading of fine aggregates plays an effective role in non-rigid concrete workability (Abu Seif 2014).

Table 1 Grain size characteristics and some physical properties of the dune sands in the study area

Site	Sample no.	Relative abundance of size fractions (%)				C_U	C_C	USCS classification	Fineness modulus (FM)	Sand equivalent (%)	Specific gravity (g/cm^3)	Absorption
		Coarse sand (4.72–2.0) (mm)	Medium sand (2.0–0.42) (mm)	Fine sand (0.42–0.075) (mm)	Silt + clay (<0.075) (mm)							
I	1	2.5	19.3	76.4	1.8	2	1.15	SP	0.98	97	2.48	0.94
	2	2.6	19.9	76	1.5	2.1	1.14	SP	0.99	96	2.49	0.95
	3	2.7	21	74.9	1.4	2.2	1.16	SP	0.97	97	2.48	0.94
II	4	2.5	19	77	1.5	2.15	1.16	SP	0.96	96	2.49	0.95
	5	2.4	19.9	75.9	1.8	2.2	1.15	SP	0.98	97	2.49	0.96
	6	2.5	22.9	73.4	1.2	2.1	1.14	SP	1.01	95	2.49	0.94
III	7	2.8	17	78.8	1.4	2	1.16	SP	1.02	96	2.48	0.97
	8	2.8	18	77.8	1.4	2.1	1.14	SP	1.01	95	2.49	0.95
	9	1.6	19.9	77	1.5	2.1	1.15	SP	0.98	96	2.48	0.94
IV	10	1.7	17	79.8	1.5	2.1	1.16	SP	0.99	95	2.48	0.95
	11	2.4	19.9	76.8	0.9	2	1.15	SP	0.97	95	2.48	0.95
	12	2.1	20.1	77.3	0.5	2	1.15	SP	0.96	95	2.48	0.94
V	13	2.4	19.9	76.6	1.1	2	1.14	SP	0.97	95	2.49	0.94
	14	2.4	22.9	73.2	1.5	2.1	1.16	SP	0.98	97	2.47	0.94
	15	2.6	22.9	73.3	1.2	2.1	1.17	SP	0.98	96	2.48	0.95
Average value		2.4	19.97	76.28	1.35	2.08	1.15	SP	0.98	96	2.48	0.94

Table 2 Relative percentages of the grain forms and roundness classes of the studied dune sands

Site	Sample no.	Grain forms (%)			Roundness classes (%)					
		Equant	Elongated	Flaky	Well rounded	Rounded	Sub-rounded	Sub-angular	Angular	Very angular
I	1	83	11	6	17	7	33	21	13	9
	2	84	11	5	16	7	33	21	13	10
	3	82	14	4	17	6	34	22	14	7
II	4	83	10	7	18	7	35	23	13	4
	5	85	11	4	19	8	32	22	14	5
	6	84	10	6	17	7	34	23	13	6
III	7	84	9	7	18	6	32	22	14	8
	8	85	9	6	17	7	33	24	12	7
	9	79	13	8	16	7	34	19	15	9
IV	10	82	14	4	18	7	33	22	13	7
	11	84	9	7	17	8	32	20	12	11
	12	84	10	6	17	8	31	23	12	9
V	13	82	12	6	18	8	34	22	14	4
	14	79	13	8	16	6	32	21	13	12
	15	81	11	8	17	7	33	22	14	7
Average value		82.8	11.1	6.1	17.2	7.1	33.0	21.7	13.3	7.7

Table 3 Minerals composition and basic chemical characteristics of the dune sands in the studied area

Site	Sample no.	Minerals composition (%)			Chemical characteristics (ppm)						
		Quartz (Qz)	Rock fragments (RF)	Feldspars (F)	pH	TDS	Calcium carbonates $(CaCO_3)^{2-}$	Sulfates $(SO_4)^{2-}$	Sodium hydroxide $Na(OH)^{-}$	Calcium hydroxide $Ca(OH)^{2-}$	Chlorides $(Cl)^{-}$
I	1	80	14	6	7.8	495	123	34	7	6	13
	2	81	15	4	7.6	497	128	36	4	4	14
	3	82	11	7	7.6	511	135	34	7	6	15
II	4	83	4	13	7.7	498	154	38	4	5	14
	5	85	5	10	7.5	511	135	34	0	5	16
	6	86	5	9	7.6	510	147	35	4	5	15
III	7	80	11	9	7.5	522	149	36	8	6	14
	8	87	4	9	7.7	511	134	34	4	6	18
	9	81	7	12	7.5	517	134	36	5	4	15
IV	10	82	9	9	7.5	519	129	34	0	5	15
	11	83	6	11	7.6	498	147	28	8	5	16
	12	85	8	7	7.5	498	149	34	4	4	15
V	13	88	9	3	7.6	513	132	35	4	6	14
	14	82	11	7	7.5	514	141	34	0	6	15
	15	81	12	7	7.5	518	149	34	4	4	16
Average value		83.1	8.7	8.2	7.58	508.8	139.07	34.4	4.2	5.13	15

This paste requirement is the main factor controlling the cost since cement is the most expensive component. The required amount of cement paste depends on the amount of void space that must be filled and the total surface area that must be covered (Mehta and Monteiro 2006). The pore size distribution of an aggregate depends mainly on its size gradation (Mazaheri and Mahmoodabadi 2012).

