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Geological and physiochemical characterisation of construction sands in Qatar

Marwa Al-Ansary [a,*], Michael C. Pöppelreiter [b], Asia Al-Jabry [c], Srinath R. Iyengar [d]

[a] *Qatar Shell Research and Technology Centre, Qatar*
[b] *Shell Kuwait Exploration and Production, Al Sahab Tower Salhiya, Kuwait City, Kuwait*
[c] *Qatar University, Qatar*
[d] *Texas A&M University at Qatar, Qatar*

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Abstract

This paper investigates the two different types of naturally occurring construction sands in Qatar (fluvial and aeolian dune). These sands are mined from natural deposits that consist of various layers formed at different geological times. After mining, sand treatment plants further process the various layers to be sold commercially for concrete and mortar applications. The booming construction industry in Qatar is only allowed to utilise the locally mined sands which are limited in quantity and are in high demand. Properties of these sands were hardly ever systematically published. This study aims at an initial characterisation and comparison of these sands, augmented by linking sand characteristics to geological processes.

Representative fluvial and aeolian sand samples were collected from natural deposits in the south of Qatar and compared to the standard European Norm sand. A rigorous testing program was carried out, comprising of geological, physical, chemical and microstructure investigations. Results were bench marked against the prevalent Qatar Construction Standards specified properties and showed compliance with the thresholds apart from sulphate contents for fluvial sand.

In conclusion, Qatar sands consist of high percentages of carbonates and traces of clay minerals and their properties strongly vary with geological layers. In contrast, European Norm sand purely consists of quartz. Thus, selective mining is recommended as a means to upgrade the quality of sand in Qatar. Hence, it is recommended to extract fluvial sand from Channel and Sand Bar geological layers while avoiding mining from abandonment paleosol layers. For aeolian dune sand, selective mining from top layers of deposits while avoiding base layers close to the sulphate and carbonate rich Sabkha is suggested.

Keywords: Construction sand; Dune sand; Aeolian sand; Fluvial sand; Qatar

1. Introduction

The state of Qatar has a total surface area of 11,437 km^2 located at the northeasterly coast of the Arabian Peninsula. Qatar is blessed with enormous natural gas reserves, the third largest in the world, that generate the highest growth domestic product (GDP) per capita in the world in 2010 (IMF, 2011). Qatar witnesses a rapid economic growth,

* Corresponding author. Tel.: +974 44599863; fax: +974 44599859.
E-mail address: m.al-ansary@shell.com (M. Al-Ansary).

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Table 1
Tests and permissible limits for physical and chemical properties of fine aggregates for concrete as stipulated by QCS (2007).

QCS requirement	QCS standard will be based on			QCS (2007) permissible limits
	British Standards	American Standards for Testing Materials	Gulf Standards	
Grading (dry)	BS 812-103 (1985)	–	–	Standard[1]
Material finer than 75 microns (natural material, wet)	BS 812-103 (1989)	–	–	3% Max
Clay lumps and friable particles	–	ASTM C142 (2010)	–	3% Max
Lightweight pieces	–	ASTM C123 (2004)	–	0.5% Max
Organic impurities	–	ASTM C40 (2004)	–	Colour standard not darker than plate No.3
Water absorption (saturated surface dried)	BS 812-02 (1995)	ASTM C128 (2007)	GS 1458	2.3% Max
Specific gravity (apparent)	BS 812-02 (1995)	ASTM C128 (2007)	–	2.6 Min
Shell content	BS 812-106 (1985)	–	–	3% Max
Acid soluble chlorides	BS 812-117 (1988)	–	–	0.06% Max for reinforced and mass concrete 0.01% Max for pre-stressed and steam cured structural concrete
Acid soluble sulphates	BS 812-118 (1988)	–	–	0.4% Max
Soundness (loss by magnesium sulphate 5 cycles)	–	ASTM C88 (2005)	–	15% Max
Potential reactivity Of aggregates: Alkali–silica reaction Alkali–carbonation reaction	–	ASTM C289 (2007) ASTM C586 (2005) ASTM C227 (2010)		Not reactive
Of cement-aggregate combination				6 Month expansion 0.10% max

[1] The lower and upper permissible limits are plotted in Fig. 8.

conspicuously reflected in the construction and building industry sector. In 2005, the construction and real estate sector in Qatar formed 5.7% and 2.3% of the GDP, respectively (Al-Khatib, 2009).

The state of Qatar has recently been awarded the 2022 football world championship. Related construction and renovation of 12 world class stadiums as well as massive investment in infrastructure are planned which includes a new international airport, an international harbour, an integrated rail network and metro system projects (Qatar 2022, 2011). Moreover, the government of Qatar has set aside USD 17 billion for the construction of hotels and other tourism related infrastructure (Qatar 2022, 2011). Consequently, a vast amount of building material is needed to accommodate this rapid industrialisation and infrastructure expansion. Especially sand, the most vital ingredient for all construction works, needs to be supplied in adequate quantity and quality. Demand for construction sand has been growing exponentially in Qatar particularly during the last 10 years for developing an adequate infrastructure (Perumal, 2009). However, the construction industry in Qatar is only allowed to utilise locally mined sands. The consumption of sand for concrete works in Qatar was reported to be 3.6 million ton in 2006 and has been forecasted to rise to 8.4 million tons in 2012 (Scacciavillani, 2007).

The construction industry in Qatar, however, faces a shortage in raw materials especially sand (John, 2007). This affects the progress of many construction works. The costs associated with washed construction sand are raising due to increasing transportation expenditures. It was reported that if the shortage in washed sand supplies continues, the factories producing a ready mix concrete may have to abandon (Qatar Construction Sites, 2007).

In 2007, Qatar National Standards for Construction and Building (QCS) was created to regulate the construction materials specifications and operational procedures used in governmental and private projects. Qatar Construction Standard (QCS, 2007) has been delineated in a set of documents comprising of 28 parts and 251 chapters that adopt many international standards such as British Standards (BS), American Standards for Testing Materials (ASTM) and Gulf Standards (GS). According to Qatar Construction Standards, Section 5.2–Table 2.1 (QCS, 2007), a series of physical and chemical properties requirements should be fulfilled for fine aggregates (i.e. sand) to be used in concrete works. These requirements are summarised in Table 1.

Table 2
Coding system of sand samples from Area (B) of sand pit.

Area	Cycle no.	Description	Code
B	1	Abandonment layer (1) – entosoil	B1
		Channel and sand bar layer (1)	B2
	2	Abandonment layer (2) – silcrete paleosol	B3
		Channel and sand bar layer (2)	B4
	3	Abandonment layer (3) – calcrete paleosol	B5

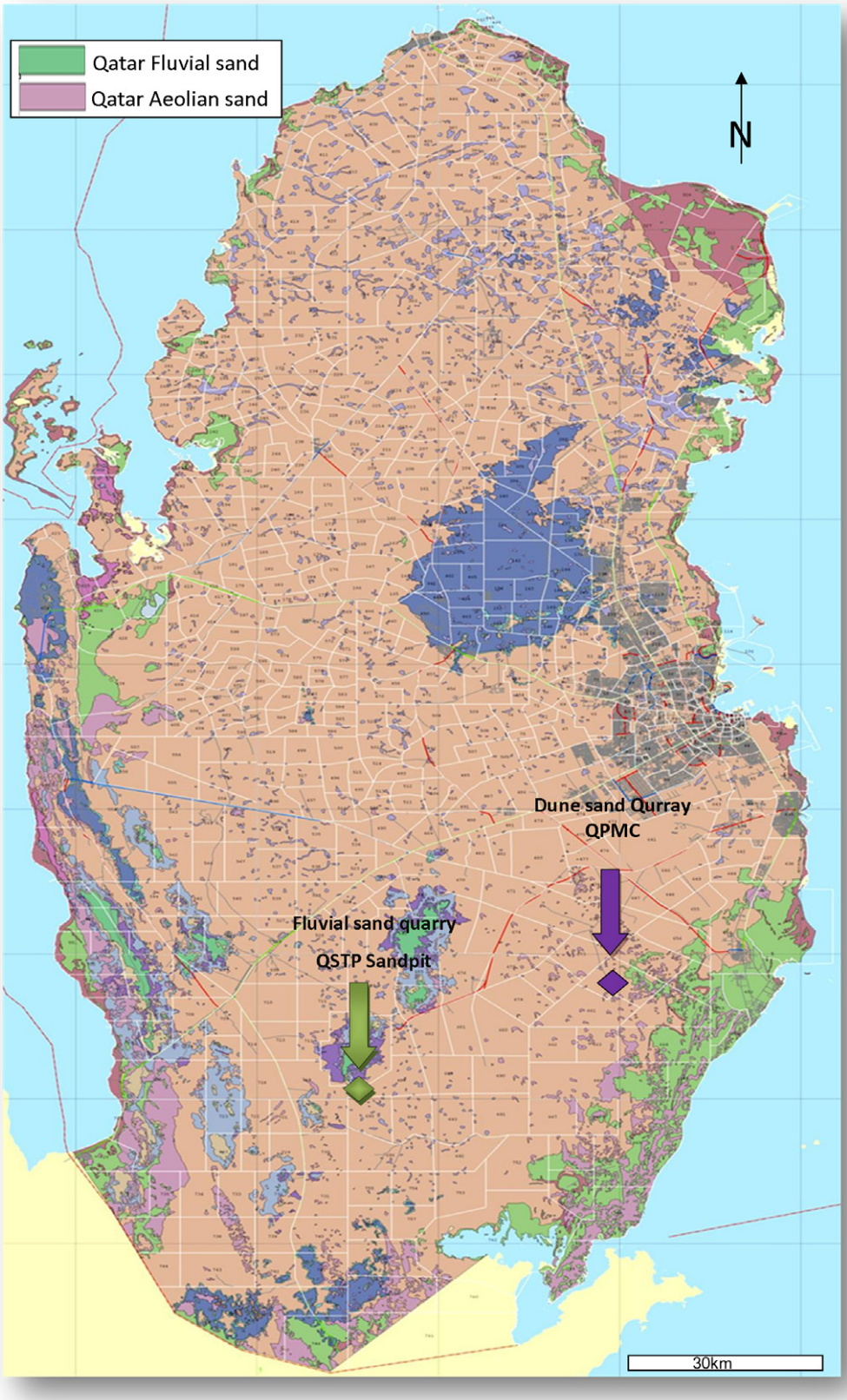

Fig. 1. Qatar geological map (adapted from Qatar Geographic Institute, 1992).

2. Occurrence and types of natural sand in Qatar

2.1. Occurrence

Natural sand deposits in Qatar are limited and occur exclusively in the south of the country. Most parts of the country are covered by karstified carbonates of the Mid Eocene Damman Formation, not suitable to be used as construction materials. The only two different types of construction sands available in Qatar are fluvial (used in concrete works) and aeolian dune (used in mortar works).

The dearth in occurrence of both natural fluvial and aeolian sands is highlighted in Fig. 1. The scarcity of sand stresses the need for a quality management of these reservoirs to sustain its availability for a maximum period of time. Moreover, the State of Qatar limits the use of imported sand in any construction work in the country. With a lack of scientific analysis and data in the literature, the construction industry is forced to deal with sand management on a pragmatic manner. This study attempts to carry out fundamental analysis to investigate the quality of sand in Qatar that could constitute a suitable and durable construction material to be used in concrete and mortar applications.

2.2. Qatar fluvial sand

Fluvial sand is quarried from several sand pits in the southern part of Qatar near the towns of Al-Karanah and Umm Said (Fig. 1). As of 2011, there are three commercial sand plants in Qatar that extract and process fluvial sand, viz.:

- Qatar Sand Treatment Plant (QSTP), a subsidiary of Qatar Industrial Manufacturing Company (QIMC).
- Qatar National Cement Company (QNCC).
- Qatar Primary Materials Company (QPMC).