Figure 5 shows the grain size distribution curves of the studied dune sands used in all concrete and mortar mix tests. These samples were predominantly coarse, medium and fine sands with average values of 2.4, 19.97 and 76.28 %, respectively, with scarcely a percent of silt and clay-size particles (around 1 %, Table 1). The studied dune sands of the different sites were characterized by unimodal

Table 4 Weight design of concrete and mortar mixes and dune sand ratio used

Test no.	Water (%)	Cement (%)	Fine aggregate (%)		Coarse aggregate (%)	Dune sands/crushed fine aggregate (%)
			Dune sands (%)	Crushed fine aggregate (%)		
Concrete mix ratio (water:cement:fine aggregates:coarse aggregates constant at 1:2:4:6)						
1	7.69	15.38	3.08	27.69	46.16	10
2	7.69	15.38	6.15	24.62	46.16	20
3	7.69	15.38	9.23	21.54	46.16	30
4	7.69	15.38	12.31	18.46	46.16	40
5	7.69	15.38	15.38	15.39	46.16	50
6	7.69	15.38	18.46	12.31	46.16	60
7	7.69	15.38	21.54	9.23	46.16	70
8	7.69	15.38	24.62	6.15	46.16	80
9	7.69	15.38	27.69	3.08	46.16	90
10	7.69	15.38	30.77	0	46.16	100
Mix ratio	1	2	4	6		

Water (%)	Cement (%)	Fine aggregate (%)		Dune sands/crushed fine aggregate (%)
		Dune sands (%)	Crushed fine aggregate (%)	
Mortar mix ratio (water:cement:fine aggregates constant at 2:1:3)				
33.33	16.67	5	45	10
33.33	16.67	10	40	20
33.33	16.67	15	35	30
33.33	16.67	20	30	40
33.33	16.67	25	25	50
33.33	16.67	30	20	60
33.33	16.67	35	15	70
33.33	16.67	40	10	80
33.33	16.67	45	5	90
33.33	16.67	50	0	100
2	1	3		

distributions and classified according to the Unified Soil Classification (Terzaghi and Peck 1968) as poorly graded sand (SP). The coefficient of uniformity (C_U) values of the studied dune sands varied from 2.2 to 2 %, whereas the coefficient values of curvature (C_C) fluctuated from 1.17 to 1.14 % (Table 1).

The fineness modulus (FM) is the most commonly computed factor for fine aggregates and was used to determine the degree of uniformity of the aggregate gradation. The fineness modulus (FM) values of the studied dune sand samples ranged from 0.98 to 1.02 (Table 1), meaning that the studied dune sands did not meet the limits for fine aggregate gradations in the specified standards. Thus, improving the gradation of these dune sands by mixing them with well-graded, crushed fine aggregates was necessary to produce an acceptable level of gradation in both the concrete and mortar mixes. The studied fine aggregates of sand dunes mainly consisted of poorly graded fine aggregates (SP, Table 1). When these dune sands were mixed with crushed, well-graded fine and course aggregates, all sizes were present. Consequently, this mixture of different-sized particles was stronger than those that are uniformly graded (Bell 2007).

Clay content (sand equivalent)

Sometimes, the natural fine aggregates contain harmful and deleterious components such as clay-sized and organic materials of sizes less than 75 µm. These materials cause lower strength and durability and affect the bond between the cement and aggregate grains (Yool et al. 1998; Dumitru et al. 1999; Hudson 1999). In the case of continental (inland) dunes, which mostly consist of sand-sized particles, some silt-sized particles are usually found attached to the surface of dune sands. Clay-sized particles are usually rare because the wind often does not pick them up; this occurred in mutual unity with each other, and perhaps the wind lifted the clay particles up into the

Table 5 Workability and shear strength of both concrete and mortar of the studied dune sands

Dune sands (%)	Slump (mm)											
	Concrete						Mortar					
	Sites					Average value	Sites					Average value
	Site I	Site 11	Site 111	Site 1 V	Site V		Site I	Site 11	Site 111	Site 1 V	Site V	
10	65	68	59	64	61	63.4	81	78	77	79	76	78.2
20	74	71	68	71	69	70.6	87	89	88	89	86	87.8
30	71	79	72	79	79	76	94	95	94	93	97	94.6
40	79	84	89	84	87	84.6	99	102	104	97	103	101
50	92	93	96	93	102	95.2	115	111	115	118	112	114.2
60	78	74	81	81	84	79.6	83	88	87	85	84	85.4
70	52	64	62	64	58	60	57	61	64	59	61	60.4
80	44	52	53	48	42	47.8	45	49	51	46	44	47
90	21	32	38	37	36	32.8	24	18	22	23	28	23
100	13	19	24	22	27	21	18	14	17	18	24	18.2
Dune sands (%)	Uniaxial compressive strength (28 days, MPa)											
	Concrete						Mortar					
	Sites					Average value	Sites					Average value
	Site I	Site 11	Site 111	Site 1 V	Site V		Site I	Site 11	Site 111	Site 1 V	Site V	
10	41	39	42	38	44	40.8	29	28	30	27	29	28.6
20	39	37	41	37	41	39	27	25	28	26	28	26.8
30	36	35	38	36	38	36.6	26	23	27	25	27	25.6
40	33	33	35	34	37	34.4	24	21	24	23	26	23.6
50	29	31	32	32	36	32	19	19	22	19	24	20.6
60	22	26	27	26	28	25.8	17	16	19	17	19	17.6
70	21	24	25	24	25	23.8	16	15	16	15	18	16
80	20	23	23	21	23	22	14	14	15	14	17	14.8
90	19	22	21	20	21	20.6	12	13	13	13	15	13.2
100	18	19	20	18	19	18.8	11	12	12	11	13	11.8

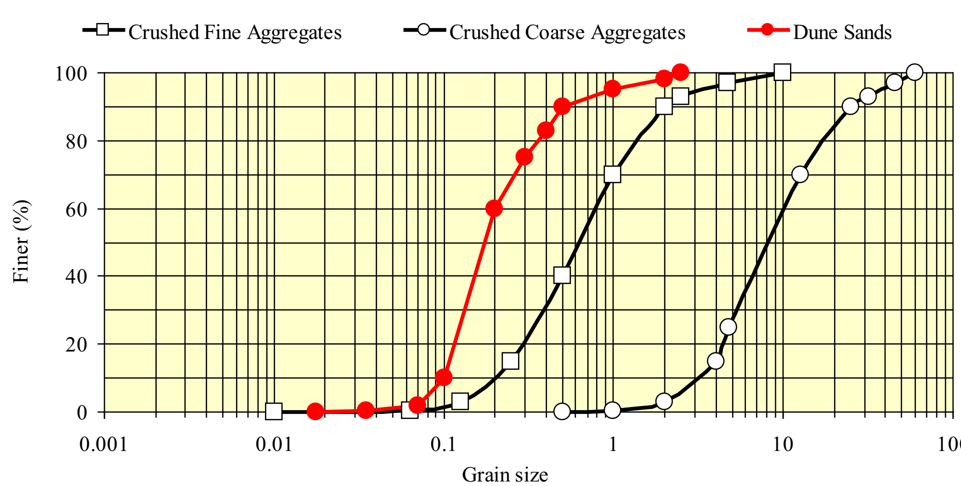


Fig. 5 Grain size distribution curves of the studied dune sands (average values) and crushed aggregates used

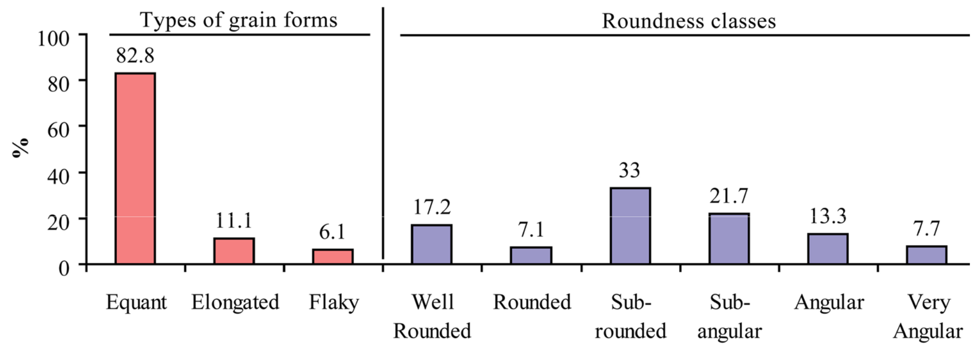


Fig. 6 Relative frequency of different forms and roundness classes of the studied dune sands (average values)

atmosphere (Folk 1968). The modes of movement and transportation of sediment grains have been studied and interpreted by many researchers (e.g., Hjulstrøm 1935, 1939; Shields 1936; Sundborg 1956; Postma 1967; Paphitis 2001). Sundborg (1956) modified the Hjulstrøm (1935) diagram and included different levels of cohesion, resulting in a more or less constant threshold flow velocity in the absence of cohesive effects for small-diameter particles and a similar behavior for cohesive sediments. The sand equivalent value of the studied dune sands varied from 95 to 97 % with an average value of 96 % (Table 1). This means that the studied fine aggregate contains negligible amounts of deleterious components (clay-sized materials, minus 75 µm).