After mining, raw fluvial sand is extracted from various geological layers and transported to the sand treatment facilities, where it is mixed. Large stones and cemented aggregates are sieved out. The product is referred to as 'unwashed bulk construction sand' and is not sold commercially. Subsequently, the bulk sand is washed to remove excess salts, fines and other impurities. The product is washed bulk construction sand. It is sold on the market as certified construction sand to be used in concrete works. In this paper, both Qatar unwashed and washed bulk fluvial sand will be referred to as unwashed and washed fluvial sand, respectively.

2.3. Qatar aeolian dune sand

The second source of natural sand is aeolian dune sand, which is deposited by wind processes. Aeolian sand occurs in the south eastern part of Qatar (Fig. 1). Qatar Primary Materials Company (QPMC) is currently the only company in Qatar to quarry aeolian sand since 2007. QPMC is a government owned company that extracts natural aeolian sand deposits from an area that is approximately 60 km south of Doha, as shown in Fig. 1.

Qatar aeolian dune sand is extracted as bulk product from all naturally occurring layers of dunes with draggers and loaded into trucks. There is no further processing phases (e.g. washing, sieving and additives) and the sand is sold as naturally occurring material marked as 'Nijian' sand (Perumal, 2009). In Qatar, bulk dune sand is usually used for plastering purposes in construction (Perumal, 2009), mortar production and specialised industries applications. In this paper, Qatar bulk aeolian dune sand will be referred to as aeolian dune sand.

3. Research methodology, materials and experimental methods

3.1. Research methodology

This paper reports the results of an extensive analysis characterising the quality of fluvial and aeolian dune sands. Representative sand samples were collected and analyzed in certified commercial laboratories in Qatar. The testing program, as summarised in Fig. 2, can be classified as requirement properties tests in accordance to Qatar Construction Standards (QCS, 2007) and characterisation properties tests. The various international standard procedures that were adopted for the analysis of the requirement and characterisation properties have been specified in Tables 3 and 4, respectively. The testing program comprises of geological field characterisation, physical, chemical and microstructure analyses for the different types of fluvial and aeolian sands. For comparison, standard European fluvial Norm sand was used as a reference.

3.2. Materials

Fig. 3 summarises the different types of sand used in this study and the subsequent sections will give more details of their characteristics.

3.2.1. European Norm sand

European Norm sand is a mixture of five sands from different natural sources specifically blended by Normensand GmbH, Beckum, Germany to be sold as standard sand. This sand constitutes properties of standard construction sand and is in accordance to CEN-STANDARDSAND EN 196-1 (CEN, 2009). This standard sand is generally used for benchmarking construction sands as well as for calibration and preparation tests such as cement strength determination.

3.2.2. Qatar fluvial sand

Washed and unwashed fluvial sands were used in this study and were purchased from Qatar Sand Treatment Plant (QSTP).

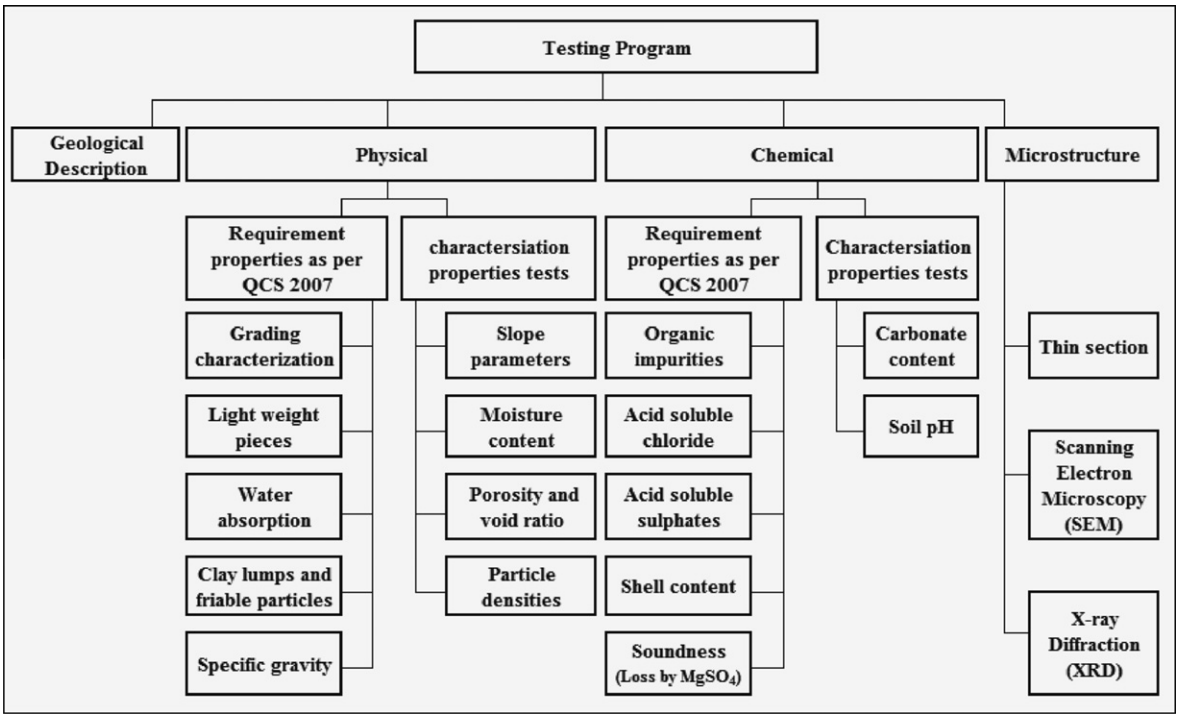

Fig. 2. Testing program.

3.2.3. Qatar fluvial (layered) sand

To assess the quality and variation of fluvial sand, a sand pit owned by Qatar Sand Treatment Plant (QSTP) was investigated in June 2009. The sand pit is located in the southwest of Qatar near Al-Karanah town (Fig. 1). The studied sand pit usually extracts lose to semi-cemented sand up to 18 m below the surface level (Fig. 4). Various sand samples were collected from different areas of the sand pit. From each area, different geological layers were sampled separately. From each layer, an average of three replicate samples was collected for analysis. Sand samples were stored in airtight plastic bags prior to analysis in the laboratory.

The thickest, most complete section sampled in the sand pit is referred to as Area (B). Thus, this paper will concentrate on data from Area (B) as a representative sample set for this location. Area (B) consists of five different geological layers/cycles. From each layer, typical sand samples were studied. The results of the five soil samples representing each individual layer will be reported in subsequent sections of the paper.

3.2.4. Qatar aeolian dune sand

Dune sand, marked as 'Nijian' sand, was used in this experimental work and was purchased from Qatar Primary Materials Company (QPMC).

3.3. Experimental methods

The standard experimental methods employed for testing of the physical and chemical properties of the sands has been specified previously in the Section 3.1. Furthermore, microstructural characterisation was carried out employing thin sections, scanning electron microscopy and X-ray diffraction techniques. These have been described below.

3.3.1. Microstructure analyses

3.3.1.1. Thin sections. Field observations were verified with thin sections investigated with a light microscope with approximate magnification of 10 times to determine sand grain composition. Six thin sections were made for petrographic characterisation using a transmission light microscope make Zeiss Axioskop 40. Cross polarised light was used for mineral identification. Strongly dolomitized samples were further investigated using white paper behind thin sections to enhance colour contrast and allow component identification.

3.3.1.2. Scanning electron microscopy (SEM). Scanning electron microscope model *Quanta 400* by *FEI Company* was used to study the surface morphology of the sands. To this effect, the fluvial and the aeolian sand fractions were first sieved to obtain the representative fractions with mean diameter D_{50}, then vacuum-dried and finally, mounted on an aluminium stub using a strong double-sided adhesive tape. No form of coating to enhance the conductivity of the samples was employed. The microscope accelerating voltage ranged between 2 kV and 5 kV to compromise between the sample charging and capturing high-resolution images. A working distance between 9 and 12 mm was used, whilst the magnifications used ranged from 30 to 6000 times.

Table 3
Results of physical and chemical QCS (2007) requirement properties for all studied sands.

Test/sample type		Fluvial sands								Aeolian sands Bulk	Permissible limits as per QCS 2007	Testing standard
		Layered from QSTP sand pit					Bulk					
		B1	B2	B3	B4	B5	European Norm sand	Washed sand	Unwashed sand	Dune sand		
Physical properties												
Material finer than 75 microns (%)		7.46	0.02	0.78	0.08	0.54	0.10	0.32	0.08	0.02	3.0% Max	BS 812-103 (1989)
Clay lumps and friable particles (%)		0.41	0.66	0.54	0.55	0.50	Nil	Nil	Nil	Nil	3.0% Max	ASTM C142 (2010)
Lightweight pieces (%)		Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil	0.5% Max	ASTM C123 (2004)
Water absorption (%)		0.61	0.70	1.08	0.82	1.29	0.55	1.70	1.30	0.50	2.3% Max	ASTM C128 (2007)
Specific gravity	Oven Dry	2.54	2.55	2.54	2.57	2.61	2.63	2.53	2.56	2.63	–	ASTM C128 (2007)
	Saturated surface dry	2.56	2.58	2.58	2.60	2.66	2.64	2.57	2.59	2.65	–	
	Apparent	2.58	2.60	2.60	2.62	2.69	2.66	2.64	2.65	2.67	2.60 min	
Shell content (%)		Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil	3.0% Max	BS 812-106 (1985)
Chemical properties												
Organic impurities		Lighter than colour standard plate No.3									Colour standard not darker than Plate No.3	ASTM C40 (2004)
Acid soluble chlorides (%)		0.01	0.03	0.03	0.01	0.01	0.01	0.01	0.01	0.01	Max 0.06% for reinforced and mass concrete Max 0.01% for pre-stressed and steam cured concrete	BS 812-117 (1988)
Acid soluble sulphates (%)		0.67	0.22	0.32	0.07	0.05	0.03	0.39	0.48	0.11	0.40% max	BS 812-118 (1988)
Soundness (loss by $MgSO_4$) (%)		1.70	1.77	1.86	1.91	1.88	1.08	1.37	1.54	0.53	15.0% max	ASTM C88 (2005)

Table 4
Results of physical and chemical Characterisation properties for all studied sands.

Test/sample type	Fluvial sands								Aeolian sands Bulk	Testing standard
	Layered					Bulk				
	B1	B2	B3	B4	B5	European Norm sand	Washed sand	Unwashed sand	Dune sand	
Physical properties										
Median diameter (D_{50}) mm	0.25	0.48	0.30	0.46	1.00	0.90	0.45	0.45	0.25	ASTM D2487 (2011)
Coefficient of uniformity (C_u)	3.50	1.96	1.83	1.82	6.67	6.01	2.08	2.21	1.33	
Coefficient of curvature (C_z)	1.03	0.94	0.89	1.01	0.51	1.0	1.00	1.02	0.93	
Classification according to USCS	Poorly graded: very uniform grading				Poorly graded: gap graded	well graded	Poorly graded: very uniform grading			
Moisture content (%) as received	1.50	0.20	0.30	0.20	1.00	0.20	1.10	0.30	0.20	AASHTO T265 (2004)
Porosity (%)	1.55	1.79	2.73	2.10	3.35	1.44	4.30	3.33	1.32	ASTM C128 (2007)
Bulk density (kg/m^3)	1548	1617	1617	1648	1525	1711	1663	1734	1687	BS 1097-3 (1998)
Inter-aggregate voids (%)	0.39	0.37	0.36	0.36	0.42	0.35	0.34	0.32	0.36	BS 1097-3 (1998)
Chemical properties										
Carbonate content (%)	7.67	9.73	4.01	6.97	8.51	Traces	3.23	5.34	14.84	BS 1377-3 (1990)
Soil pH	8.11	8.68	8.42	8.72	8.06	7.75	8.31	8.50	8.66	ASTM D4972-1 (2007)

3.3.1.3. X-ray powder diffraction (XRD). The crystalline phases and the corresponding intensities of compounds were identified using the *Theta–Theta type* X-ray diffractometer model *Ultima IV* manufactured by *Rigaku Corporation* fitted with a copper anode. The diffraction X-ray tube operated at 40 kV and 40 mA. The XRD sample was prepared by vacuum drying a representative quantity of the soil specimens. Subsequently, all the samples were crushed using pestle and mortar and screened primarily through 425 μm sieve. Since, the primary interest of this study was to analyse the sand for its composition and to identify clay minerals (if any), the samples for XRD analysis sieved into two fractions. In addition to the 425 μm sieve, 75 μm was employed. The particles passing through the former but retained on the latter sieve were considered to be sand fraction. This is referred to as coarse fraction in this paper whilst the fraction passing through 75 μm is referred here as fines (i.e. no sand present but only a mixture of clay minerals and silt). The individual fractions were packed into a 50 mm by 35 mm rectangular glass sample holder, with a centred 20 mm × 20 mm square depression 0.5 mm deep in such a way so as to have an undisturbed and randomly positioned surface for the analysis. The samples were subjected to continuous scanning with 2Theta/Theta scanning mode. The data was collected using the *Measurement Monitor* software provided by Rigaku. The following operating variables were adopted: scanning range of $2\Theta = 2°$ and 50°, step size of 0.02° and rate of 1.0 deg/min. Subsequently, the *Peak Search* and *Qualitative Analysis* software provided by Rigaku was employed to identify the peaks of the raw XRD data and then link them with the Joint Commission on Powder Diffraction Standards–International Centre for Diffraction Data (JCPDS–ICDD) library card database (PDF-2 Release 2007).

4. Geological characterisation

4.1. European Norm sand

European Norm sand is of fluvial origin, similar to that of Qatar fluvial sand. European Norm sand is composed of various weathered crystalline basement rock with angular to sub-angular grains with spheroidal grain appearance. The grain size ranges from fine to coarse sand size with wide particle size distribution. Moreover, European Norm sand grains consist of a mixture of mostly volcanic quartz with some metamorphic quartz grains.

4.2. Qatar fluvial sand

Qatar fluvial sand geologically belongs to the Hofuf formation, which was deposited about 5 million years ago (Al-Saad et al., 2002). River systems, sourced from the Saudi mountain probably near Wadi Nisah (Hussain et al., 2001), has transported sediment over 450 km to Qatar.

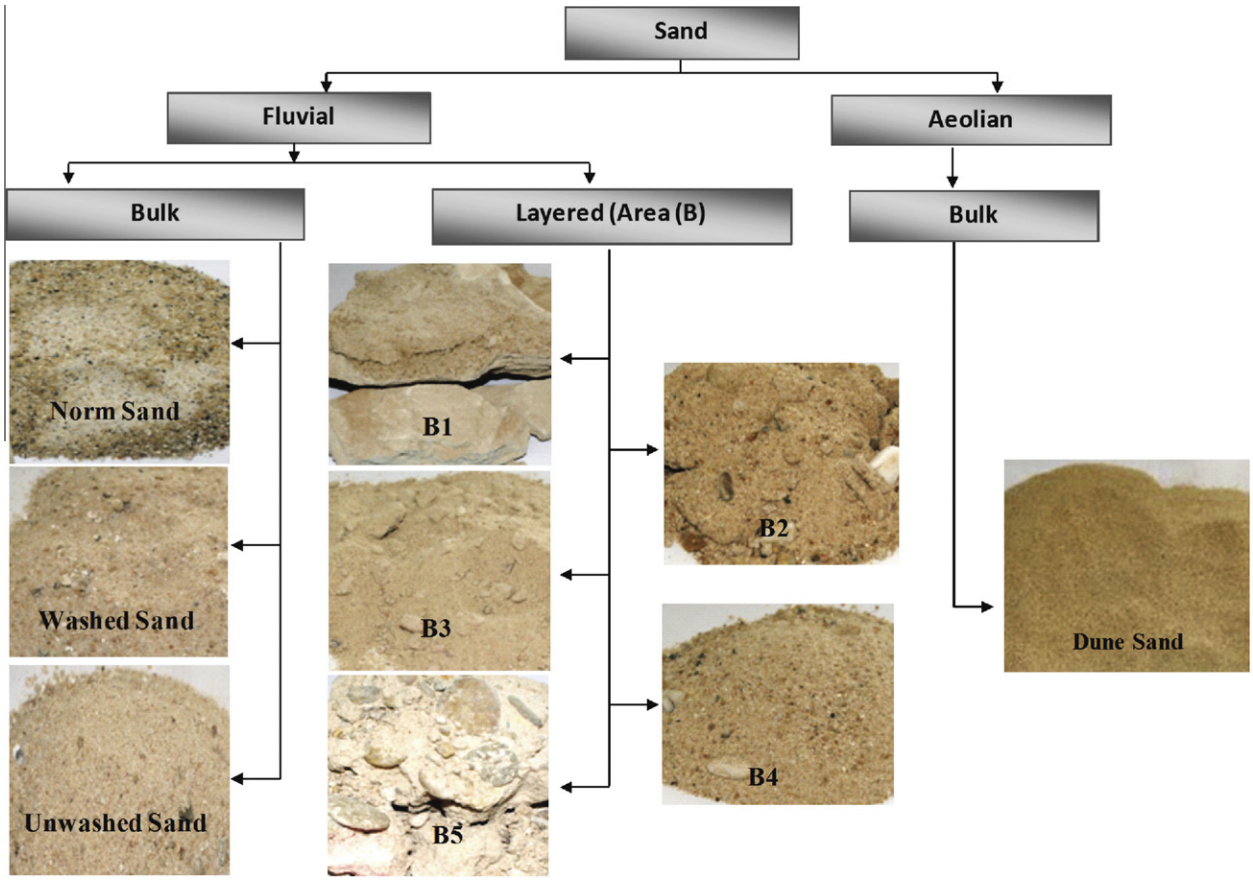

Fig. 3. Sand used in this study.

Fig. 4. QSTP sandpit.

The thickness of the Hofuf formation is typically less than 12 m and has a maximum thickness of 18 m.

Fluvial sand is usually loose to semi-consolidated and ranges in grain size from silt to gravel with pebbles. Cemented streaks, also called duricrusts, are interbedded in between the sand layers. In summary, sediments of Qatar fluvial sand can be comprised of three distinct grain size classes, mainly:

- Gravel intermixed with pebbles.
- Coarse-to fine-grained sand.
- Silt and clay.

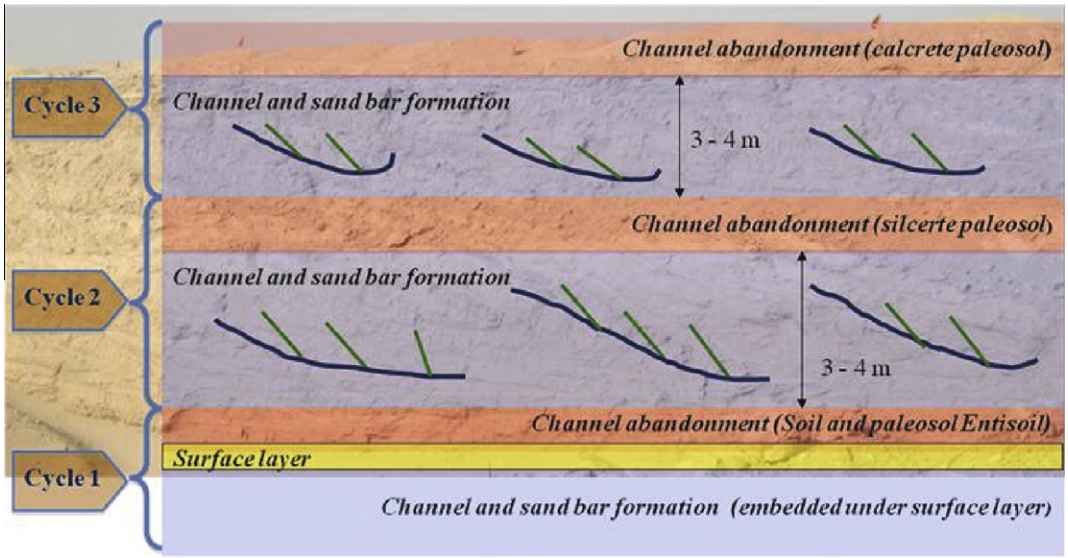

Fig. 5. Geological stratification description of QSTP sandpit.

The investigated (Area B) section of Qatar fluvial sand in the Al-Karanah sand pit is typically comprised of three distinct cycles, which are several meters thick as presented in Fig. 5. Each cycle constitutes an overall fining up geological unit with gravel and pebbles at the base and argillaceous fine sand to silt at the top that is often cemented. The geological stratification of the three distinct cycles can be described as follows:

- *Lower cycle (Cycle 1)* consists of 1 m horizontal bedded to slightly cross-bedded silty sand and fine gravel, with interdispersed clay. This studied sand pit only exposes the uppermost fine-grained part of the lower cycle.
- *Middle cycle (Cycle 2)* is 3–5 m in thickness and consists of trough cross-bedded gravel and sands with set heights of 10–50 cm. The grain size varies from pebbles and stones to coarse gravel at the base to medium sand at the top with upwards increasing silt content. Channel features are visible in the sand pit, 2–5 m wide and 0.5 m thick. Pebbles and coarse gravel occur at the base of each channels. These pebbles consist of polymict clasts, i.e. fossiliferous limestones, sandstones, dolorite and granite. At the top of the middle cycle appears a 0.2 m thick argillaceous, destratified, in places tightly cemented, layer (silcrete). The unit can be interpreted as fluvial sand bar sequence infilling fluvial channels.
- *Upper cycle (Cycle 3)* is 2–3 m in thickness and consists of planar to cross-bedded sands that show an overall fining up trend. Pebbles and coarse gravel appear at the bottom. Planar cross-bedded sand appears in the middle and towards the top. The top is covered by a 20 cm thick silty layer penetrated by fossil rootlets. These dissect the underlying channel sediments up to 40 cm deep and show clear bifurcation. Above this layer a 5–10 cm thick cemented carbonate bed is observed which can be interpreted as calcrete paleosol.

Each of the three cycles exhibits diagnostic features of fluvial deposits as illustrated in Fig. 5, and as follows:

- *Erosive base covered with pebbles and gravel.* This can be interpreted as initial river channels incision, which was formed when the river system was active. Coarse gravels with pebbles and sand are deposited at erosive channel bases.
- *Cross-bedded sand.* This can be interpreted as intermediate filling of river channels with fluvial sand bars.
- *Argillaceous sand, silt (with rootlets).* This can be interpreted as terminal phase, channel abandonment. It occurred when the river channel dried up or shifted laterally. In places vegetation developed, leaving a cemented layer with rootlets behind (paleosoil). Depending on the processes that formed this abandonment layer, paleosoils have different properties.

As previously explained in Section 3.2.3, Area B will be used as a representative section for this study. Fig. 6 shows a representative section of Area B as is typically found in this sand pit. Representative samples from the three geological cycles of Area B were collected and studied. Table 2 summarises the coding system used for the sand samples extracted from Area (B) of the sand pit for laboratory analysis.

As shown from Table 2, Area B has 3 different cycles, of which 5 samples were extracted. From each sample point, three replicate samples were collected for analysis. The different samples can be further described as follows:

- Sample B1: consists of both silty sands with fossil rootlets and sands cemented with clay minerals (entisol paleosol).
- Sample B2: is cross-bedded sand (channel bar) with some sandy gravel (channel base).