Specific gravity (G_S)

The specific gravity of aggregates can be used as a useful indicator of their suitability. Also, the specific gravity determination of aggregates is an essential parameter during the design stage of structural elements to establish the concrete maximum and minimum weights. Very low specific gravity suggests that the aggregate is porous, weak and absorptive. The specific gravity of the studied dune sands ranged from 2.47 to 2.49 g/cm^3 with an average value of 2.48 g/cm^3 (Table 1). This means that the specific gravity of the studied dune sands met the standard characteristics of fine aggregates (Smith 1979).

Absorption

From the durable mortar point of view, fine aggregates with lower absorption generally develop lower strength bonds and produce less durable mortars than those with slightly higher absorption (Ahn 2000). Moreover, fine aggregates with a high absorption value will absorb greater amounts of the cement into the aggregate and thus increase costs. The absorption value of the studied dune sand aggregates varied from 0.94 to 0.97 (Table 1). This indicates that the studied fine aggregates have standard limits for fine aggregate absorption in the specified standards.

Textural characteristics

The textural characteristics (shape and roundness) of fine aggregates have an important effect on the workability (fresh mix), strength and durability (hardened mix) of both concrete and mortar. Rounded and poorly graded grains necessarily have higher void contents than angular and well-graded ones. The angular particles of aggregates tend to be more packed and will be more strength and durability in hardened mixes of concrete and mortar.

The studied fine aggregates of dune sands consist mainly of equant or spherical particles (Table 2; Fig. 6). Accordingly, these grains need less cement paste and water content for an acceptable degree of concrete and mortar workability. This view agrees with the findings of many published sutdies (e.g., De Larrard et al. 1997; Hudson 1999; Shilstone 1999).

Generally, sand dune grains are more rounded because air-transported grains are intensively subjected to pitting and become round faster than those transported in aqueous media (El Sayed 1999). The studied fine aggregates of dune sands were mainly well rounded (17.2 %), rounded (7.1 %), sub-rounded (33 %), sub-angular (21 %), angular (13.3) and very angular (7.7 %, Table 2; Fig. 6).

Higher percentages of sub-angular, angular and very angular grains (42 %) were found mainly in the coarser grains of the studied dune sands because of the locally nearer sources and the short transportation distance. The bimodal angularity of the studied dune sands was due to local transportation by channels from the high surrounding lands and re-transport by winds.

Thus, crushed fine aggregates of angular grains can improve and balance the higher percentages of well-rounded and rounded grains in the studied dune sands.

Mineralogy and chemical stability

Both the mineral composition and chemical stability of the aggregates play an effective role in the strength and permanence of the bond between the cement and aggregate of both concrete and mortar. In most cases, aggregates contain