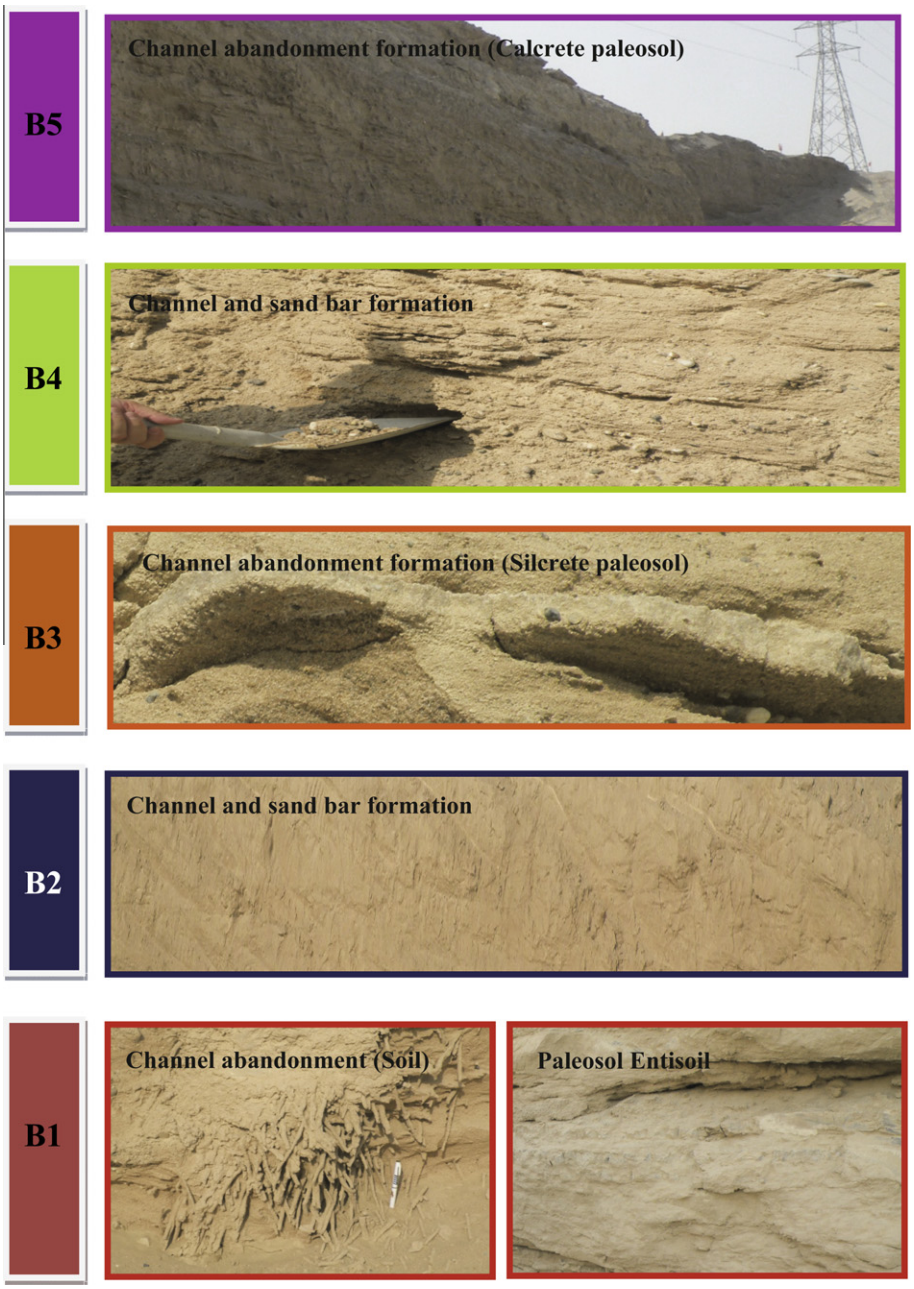

Fig. 6. Pictorial representation of the different layers of Area (B) at QSTP sandpit.

- Sample B3: is sand with some silt and clay cemented with silica (silcrete paleosol).
- Sample B4: is cross-bedded sand (channel bar) with gravel (channel base).
- Sample B5: is a mixture of sand and gravel cemented by calcium carbonate (calcrete paleosol).

The observations from the sand pit highlighted that the geological processes such as channel erosion, channel infill with bars and channel abandonment has controlled the properties of the sands, depending on which part of the fluvial Hofuf Formation has been studied. While cross-bedded sand (channel bars) is rather clean and well sorted, channel abandonment sand contains fines, is less well sorted and cemented in places.

4.3. Qatar aeolian dune sand

Aeolian dune sands are considered the geologically youngest deposits of Qatar, formed during the Holocene onwards (Cavelier, 1973). Fig. 7 presents one of the dune sand deposits in Qatar. Qatar's aeolian sand deposits are shaped by southwards blowing Shamal winds, resulting in well sorted, well rounded sand grains. Source area for the sand is the Gulf region to the north-west of Qatar. Hundred thousand years ago, during a major sea level

Fig. 7. Dune sand deposit at Qatar.

drop, rivers systems covered the area and Shamal winds spread river sands across Qatar (Walkden and Williams, 1998). The subsequent sea level rise shifted rivers northward and the gulf filled with sea water, thus cutting off the sand supply. Subsequently, Shamal winds steadily blow of the sands from Qatar surface (carbonates) into the Gulf in the south-east direction. Last reminders of the previous sand cover are the barchanoid dunes in the south of Qatar, which can be several hundred meters long, few hundred meters wide, and few tens of meters high.

Properties of these dune sands, such as grain size and sorting, change from dune base to dune crest. Typically, sand at the dune crest tends to be cleaner with little fines and better sorting. Sand at the base of a dune contains a higher percentage of fines (including carbonate grains from the underlying carbonate beds and gypsum) and is in places less well sorted. The floor of the dunes is within the tidal range covered by Sabkha deposits (Cavelier, 1973). Sabkhas are impervious, poorly cemented flat area between arid regions and the sea and usually contains deposits such as salt, sulphates (e.g. gypsum/calcium sulphates and magnesium sulphates), and carbonates (e.g. shell fragments).

5. Experimental results and discussions

5.1. Physical and chemical properties

Table 3 presents the results of physical and chemical properties required by QCS (2007). Analyses were specifically conducted for this study by one of the local construction materials quality control laboratories, Arab Centre for Engineering Studies (ACES, 2009). Table 4 presents average values of physical and chemical characterisation properties. Fig. 8 presents particle size distribution for all the different sand samples in this study in comparison to the lower and upper limit specified by QCS (2007). Percentages by weight of gravel, sand, silt and clay were calculated by weight in accordance to USCS and presented in Figs. 9 and 10.

From the results of the physical and chemical properties as stipulated by QCS (2007) as well as for characterisation proposes, the following can be observed:

- Norm European sand has a wide particle size distribution that perfectly fits within the upper and lower limits stipulated by QCS (2007) and classified under USCS (ASTM D2487, 2011) as well graded. In contrast, Qatar sand samples display lower coefficient of uniformity (C_u) and are classified as poorly graded and very uniform soil; apart from B5 which is gap graded with the largest median diameter (D_{50}) of 1.0 mm (medium sand).
- Washed and unwashed fluvial sand had an identical particle size distribution curves that fit within the upper and lower limit curves stipulated by QCS (2007). This is also reflected in similar particle size parameters (i.e. D_{50}, C_u, and C_z) for both types of sand, which is expected as the washing processing would not expect to alter the size distribution.
- Aeolian dune sand was the finest bulk sand with a median diameter (D_{50}) of 0.25 mm (fine sand) and grading curve that is outside the lower limit stipulated by QCS (2007).
- Layered sand samples from Area B extracted from channel and sand bar formation (B2 and B4) has identical particle size distribution curves as well as parameters to those of washed sand. The particle size distribution curves of B2 and B4 also fit within the upper and lower limit curves stipulated by QCS (2007).
- Layered sand samples from abandonment formation (B1, B3 and B5) had different gradations than that of washed sand. Although B1 is consolidated and agglomerated, the particle size of the individual particles has a wide range of particles but mostly finer than the upper limit of QCS (2007). Sand sample B3 was also finer in gradation than that upper limit of QCS (2007); while B5 has the largest percentage of gravel and thus contains coarser fractions of sand than that of lower limit of QCS (2007).
- All sand samples were within the maximum QCS (2007) permissible limit for material finer than 75 microns of 3% apart from B1 (paleosol). However, sand samples B1, B3 and B5 have materials finer than 75 microns (i.e. silt and clay percentages) of more than 0.4%. Thus, soil fractions finer than 75 microns were further analysed, by a laser diffraction particle size analyser, to determine the individual percentages by volume of silt and clay of these samples. In samples B1 and B3, the clay percentage by volume was very low in comparison to silt content which ranged between 2–4%. B5 had relatively higher clay content by volume in comparison to silt percentage of 12%. However, in comparison to the total particle size distribution of the soil, the clay content only amounted to approximately 0.9%.

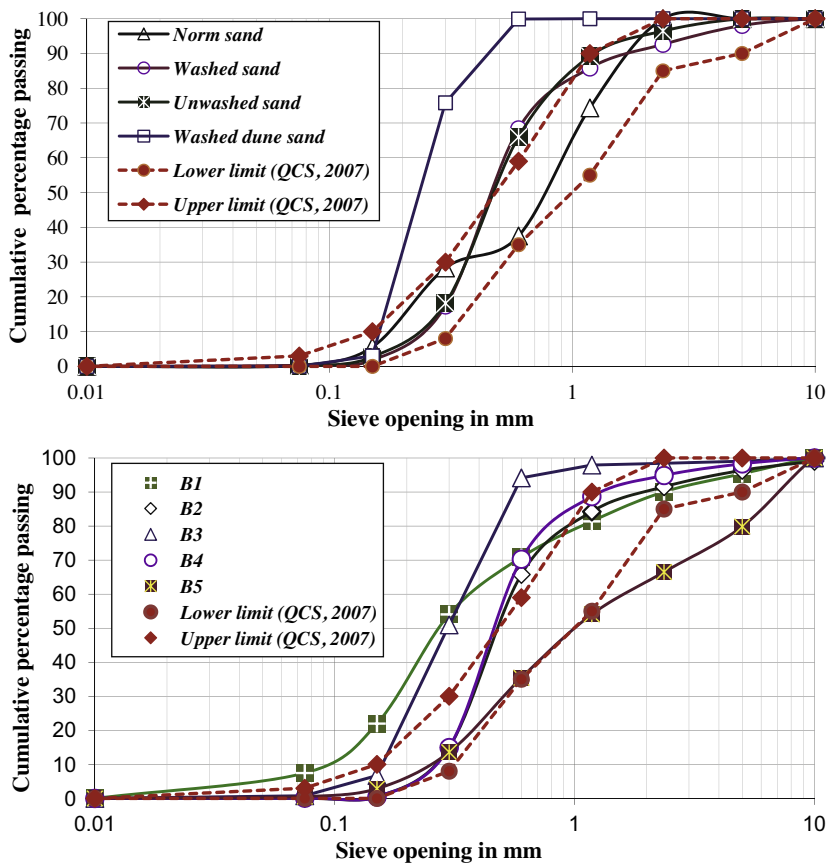

Fig. 8. Particle size distribution for bulk and sand samples from Area (B).

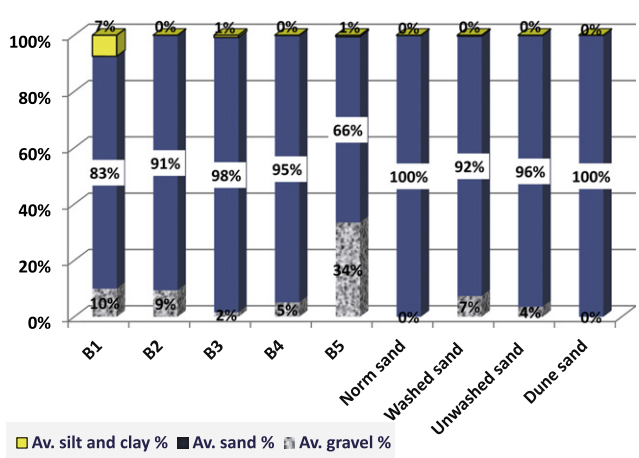

Fig. 9. Percentage gravel, sand, silt and clay for all sand types.