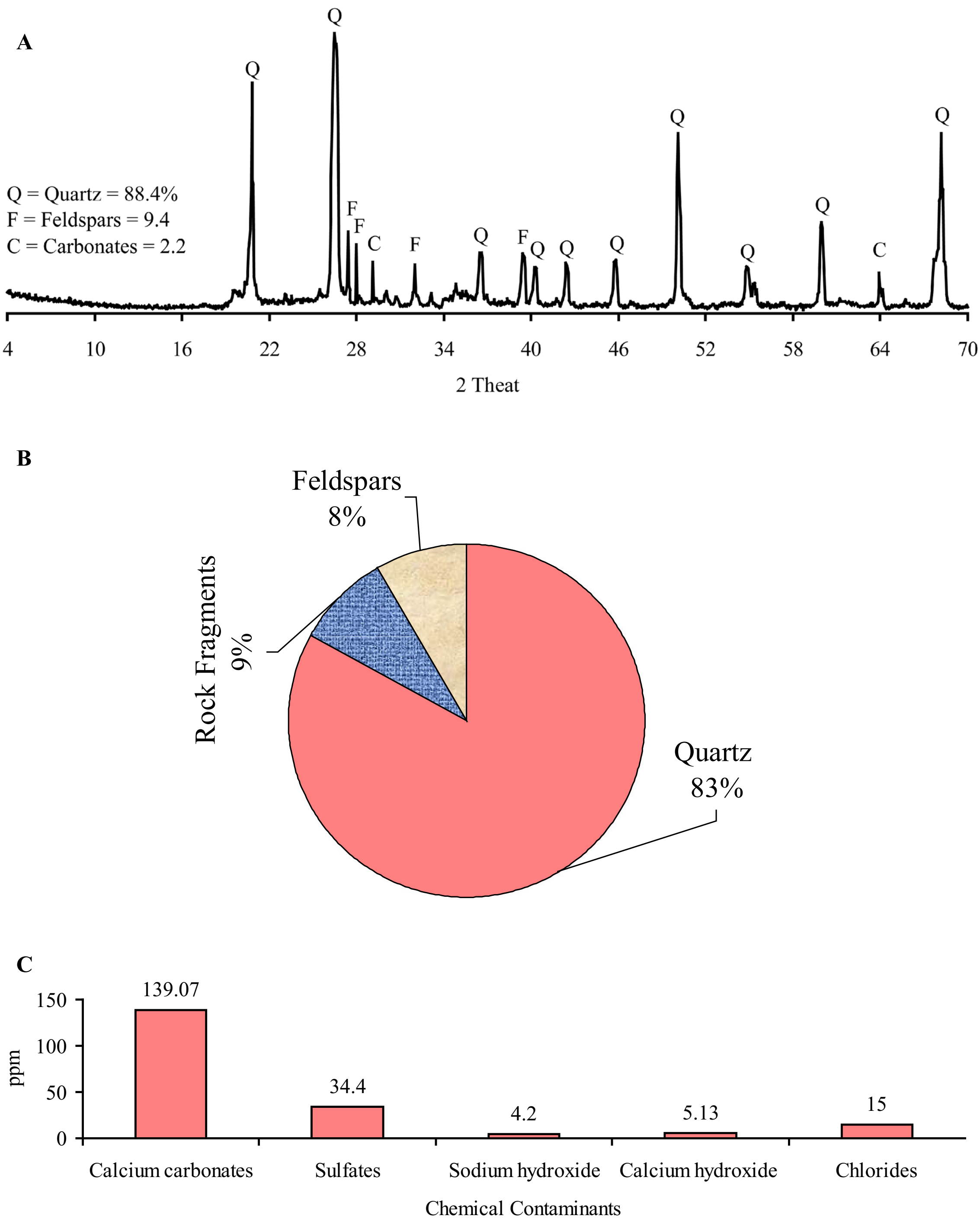
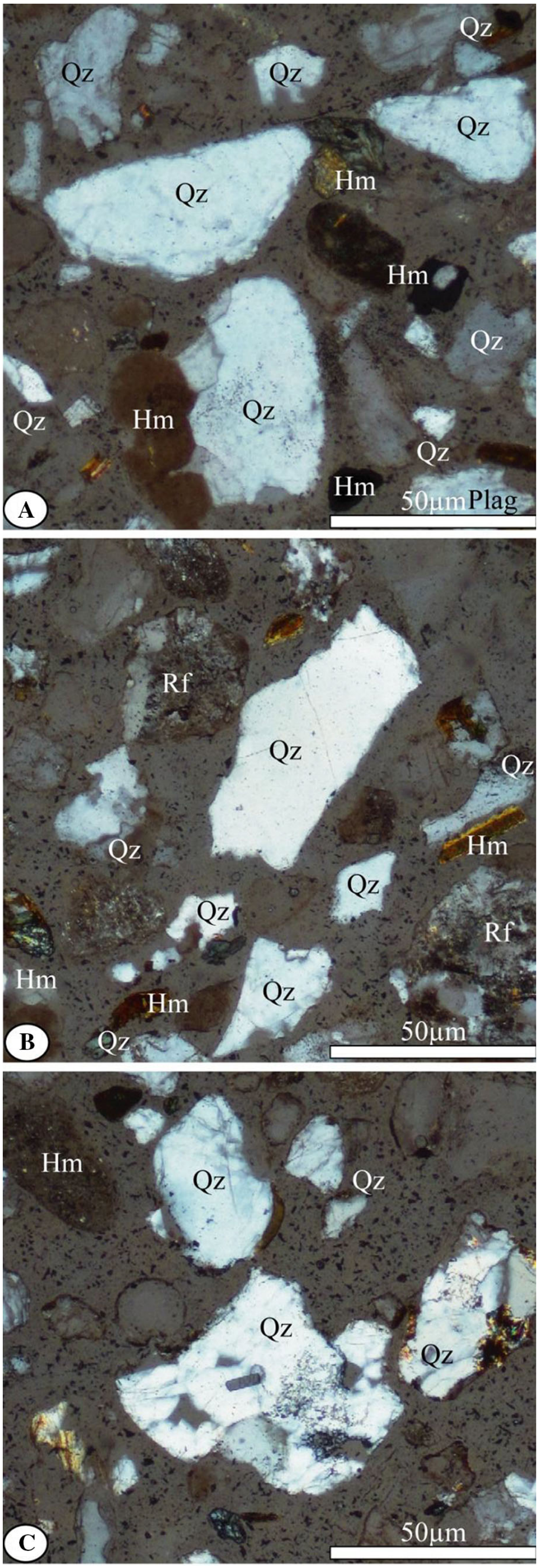


Fig. 7 **a** X-ray diffraction of the studied fine aggregates of dune sands; **b** mineral constituuents of the studied dune sands; **c** chemical contaminants of the studied dune sands (average values in ppm)

certain active and harmful constituents (active silica, carbonates, sulfates, hydroxides and chlorides) that can cause a reaction (alkali-aggregate reaction, AAR) in cement in concrete with cement in concrete and mortar mixes. Consequently, over long time periods, the alkali-aggregate reaction (AAR) will negatively affect the strength and durability of hardened concrete and mortar. The alkali-aggregate reaction has two forms: the alkali-silica reaction (ASR) and alkali-carbonate reaction (ACR).

The alkali-carbonate reaction (ACR) takes place when aggregates contain active carbonate aggregates (e.g., dolomite). Brucite [Mg $(OH)_2$] and calcite ($CaCO_3$) are



◀**Fig. 8** Photographs of freshly unstrained quartz grains (Qz), plagioclase (Plag), rock fragments (Rf) and some heavy minerals (Hm) of the studied dune sands under cross-Nicoles

produced by the reaction between alkalis of the cement and dolomite in the aggregate. Brucite could be responsible for the volumetric expansion after de-dolomitization of the aggregate due to water absorption (Swenson and Gillott 1964).

$$CaMg(CO_3H)_2(\text{dolomite}) + 2NaOH \rightarrow CaCO_3(\text{calcite}) + Mg(OH)_2(\text{brucite}) + Na_2CO_2 \quad (1)$$

The alkali silica reaction (ASR) is a destructive chemical reaction between the alkaline cement paste and active silica of the aggregates. This reaction forms an alkali silica gel, which causes expansion cracks in concrete (Multon et al. 2009). When sodium chloride is present in the aggregates or mix water, the tricalcium aluminate in Portland cement may react with chloride, taking some of the chloride out of the solution with separation of the sodium ions in the solution. Similar enhancement of alkalis has also been found to occur for sulfates and nitrates (Metha 1978).

In consequence, these chemical reactions may lead to expansive reaction products such as ettringite. In turn, the ettringite may cause the overall expansion of structural elements and lead to extensive damage progressing from the outer surface toward the specimen's inner core (Skalny et al. 2002). This process may result in a gradual loss of concrete strength accompanied by surface spalling and exfoliation (Biczok 1972). The newly produced gypsum can react with some alumina-bearing phases such as unhydrated tricalcium aluminate ($3CaO{\cdot}Al_2O_3$) or hydrated calcium sulfoaluminate (monosulfate) to form ettringite (Basista and Weglewski 2008).

$$Ca(OH)_2 + Na_2SO_4 + 2H_2O \longrightarrow CaSO_4.2H_2O(\text{gypsum}) + 2NaOH \quad (2)$$

$$3CaO.Al_2O_3 + 3(CaSO_4.2H_2O) + 26H_2O \rightarrow 3CaO.Al_2O_3.3CaSO_4.32H_2O(\text{ettrignite}) \quad (3)$$

The results of the mineralogical composition and chemical analysis of the studied dune sands are given in Table 3. An X-ray chart (Fig. 7a) of the studied dune sands indicated that these fine aggregates are composed mainly of quartz (88 %), feldspars (9 %) and a negligible amount of carbonates (2.2 %). The quartz grains of the studied dune sands are a nonreactive silica type (quartz >83 %, Table 3 and Fig. 7b). Thus, the alkali silica reaction (ASR) between the studied fine aggregate and alkali hydroxides in the pore solution of cement-based materials did not occur (Neville

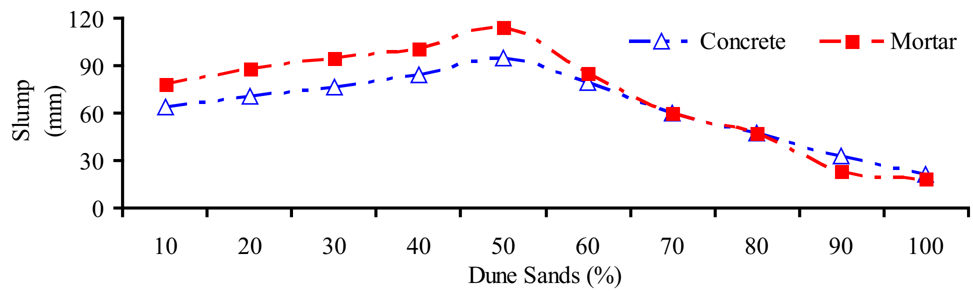


Fig. 9 Comparison between the effects of the dune sand content on the workability of concrete and cement mortar (average value)

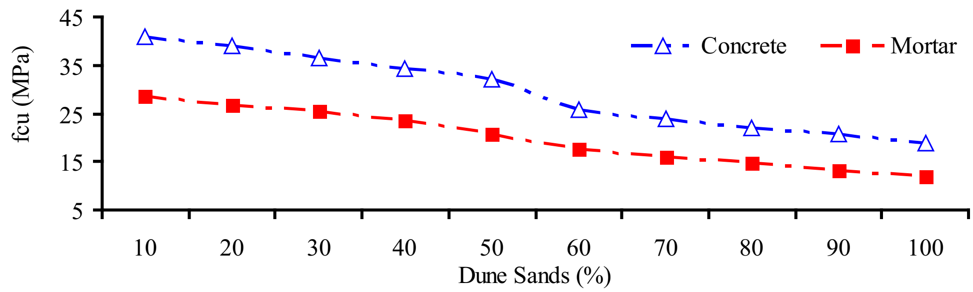


Fig. 10 Comparison between effects of the dune sand content on the concrete and cement mortar strength (average value)

1995; Marzouk and Langdon 2003; Garcia-Diaz et al. 2006).