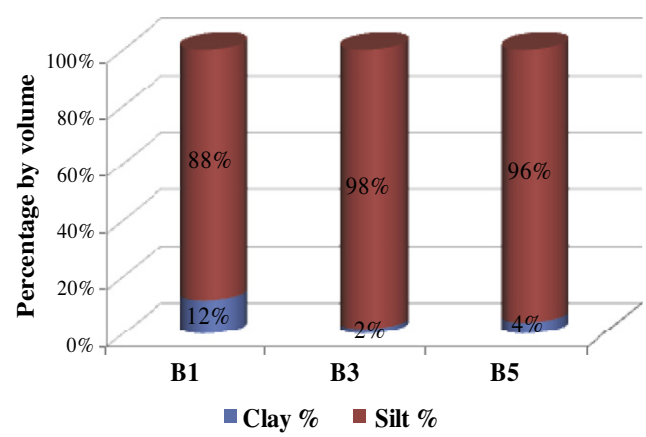

Fig. 10. Silt and clay percentages by volume of sand samples B1, B3 and B5.

- Water absorption of sand samples was below the maximum stipulated value of 2.0% as per QCS, 2007 requirements. However, surprisingly the washed Qatar sand displayed the highest water absorption of 1.7%. Dune sand displayed the lowest water absorption value (0.5%) which is similar to that of the Norm sand (0.55%) and 3 times lower than that of washed and unwashed fluvial sand.
- Porosity of fluvial sand is significantly higher than that of the Norm sand and aeolian dune sand, which has also been reflected in the water absorption results. Dune sand porosity is much lower than that of Norm sand.
- It is shown from the data that there is a direct positive relationship between the water absorption value and the porosity percentages of all investigated sands.
- Porosity of layered sand is significantly high especially for B3 and B5 (paleosol abandonment layer) which justifies their high water absorption.
- All samples had similar apparent specific gravity which was slightly higher than the minimum specified value

of QCS (2007), apart from B1 which was slightly lower than the 2.6 minimum values.

- For all investigated sand samples, the parameters of clay lumps and friable particles, lightweight pieces, shell content and soundness by loss of magnesium sulphate and organic impurities were lower than the maximum permissible limits stated by QCS (2007) (see Table 3).
- Although, most studied sand samples had acid soluble chlorides percentages lower than the maximum permissible limits for reinforced concrete and mass concrete, only samples B2 and B3 had acid soluble chloride percentages higher than maximum permissible limits for pre-stressed and steam cured concrete (see Table 3).
- Most investigated sand samples had acid soluble sulphates values lower than the maximum permissible limits apart from B1 and unwashed fluvial sand. This indicates that the washing process could successfully remove some percentage of acid soluble sulphates; even though the sulphate content of washed fluvial sand was almost at the maximum permissible limit value.
- The bulk density values of all sands are higher than that of the layered sands. In addition, the inter-aggregate voids of all sands are lower than that of layered sand. It is also shown that there is an inverse relationship between the bulk density and inter-aggregate voids ratio, which is consistent with findings of Lamond and Pielert (2006).
- Carbonate content was very high in all sand samples apart from Norm sand.
- The pH of all Qatar sand samples, whether bulk or layered, ranged between 8.06 and 8.72, which indicate slightly higher alkalinity in these sands, in comparison with pH of Norm sand which was 7.75.

5.2. Microstructure analysis

5.2.1. Thin sections descriptions

Thin sections for all sand samples investigated in this study for grains are presented in Fig. 11. Fig. 12 is a semi-quantitative comparison, based on analysis of thin sections, between the different studied sand compositions. It was observed that most of Qatar sand consists of carbonates (limestone/calcite or dolomite), silicates (quartz or feldspar (orthoclase or plagioclase)), and rock fragments sandstones (such as quartzites). The following sub-sections details the observed characteristics for each sand sample in thin sections.

5.2.1.1. European Norm sand. Grain size ranges from fine to coarse sand, with a wide range in grain sizes as shown in Fig. 11(a) and consistent with the particle size distribution results. Grains are angular to sub-angular. Norm sand consists almost exclusively of chemically stable grains such as quartz (99% of composition). The quartz grains appear to be mostly of volcanic origin, with some metamorphic and few chert fragments (i.e. sedimentary rock material) present. There are also traces of mica, rock/lithic fragments (such as sandstones and gneiss) and heavy minerals. No feldspars grains were observed in the samples analysed.

5.2.1.2. Qatar washed fluvial sand. Grain size ranges from medium to coarse sand as shown in Fig. 11(b) and consistent with the particle size distribution results seen in Fig. 8. Grains are poorly sorted and range from angular to well rounded particles. The sample can be classified as rounded to sub-angular medium sand. The sample consists of 50–60% quartz grains, some are of volcanic origin, and others are of metamorphic origin. There are about 10% feldspar grains of which most consist of orthoclase; some plagioclase is observed. Feldspars are partly weathered and converted to clay minerals.

Qatar fluvial washed sand also contains 30% rock fragments and as such is petrographically a lith-arenite. Rock fragments consist of sandstones (quartzites), carbonates (fossiliferous limestone and crystalline dolomite) and volcanic grains. Traces of mica, mostly muscovite are observed. Heavy mineral constitute less than 1% of all grains. Also observed are tourmaline, epidote and most commonly zircon.

5.2.1.3. Qatar unwashed fluvial sand. The sample consists of fine sand to fine gravel as shown in Fig. 11(c). The shape ranges from angular to well rounded grains. The grains consist of 70% quartz (volcanic and metamorphic), 10% limestone, 10% feldspar (mostly orthoclase, less plagioclase), and minor lithic fragments such as garnet shists. Traces of heavy minerals, such as epidote and tourmaline, are present; in addition to some percentages of mica.

5.2.1.4. Qatar layered fluvial sand. Layered samples from Area B, as in Fig. 11(e–i), typically consist of fine sand to fine gravel with angular to well rounded grains. The lithology is similar to that of Qatar fluvial sand. The grains consist of 70% quartz (volcanic and metamorphic), 10% limestone, 10% feldspar (mostly orthoclase, less plagioclase), minor lithic fragments, such as garnet shists. The presence of some mica and traces of heavy minerals such as epidote and tourmaline is observed.

5.2.1.5. Qatar aeolian dune sand. The sample consists of yellowish sand and appears macroscopically dull as shown in Fig. 11(d). Grain diameters range from fine to medium sand size. The aeolian sand is well sorted, consisting of single uniform size, with sub-angular to well rounded grains. The sample is virtually free of fines. Mineralogically, Qatar aeolian dune sand consists of 55–60% quartz (mostly of volcanic but also some of metamorphic origin), 5–10% lithic fragments (mostly sandstone fragments, few volcanic fragments), 30–35% carbonates (such as fossiliferous limestone components such as shells, preserved ooids, bivalves, green algae, foraminifera, echinoids suggest its origin at a modern Sabkha). There are a few feld-

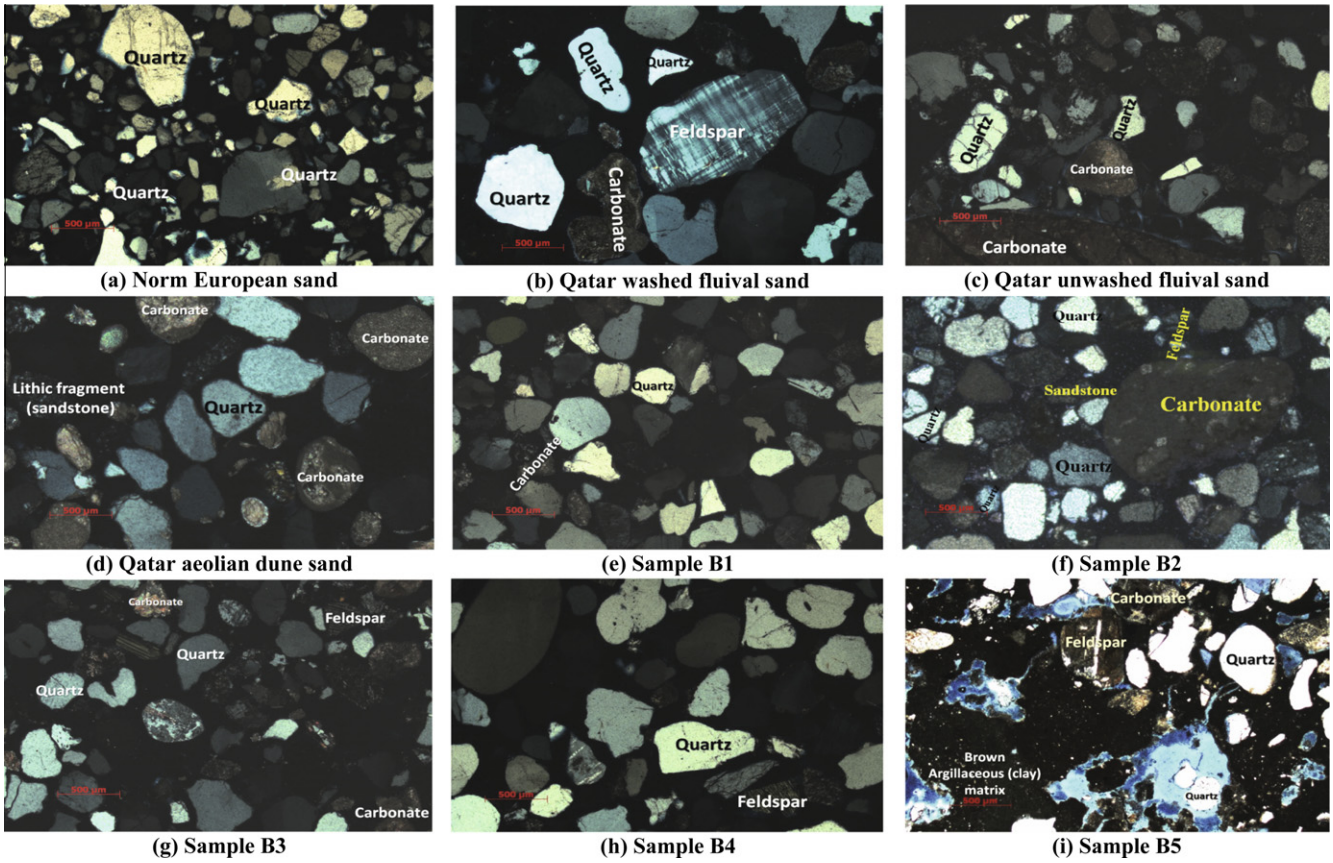

Fig. 11. Thin sections of studied sand.

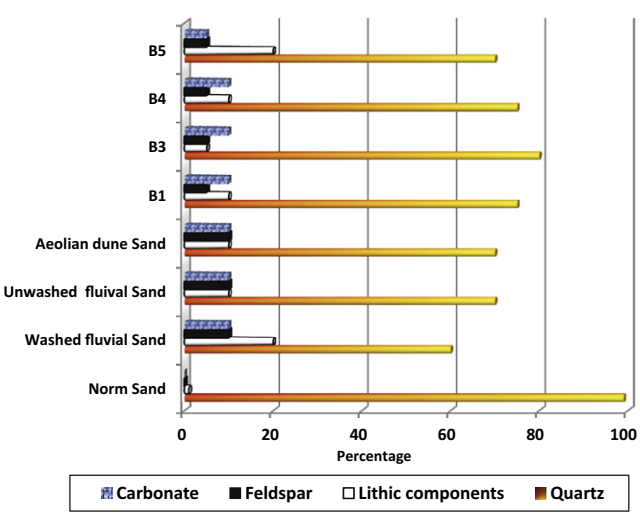

Fig. 12. Semi-quantitative estimate of different sands compositions based on thin sections study.

spar grains (mostly orthoclase, some plagioclase) observed. Some grains show weak weathering, thus clay mineral might by present (partly seriscitic). Traces of heavy minerals (such as epidote, zircon, hornblende, as well as ilmenite, magnetite) are present. Many grains show microscopic 'dust rimn' which commonly consist of iron-oxides.