The chemical agents, which are normally aggressive toward concrete and mortar, are sulfates and chlorides. The total dissolved salt (TDS) values of the studied samples range from 495 to 522 ppm. The average values of sulfates and chlorides are very small and nearly negligible, whereas calcium carbonate values are variable with a value of 139 ppm. Sulfates $(SO_4)^{2-}$ were recorded with an average value of 34 ppm. Also, magnesium, calcium, potassium and sodium hydroxides were recorded with scarce concentrations (Table 3; Fig. 7c).

Petrographically, the studied dune sands were dominated by unstrained quartz grains with an absence of chert and flint grains (Fig. 8).

From the concrete and mortar strength and durability points of view, the above-mentioned mineralogical and chemical analyses indicated no harmful contaminants that reacted adversely when used as concrete and mortar fine aggregates within the studied dune sand aggregates.

Workability of dune sand concrete and mortar

The word workability describes the ability of concrete and mortar to be moved, reshaped and consolidated. Workability is considered a very important property of fresh concrete and mortar; it depends mainly on the grain size distribution, textural characteristics of aggregates as well as the mix ratio of water, cement and aggregates. Also, workability has a direct affect on the strength and durability of both hardened concrete and mortar. The mix ratio of water, cement and aggregates must be balanced to avoid bleeding and segregation. Workability is affected by every component of concrete and essentially every condition under which concrete is made.

Moreover, the workability of mortars plays an important role in the construction process of masonry structures. Workability can be considered one of the most important properties of mortar because it directly influences the bricklayer's work (Sabatini 1984). The slump test is the most common workability measuring test; it gives an indication of the water content and thus the hardened strength of concrete (Ferraris 1998). For high workability pumpable concrete, the slump ranges from 100 to 150 mm slump, which needs 40 % fine aggregate by weight of total aggregates (Maiti and Agarwal 2009).

Figure 9 shows the effect of the dune sand content on the workability degree of both cement mortar and concrete of the studied dune sands. The results show that when the dune sand content increases, the slump values initially increase because of the high sphericity and roundness of the dune sand grains. However, the slump decreases abruptly in both cement mortar and concrete at dune sand contents >50 % (Table 5; Fig. 9). At the same time, the workability degree of mortar is higher than that of concrete because of the presence of coarse aggregates in the concrete mixture and fine aggregates filling the pore space of coarse aggregates. Thus, the concrete paste has less flow than free coarse aggregate mortar paste.

The studied dune sands have an abundance of rounded and cubical shapes and relatively smooth surfacees. Therefore, this type of natural fine aggregate must be