5.2.2. Scanning electron microscopy (SEM)

Scanning Electron Microscopy was employed to study the differences in the surface morphology of all the bulk and layered fluvial and aeolian samples. The magnifications ranged between 30 to 6000 times for the representative fraction (D_{50}) of sand sample so as to differentiate from the thin sections images of the overall particle size distribution of sand grains observed at 10 times magnifications. This section thus delineates and discusses the various observations made.

Fig. 13(a–d) depicts the secondary electron images for the representative bulk sand samples. Fig. 13(a) shows the surface structure for the European Norm sand samples, which has a dense and clear microstructure, nearly devoid of any form of deposits. This dense structure could be attributed primarily to the pure silica (quartz) composition of this sand. Washing the sands had a conspicuous effect on the observed microstructure. This can be seen in Fig. 13(b) depicting the unwashed sand wherein the surface appears to be covered by argillaceous and clayey fines whilst, after subjecting to washing clearly reveals the distinct calcite (calcium carbonate) crystals as observed in Fig. 13(c). Fig. 13(d) depicts the microstructure of dune sand seen which appears to be clean with minimal fines.

Fig. 14(a–e) depicts the secondary electron images for the representative sand layers from QSTP sand pit. The representative fraction (i.e. D_{50}) of the soil sampled from

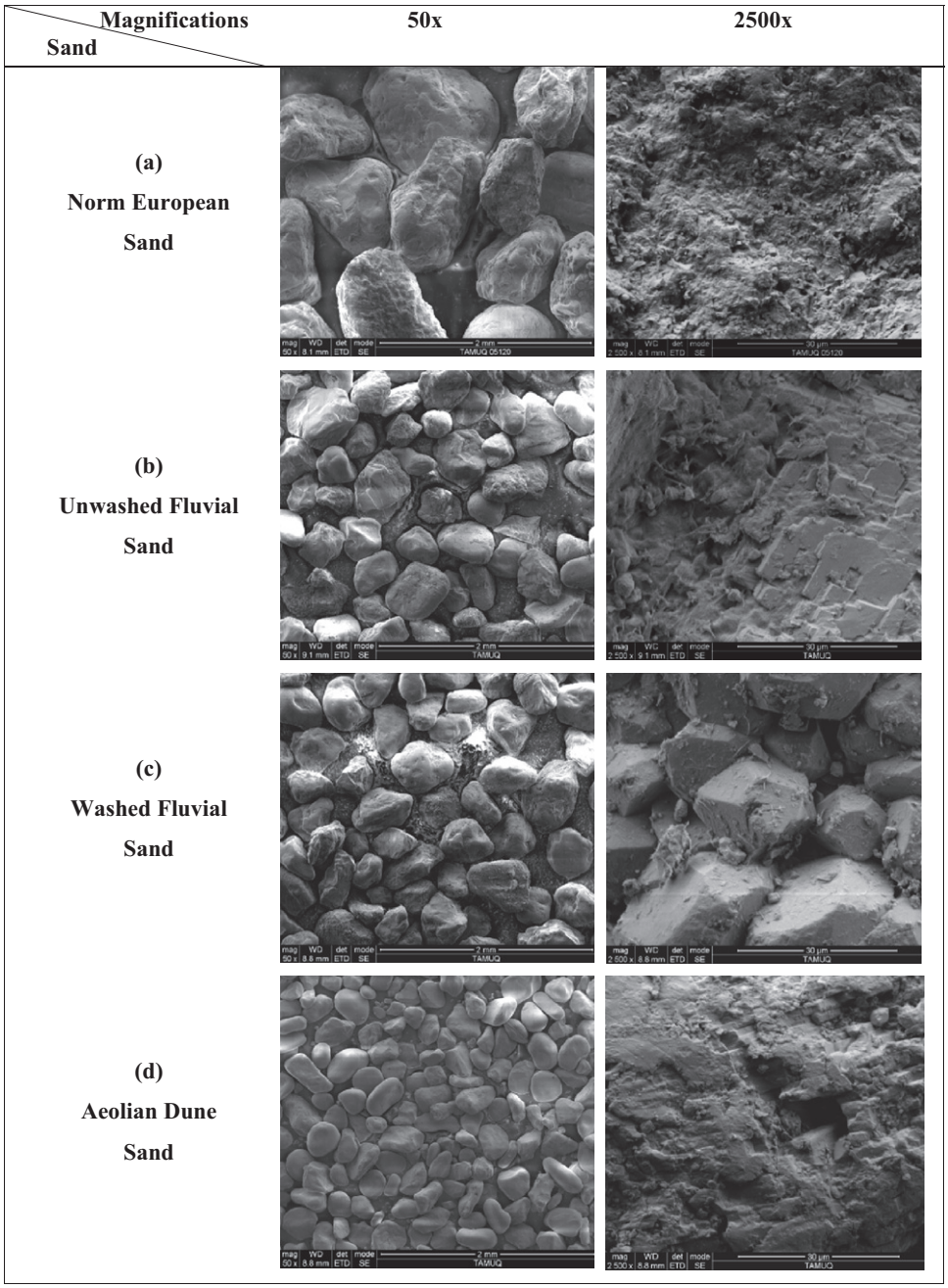

Fig. 13. Typical SEM micrographs of bulk sand samples at two different magnifications.

different cycles was analysed and the same have been presented in Fig. 14. At lower magnifications, all the sand samples appeared to be made up of angular to well rounded grains, which is in agreement to what has been previously reported in their thin section analysis. Some of the salient differences observed in the surface morphological characteristics at the different zones have been highlighted as follows:

- B1 (Fig. 14a): Surface covered with a fabric of elongated lath-like crystals typical to clays such as palygorskite.
- B2 (Fig. 14b): Crystals of calcite cemented by fines evident, similar to the morphology of washed Qatar sand.
- B3 (Fig. 14c): Surface covered with a network of bundled elongated crystals typical to clays such as palygorskite.
- B4 (Fig. 14d): Cleaner surface with minimal fines depositions and evidence of horizontally striated quartz crystals, similar to the morphology of Norm sand.
- B5 (Fig. 14e): Heavy fines deposition in the form of palygorskite interlaced fibers is depicted, which is consistent with the observations from thin section images.

5.2.3. X-ray powder diffraction (XRD)

The XRD technique was employed on all Qatari fluvial and aeolian sand samples as well as the European Norm

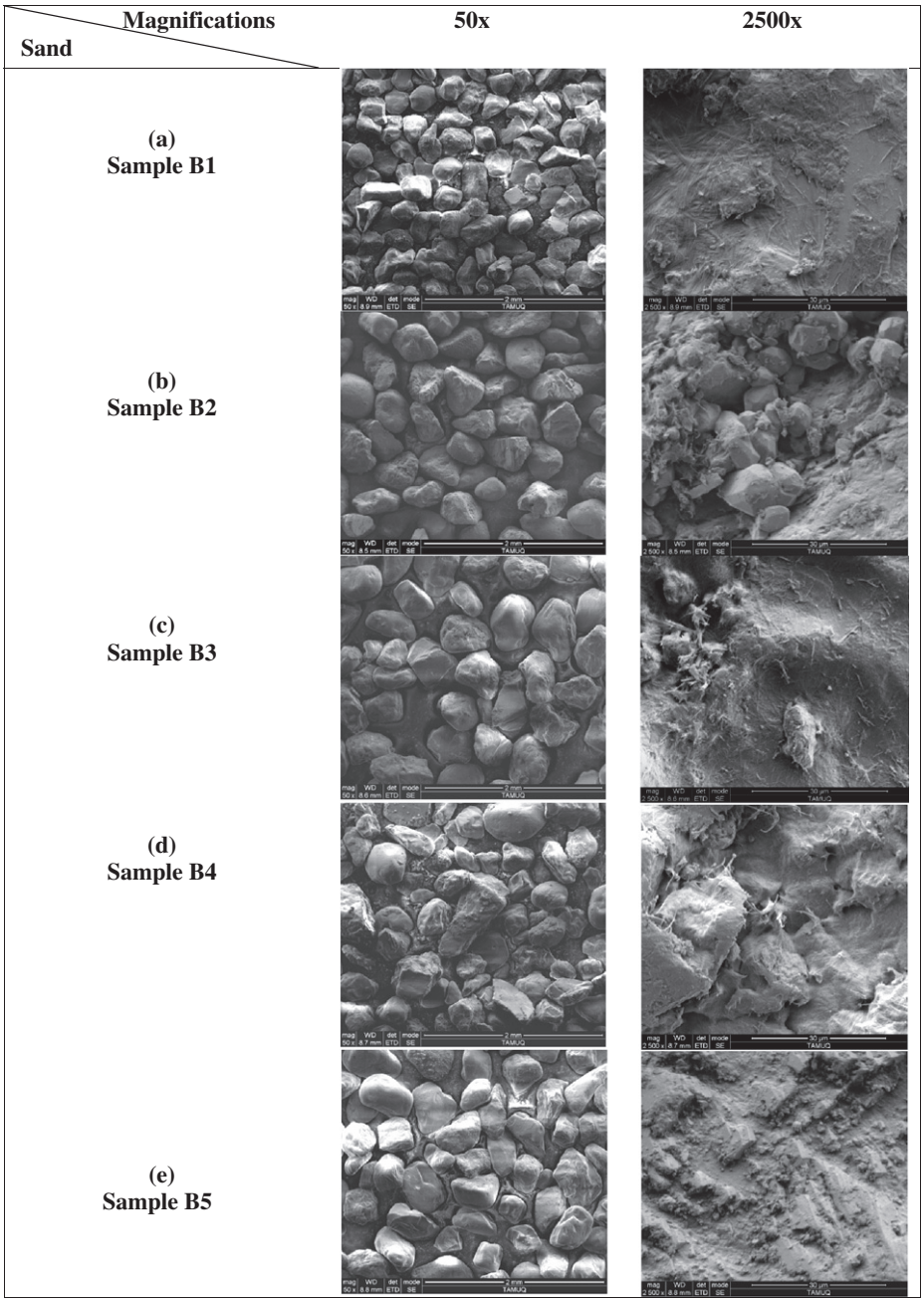

Fig. 14. Typical SEM micrographs of sand samples from QSTP Sand Pit at two different magnifications.

sand samples to identify the different mineral phases present. These results are discussed in context with the coarse and fine fractions as detailed previously in Section 3.2.2. The abbreviations that have been adopted for representing the major phases present in the mixes are summarised in Table 5. Quartz, calcite and gypsum peaks, attributed to the sand in these samples, were prominent in all the tested Qatar sand samples. This is in agreement with the findings of the chemical characterisation results as well as those of thin section for these samples.

Fig. 15 depicts the X-ray diffractograms for the bulk sand samples (both coarse and fine). Peaks of calcite, quartz and gypsum were prominent in all the mixes which are the principal phases present in such representative Qatari bulk sands and this agrees well with the reported literature for Qatar soils (Al-Saad, 2005). Sieving through

Table 5
Abbreviations employed for the major phases detected in XRD analysis.

Abbreviation used	Chemical phase represented	Chemical formula
c	Calcite (calcium carbonate)	$CaCO_3$
q	quartz	SiO_2
g	gypsum	$CaSO_4{\cdot}2H_2O$
p	palygorskite clay	$Mg_5(Si,Al)_8O_{20}(OH)_2{\cdot}8H_2O$

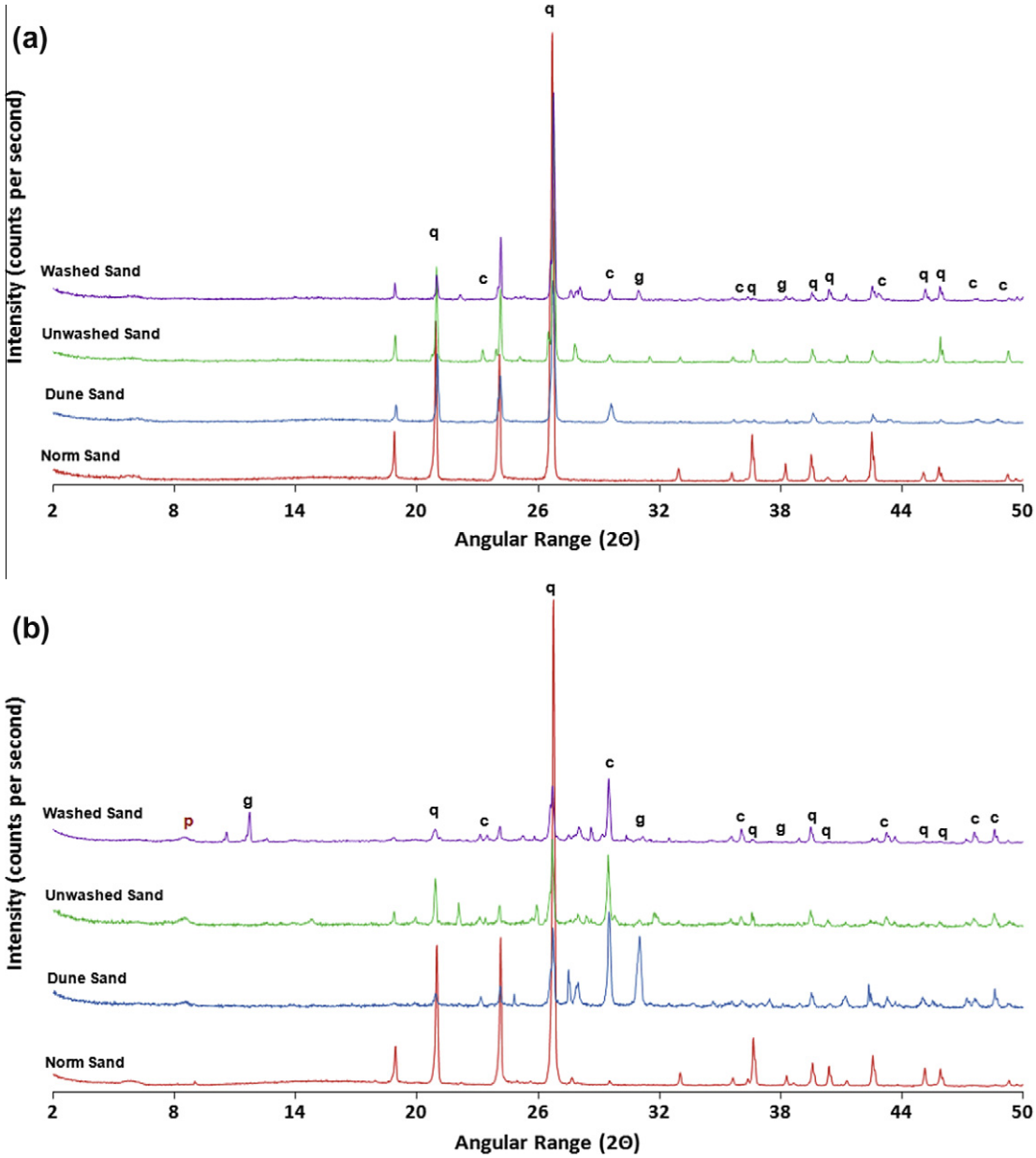

Fig. 15. X-ray diffractograms for the bulk sand samples (a) coarse and (b) fine fractions.

Table 6
Qualitative analysis of coarse fractions of Qatari sands.

Mineral/phase	Notation	Chemical representation	Relative % composition of sample			
			Norm sand	Washed fluvial sand	Unwashed fluvial sand	Aeolian dune sand
Quartz	q	SiO_2	100. 00	79.64	67.66	84.45
Gypsum	g	$CaSO_4{\cdot}2H_2O$	–	10.61	30.21	7.71
Calcite	c	$CaCO_3$	–	9.75	2.13	7.84

75 microns was observed to minimise the interference posed by large quartz peaks and further revealed peaks at 8.16° indicating palygorskite clay. The presence of palygorskite clay identified concords with geological studies undertaken by Holail and Al-Hajari (1997) on middle Eocene carbonate sequence obtained from Ras Laffan area in North Qatar wherein it was reported that clay minerals contained were mainly palygorskites.

Tables 6 and 7 give an approximate qualitative distribution of the various phases of coarse and fine fractions, respectively, of various bulk sand, viz. European Norm, and Qatar fluvial and aeolian sands. Moreover, it is

Table 7
Qualitative analysis of fine fractions of Qatari sands.

Mineral/phase	Notation	Chemical representation	Relative % composition of sample			
			Norm sand	Washed fluvial sand	Unwashed fluvial sand	Aeolian dune Sand
Quartz	q	SiO_2	100.00	30.24	36.88	24.25
Gypsum	g	$CaSO_4{\cdot}2H_2O$	–	7.03	9.26	15.35
Calcite	c	$CaCO_3$	–	53.96	28.05	26.54
Palygorskite	p	$Mg_5(Si,Al)_8O_{20}(OH)_2{\cdot}8H_2O$	–	8.77	25.81	33.86

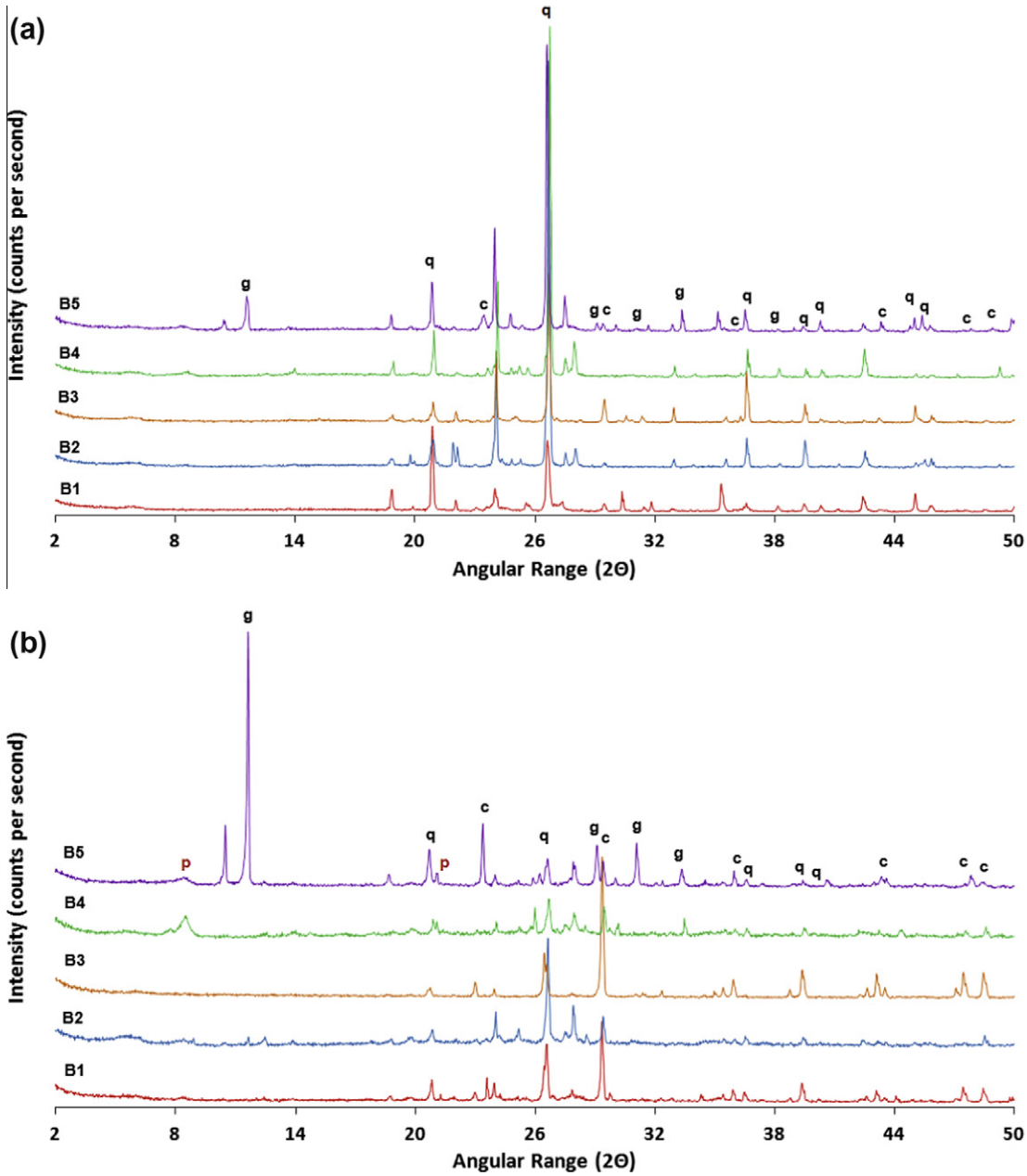

Fig. 16. X-ray diffractograms for sand samples from QSTP sand pit (a) coarse and (b) fine fractions.

observed that the presence of these clay minerals were conspicuous in both the fluvial as well as the aeolian samples. Apart from these, the diffractograms of the bulk sands were more or less similar. The Norm sand samples were almost exclusively composed of quartz and even after sieving (i.e. fine fraction) no presence of clays were detected. This agrees well with the earlier stated description of such control sands in Sections 3.2.1 and 4.1.

Table 8
Qualitative analysis of coarse fractions of the QSTP sand pit samples.

Mineral/phase	Notation	Chemical representation	Relative % composition of sample				
			B1	B2	B3	B4	B5
Quartz	q	SiO_2	84.84	97.02	85.25	96.77	92.47
Gypsum	g	$CaSO_4{\cdot}2H_2O$	–	–	–	3.23	6.15
Calcite	c	$CaCO_3$	15.06	2.98	14.75	–	1.38

Table 9
Qualitative analysis of fine fractions of the QSTP sand pit samples.

Mineral/phase	Notation	Chemical representation	Relative % composition of sample				
			B1	B2	B3	B4	B5
Quartz	q	SiO_2	66.98	70.08	18.41	42.37	17.18
Gypsum	g	$CaSO_4{\cdot}2H_2O$	–	5.68	5.15	–	57.48
Calcite	c	$CaCO_3$	21.49	17.50	76.44	32.95	16.28
Palygorskite	p	$Mg_5(Si,Al)_8O_{20}(OH)_2{\cdot}8H_2O$	11.53	6.74	–	24.68	9.09

The coarse fraction of the sand sampled from the aforementioned different zone depths was analysed and the same have been presented in Fig. 16(a). Table 8 gives an approximate qualitative distribution of the various phases determined for each zone. It is evident from the diffractograms as well as the qualitative analysis that all the sands have very high quartz content. This is not surprising as similar observations were made and reported in the thin section analysis. As moving away from the surface (i.e. B5) towards greater depths (i.e. B1), the gypsum content decreases. Calcite peaks however, do not follow such trends. A small bump in the diffractograms was observed for some of the samples in the range between 3° and 10° (2Θ) which indicated the possibility of the presence of clay minerals. Hence, fine sieving was conducted to minimise the interference due to quartz peak and subsequently enhance the peaks of clay minerals if any.