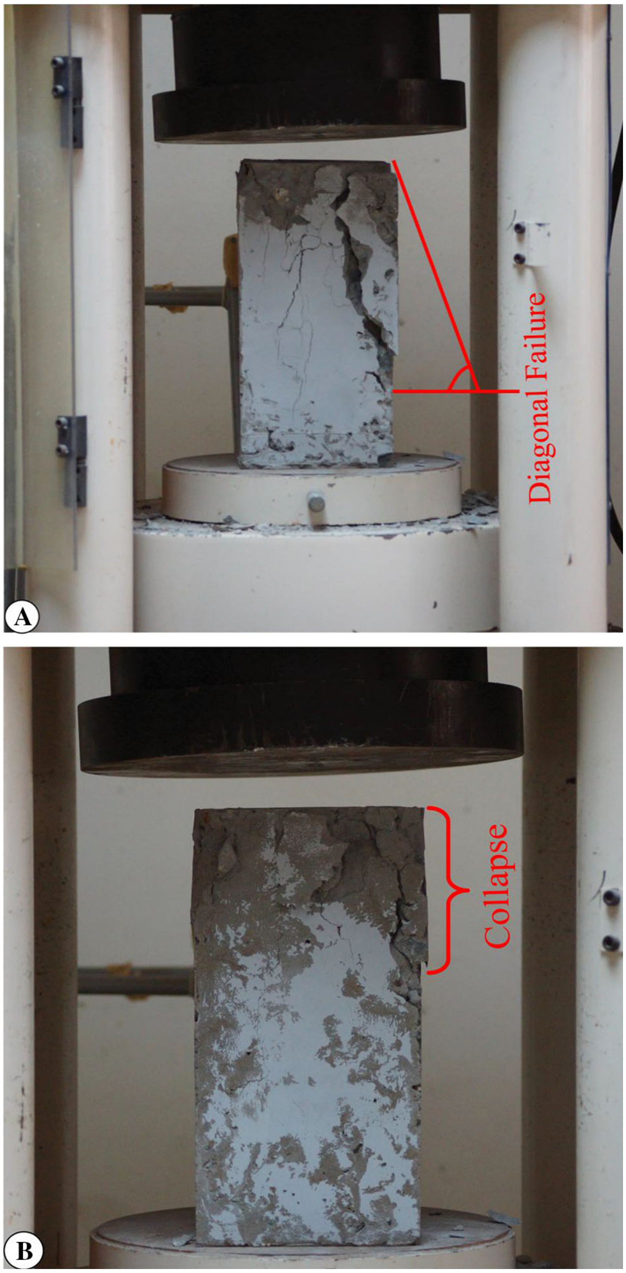


Fig. 11 Failure mode of concrete sample under uniaxial compressive; **a** diagonal mode (<50 % dune sands of the total fine aggregates); **b** collapse mode (>50 % dune sands of the total fine aggregates)

mixed with crushed fine aggregates of angular shape and rough-textured surfaces to avoid bleeding and segregation of these grains within the fresh mortar and concrete before hardening processes. It has been concluded that the workability degree of the studied dune sands fluctuates from a low to medium degree, meaning that the degree of workability is suitable for concrete of normal reinforced work without vibration and heavily reinforced sections with vibration. This conclusion agrees with previous studies (e.g., Powers 1968; Wilby 1991).

Fig. 12 Failure mode of cement mortar sample under uniaxial compressive strength; **a** and **b**: internal failure combined with cracking and shrinkage in length mode

Strength of dune sand concrete and mortar

The compressive strength of cement mortar and concrete is one of the most common measures usually used to evaluate the performance of mechanical properties of concrete and cement mortar. Mechanical properties are controlled mainly by the strength of the cement-aggregate bond and cement-water-aggregate ratio as well as by the degree of compaction. Round and smooth sand grains require less mixing water in the cement mortar and concrete. It produces better strength at the same cement content because of its lower water:cement ratio. However, angular sands require more mixing water but still may not be workable enough for many applications such as pumping concrete (Gillott 1980; Langer 1993; Rocco and Elices 2009). The type of fine aggregate has a significant influence on both the rheological and mechanical properties of concrete and cement mortars (Neville 1995). On the other hand, the surface texture has a significant effect on the strength; for example, rough surfaces enhance the bond between particles and paste and thus increase the strength (Galloway 1994).

Figure 10 shows the compressive strength values for the mix (28 days), which was calculated by dividing the failure load of the cross sections and repeated in megapascal units. These values indicate that the strength of concrete and cement mortar generally decreases with increasing dune sand content owing to the increasing surface area of the dune sand grains, characterized by a high surface area. Also, notably, decreasing concrete and mortar strength occurred abruptly at dune sand contents >50 % (Table 5). Higher contents of dune sand aggregates (up to 50 %) cause decreasing cement mortar strength because of the increasing surface area of these smooth grains, which may lead to increased bleeding and segregation of these grains within the fresh concrete and mortar before hardening processes (Abu Seif 2013a, b).

It was clearly found that at the constant dune sand percents, the compressive strength values of concrete are higher than mortar that owing to the presence of coarse aggregates within concrete mix that have higher resistance than fine aggregates against the applied load (Table 5; Fig. 10).

Figures 11 and 12 represent the failure mode of both concrete and mortar during uniaxial compressive strength test. The concrete samples were observed to fail diagonally with cracking up to 50 % dune sands of the total fine aggregates (Fig. 11a) and collapsed with cracking in the case of samples having >50 % dune sands of the total fine aggregates of mixture (Fig. 11b). This collapse failure was combined with shortening of the length of the uppermost part of the concrete samples, which was related to segregation of dune sand grains within the fresh concrete before the hardening processes. Consequently, the failure mode of mortar samples was expressed by cracking and shortening in length only (Fig. 12). This failure seems to be related to internal failure and the absence of segregation and bleeding of dune sand grains within the fresh cement mortar before hardening processes.

Conclusions and recommendations

Based on the experimental results obtained in this work, the most important conclusions and recommendations can be summarized in the following points:

- Aeolian sands must be evaluated with intensive geotechnical studies for the use of these fine aggregate natural resources as construction materials with minimized environmental risks.
- The studied dune sands do not meet the international standard of size gradation; thus, the dune sands are not suitable for use as construction aggregates alone but must be mixed with crushed fine aggregates to improve their poor gradation (ASTM-C33 1999).
- From a compositional point of view, the studied dune sands were stable mineralogically and are chemically suitable for use as concrete and cement mortar fine aggregates without alkaline attack.
- Texturally, the dune sands could improve the workability degree of cement mortar and concrete when mixed with crushed fine aggregates.
- The workability and compressive strength of the dune sand concrete and cement mortar were acceptable when the dune sands did not exceed 50 % of the total volume of fine aggregates at a constant mix ratio of 2:1:3 (water:cement:aggregates) and 1:2:4:6 (water:cement:fine aggregates:coarse aggregates), respectively, for cement mortar and concrete.

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