The fines of the soil sampled from the different zone depths were analysed and the same have been presented in Fig. 16(b). Table 9 gives an approximate qualitative distribution of the various phases determined. Fine sieving was able to reduce the suppression of the clay mineral peaks due to the large intensity quartz peaks; although fine quartz was still present. The clay mineral in the samples was interpreted as Palygorskite. Despite the fact that, the outcome of the qualitative analysis cannot be used as absolute values, it still gives a good indication that sufficient amounts of clay minerals could be present at various zone depths.

6. Salient findings

The dearth occurrence of the naturally occurring sands in Qatar, i.e. fluvial and aeolian dune sands, stresses the need for a quality management of these reservoirs in a scientific manner rather than a pragmatic one to sustain its availability for a maximum period of time. These two types of sands are the only certified sands by the State of Qatar to be used in concrete and mortar applications at present, respectively. The work presented in this paper provides a comprehensive comparative assessment of the various types of sands available in Qatar in terms of their intrinsic properties per se as well as their effectiveness for various local construction applications. Commercial bulk sands, as well as layered fluvial sands mined from one of the natural deposits south of Qatar, were studied and their results were compared to the Standard European fluvial Norm sand. Results show striking differences in the geological characteristics, physical and chemical properties and microstructure traits between fluvial and aeolian sands as being summarised below.

6.1. From the geological characterisation the following conclusions can be deducted

- The QSTP sand pit gave a good insight of the various geological cycles deposited in the region, which have led to characteristic properties of fluvial deposition. The various probable processes responsible for the different layers were identified.
- Qatar fluvial sand is part of Hofuf Formation and has similar geological origin to European Norm sand. It is composed from different grain sizes, ranging from silt to pebbles and has been shaped by ancient river processes. It consists of quartz, some carbonates, and lithic components and has angular grains.
- Qatar fluvial sand deposits consist of different geological cycles. Each cycle is made up of channel and sand bar layer as well as abandonment paleosol layer. While cross-bedded sand (channel bars) are dominated by sand and are rather clean and well sorted; channel abandonment sand contains fines, has high percentage of argillaceous material and is less well sorted and cemented in places.

- Qatar aeolian dune sands geologically the youngest deposits in Qatar, which has been shaped by Shamal winds resulting in well rounded grains.

6.2. From the physical and chemical analyses the following conclusions can be deducted

- All the commercial bulk sands (viz. washed fluvial and dune sand) in Qatar that are used in concrete and mortar applications have passed the physical and chemical properties requirement stipulated by Qatar Construction Standard (2007). Namely; grading, material finer than 75 microns, clay lumps and friable particles, lightweight pieces, water absorption, apparent specific gravity, shell content, organic impurities, acid soluble chlorides, acid soluble sulphates and soundness by loss of magnesium sulphate. However, both the acid soluble chlorides for pre-stressed and steam curing concrete as well as acid soluble sulphates percentages of Qatari construction sand was very close to the maximum permissible limit.
- On the other hand, some of the layered sand and unwashed sand does not comply with all the requirements stipulated by QCS (2007), such as B1 sample which failed the maximum limits for materials finer than 75 microns; B1 and unwashed Qatar sand which failed the maximum limits of acid soluble sulphates percentage and B2 and B3 which failed the maximum limits of acid soluble chloride to be used in pre-stressed and steam cured concrete.
- Some of the layered fluvial sand showed higher chlorides and sulphates contents. Thus washing of construction bulk sand at the sand treatment facilities is required to reduce the acid soluble chlorides and sulphates that are deleterious to concrete especially for the steel reinforcement. However, unwashed dune sand has low concentrations of both acid soluble chlorides and sulphates; in addition it is only used for mortar applications, that could explain the non processing/washing of dune sand in Qatar.
- All Qatar sand is slightly alkaline in comparison to Norm European sand. Carbonate content of dune sand was significantly higher than that of all other fluvial sands. The bulk density values of all the bulk fluvial sands are higher than that of the layered fluvial sands. In addition, the inter-aggregates voids of all bulk fluvial sands are lower than that of layered fluvial sand. It is also shown that there is an inverse relationship between the bulk density and inter-aggregate voids ratio.

6.3. From the microstructure analysis the following conclusions can be deducted

- While sand of fluvial origin is rather angular and has a wide grain size distribution, the aeolian sand is rounded, has a narrow grain size spectrum and very well sorted.
- Fluvial sands have more unstable minerals such as carbonates in form of limestone and, consist of up to 10% of weathered feldspar that may be converted to clay minerals that is usually deleterious to concrete.
- Aeolian dune sands in contrast, are composed of a high percentage of very stable quartz but also contain a high percentage of unstable carbonates in form of limestone grains.
- Some fluvial deposits are dominated by coarse grained sediments, i.e. gravel and sand; while other fluvial deposits are dominated by sand containing silt and clay (i.e. argillaceous material).
- Presence of palygorskite clay mineral and gypsum was evident in both fluvial and aeolian sands.

7. Conclusions

1. In conclusion, Qatar sands (both fluvial sand and aeolian sand) contain chemically unstable carbonates grains with traces of clay minerals in virtually all samples, which is strong contrast different than European Norm fluvial sand which effectively consists of 100% quartz.
2. It is recommended to use selective mining to differentiate sands of different qualities. Some layers have clearly a better quality than others. Thus, for fluvial sand, it is recommended to mine from channel and sand bar layer and to avoid abandonment paleosol layers. For dune aeolian sand, selective mining from top layers of deposits and avoiding base layers which is close to the carbonate and gypsum rich surface deposits is recommended. The presence of such carbonates (e.g. calcium carbonate) and sulphates (e.g. gypsum and magnesium sulphates) components is deleterious to concrete and mortars. Therefore, selective mining may help in upgrading the quality of sand used in Qatar's construction whether in concrete or mortar applications.

Acknowledgments

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References

AASHTO, 2004. T265 – Laboratory Determination of Moisture of Soils. American Association of State Highway and Transportation Officials, USA.

ACES, 2009. Shell Report. Arab Consultants Engineering Service Report, Doha, Qatar.

Al-Khatib, K., 2009. Qatari construction industry including supply. In: The 7th Conference on the Markets, Trade, Transportation and Handling of cement in the MENA region (Intercem), January 2009, Doha, Qatar.

Al-Saad, H., 2005. Lithostratigraphy of the Middle Eocene Dammam Formation in Qatar, Arabian Gulf: Effects of sea-level fluctuations along a tidal environment. Journal of Asian Earth Sciences 25 (5), 781–789.

Al-Saad, H., Nasir, H., Sadooni, F., 2002. Stratigraphy and sedimentology of the Hofuf Formation in the State of Qatar in relation to the tectonic evolution of the Eastern Arabian Block. Neues Jahrbuch fur Geologie und Palaeontologie Monatshefte 7, 426–448.

ASTM, 2004. C40 – Standard Test Method for Organic Impurities in Fine Aggregates for Concrete. American Society for Testing and Materials, USA.

ASTM, 2005, C586 – Standard Test Method for Potential Alkali Reactivity of Carbonate Rocks as Concrete Aggregates (Rock Cylinder Method). American Society for Testing and Materials, USA.

ASTM, 2005. C88 – Standard Test Method for Soundness of Aggregates by Use of Sodium Sulfate or Magnesium Sulfate. American Society for Testing and Materials, USA.

ASTM, 2007. C128 – Standard Test Method for Density, Relative Density (Specific Gravity), and Absorption of Fine Aggregate. American Society for Testing and Materials, USA.

ASTM, 2007. C289 – Standard Test Method for Potential Alkali Silica Reactivity of Aggregates (Chemical Method). American Society for Testing and Materials, USA.

ASTM, 2007. D4972-01 – Standard Test Method for pH of Soils. American Society for Testing and Materials, USA.

ASTM, 2004. C123 – Standard Test Method for Lightweight Particles in Aggregate. American Society for Testing and Materials, USA.

ASTM, 2010. C142 – Standard Test Method for Clay Lumps and Friable Particles in Aggregates. American Society for Testing and Materials, USA.

ASTM, 2010. C227 – Standard Test Method for Potential Alkali Reactivity of Cement-Aggregate Combinations (Mortar-Bar Method). American Society for Testing and Materials, USA.

ASTM, 2011. D2487 – Standard Practice for Classification of Soils for Engineering Purposes (Unified Soil Classification System). American Society for Testing and Materials, USA.

BSI, 1985. BS 812-103.1: Testing aggregates. Method for Determination of Particle Size Distribution. Sieve Tests, British Standards Institution, London, UK.

BSI, 1985. BS 812-106: Testing aggregates. Method for Determination of Shell Content in Coarse Aggregate. British Standards Institution, London, UK.

BSI, 1988. BS 812-117: Testing aggregates. Method for Determination of Water-Soluble Chloride Salts. British Standards Institution, London, UK.

BSI, 1988. BS 812-118: Testing aggregates. Method for Determination of Sulphate Content. British Standards Institution, London, UK.

BSI, 1989. BS 812-103.2: Testing aggregates. Method for Determination of Particle Size Distribution. Sedimentation Test. British Standards Institution, London, UK.

BSI, 1990. BS 1337-3: Methods of test for soils for civil engineering purposes. Chemical and Electro-Chemical Tests. British Standards Institution, London, UK.

BSI, 1995. BS 812-2: Testing aggregates. Methods for Determination of Density. British Standards Institution, London, UK.

BSI, 1998. BS 1097-3: Tests for mechanical and physical properties of aggregates. Determination of Loose Bulk Density and Voids. British Standards Institution, London, UK.

Cavelier, C., 1973. Geological description of the Qatar Peninsula (Arabian Gulf). Publication of the Government of Qatar, Department of Petroleum Affairs, p. 39.

CEN, 2009. EN 196-1: Sand for Strength Measurements. European Committee for Standardization, Brussels, Belgium.

Holail, H., Al-Hajari, S., 1997. Evidence of an authigenic origin for the palygorskite in a Middle Eocene carbonate sequence from North Qatar. Qatar University Science Journal 17 (2), 405–418.

Hussain, M., Al-Khalefah, F., Raza, M.J., 2001. Geology of Jabal Al-Qarah caves, Al-Hassa, Northeast Saudi Arabia. In: Proceedings, First Saudi Science Conference.

IMF, 2011. Data refer to the year 2010. World Economic Outlook Database-April 2011, International Monetary Fund. [Accessed April 11, 2011].

John, P., 2007. Severe Sand Shortage Hits Qatar's Construction Sector. Gulf Times, 4 February, 2007, Doha, Qatar.

Lamond, J.F., Pielert, J.H., 2006. Significance of Tests and Properties of Concrete and Concrete-Making Materials. ASTM International Standards Worldwide STP 169, Bridgetport, NJ.

Perumal, S.V., 2009. Firm Invests QR100mn in Washed Sand Plant. Gulf Times, Thursday 10/9/2009. Available from: <http://www.gulftimes.com/site/topics/article.asp?cu_no=2&item_no=313914&version=1&template_id=36&parent_id=16>.

Qatar 2022, 2011. Qatar 2022 Bidding Committee Official Website, 16 December 2010. Available from: <http://www.qatar2022bid.com>.

Qatar Construction Sites, 2007. Sands of Time Running Out. Qatar Construction Sites Magazine, Doha, Qatar, p. 25.

Qatar Geographic Institute, 1992. Qatar Geological Map.

QCSm, 2007. The Qatar National Construction Standards. Qatar General Organization for Standards and Metrology, Qatar.

Scacciavillani, F., 2007. Forecast of Demand for Selected Construction Materials in Qatar. Gulf Organization for Industrial Consulting (GOIC), July 2007, Doha, Qatar.

Walkden, G., Williams, A., 1998. Carbonate ramps and the Pleistocene-recent depositional systems of the Arabian Gulf. Geological Society, London, Special Publications 149, 43–53.