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Treatments to improve the aeolian sand foundation in solar park construction

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The aeolian sand in the Mohammad bin Rashid Al Maktoum (MBR) Solar Park Phase IV Project site in Dubai, United Arab Emirates, is cohesionless, uniformly graded, non-plastic fine sand, with high permeability, low shear strength and low bearing capacity, which are properties that cause many geotechnical and structural challenges. With aeolian sand used as backfill soil, sandstone and sabkha (gatch, gypsum) excavated during field levelling were used as sand fixation material to improve the aeolian sand foundation. In a field compaction test, the compaction method, moisture content, paving thickness, number of rolling passes, backfill layer deformation, compaction coefficient and California bearing ratio were analysed to summarise the technological aspects of the compaction process. Rolling greatly improved the aeolian sand foundation, achieving the required capacity for various projects. The surface layer was stabilised by sandstone–gatch, which had the strongest resistance to wind erosion. By contrast, the resistance of the sandstone–gypsum layer to wind erosion was moderate, and that of the sandstone layer was weak. The experiments used to improve the aeolian foundation in this study can be applied to similar desert areas on the Arabian Peninsula and in North Africa.

Notation

C_c	curvature coefficient
C_u	uniformity coefficient
m_w	water added to the backfill material for rolling
V	volume of backfill material
w	moisture content of backfill material
w_{opt}	optimum moisture content
λ_c	compaction coefficient of backfill material
ρ	density of backfill
ρ_d	dry density of backfill
ρ_{dmax}	maximum dry density of backfill material

Introduction

Desert areas occupy approximately one-third of the total land area of the Arabian Peninsula (Edgell, 2006). With vast resources of petroleum and solar energy, many construction projects are currently underway in the deserts (Olmstead and Tessler, 2008). Aeolian sands are the richest materials in desert areas (Elipe and López-Querol, 2014). However, the allowable bearing pressure of these soils is low, ranging from 49 to 118 kPa (Abu Seif *et al.*, 2016; Al-Sanad *et al.*, 1993; Al-Taie *et al.*, 2013; Padmakumar *et al.*, 2012), which is considered poor for construction practices. One of the solutions to the problem is to improve the geotechnical properties of aeolian sand so that these soils with poor bearing capacity can also be used in construction. Geotechnical properties can be improved by procedures that increase the shear strength, decrease compressibility or otherwise render the physical properties of soil more suitable for projected engineering uses. Many studies have been conducted on improving the geotechnical properties of aeolian sand in desert areas of the world (Aiban, 1994; Albusoda and Salem, 2012; Stipho, 1984; Tiwari *et al.*, 2016). These studies show that cementation results in a slight increase in friction and cohesion intercept and that residual strength parameters are the same for cemented and uncemented sands (Ismael *et al.*, 1986). Among the principal cementing agents are gypseous soil, lime–silica fume, plastic waste strips and silica fume, among others (Albusoda and Hussein, 2013; Fattah *et al.*, 2016; Kumar *et al.*, 2016; Rahman and Ahmed, 2017).

Cemented aeolian sands possess distinctive geotechnical properties that are different from other soils, and they are used in construction associated with the oil industry, railways, highways and solar parks (Ismael *et al.*, 1986). However, many cementations are expensive and also harmful to the environment and humans (Andavan and Kumar, 2020; Hall *et al.*, 2012; Gholipoor Noroozi *et al.*, 2015). Therefore, other economical and harmless sand stabilisers are needed.

This paper presents the results of an in situ compaction testing programme conducted to determine the geotechnical properties of backfill soils in the Mohammad bin Rashid Al Maktoum (MBR) Solar Park, the largest single-site solar energy project in the world, with a planned total production capacity of 5000 MW by 2030. The site is in Saih Al Dahal (24°42′19″ to 24°48′7″N, 55°17′57″ to 55°26′23″E), Dubai, UAE, approximately 55 km south of Dubai City. The site is mainly covered with sand dunes and gravel plains. The most abundant building material in the project site is aeolian sand, which is non-cohesive, poorly graded fine sand with high permeability, low shear strength and low bearing capacity. The greatest problem faced by the project is how to use compaction treatment of aeolian sand as backfill soil and excavated sandstone and sabkha (gatch, gypsum) as sand fixation materials to achieve the requirements of various projects, including both sand fixation and bearing capacity. In this study, two sites were chosen to conduct compaction tests, in which moisture content, paving thickness, number of rolling passes, backfill layer deformation, compaction coefficient and California bearing ratio (CBR) were measured.

Study area

The geology of the study area has been substantially influenced by the deposition of marine sediments associated with numerous sea-level changes during relatively recent geological time. The site is relatively low-lying with near-surface geology dominated by Quaternary- to Late Pleistocene-age mobile aeolian sands and sabkha/evaporate deposits. Alternating beds of calcarenite, carbonate sandstone, sands and cemented sands are under superficial deposits.

The site is in the hot, arid climate of Dubai, and in such climates, evaporation exceeds precipitation (rain, snow and dewfall). This climate regime produces characteristic hot desert terrains. Average annual rainfall may be only a few centimetres (even only a few millimetres in some parts), which usually occurs seasonally and sometimes only from a single cloudburst. Summer shade temperatures frequently exceed 40°C, and humidity may approach 100% near the coast. The contrast between maximum night and day temperatures and between night and day humidity is often great. Strong, persistent winds are normal in many areas. In this unfavourable climate, concrete structures are adversely affected by the conditions, including high and large seasonal changes in temperature, high and large changes in relative humidity, strong desiccating winds, nighttime condensation, windborne salt-laden dust and high solar radiation.

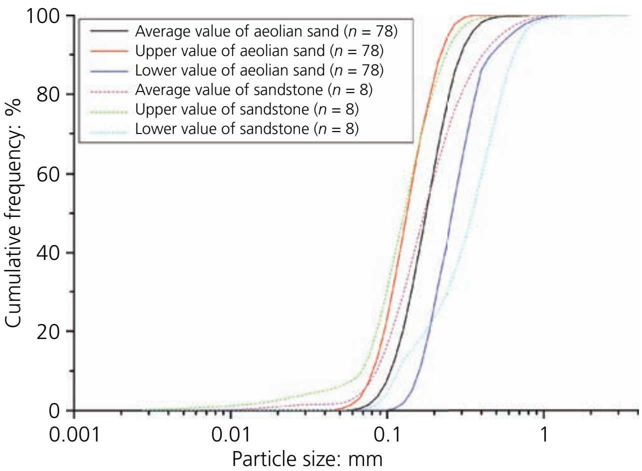


Figure 1. Grain size distribution curves of aeolian sands and sandstones in the project site. The 78 aeolian sand samples were collected at the top of dune ridges, and the eight sandstone samples were obtained from exploration pits

Aeolian sand

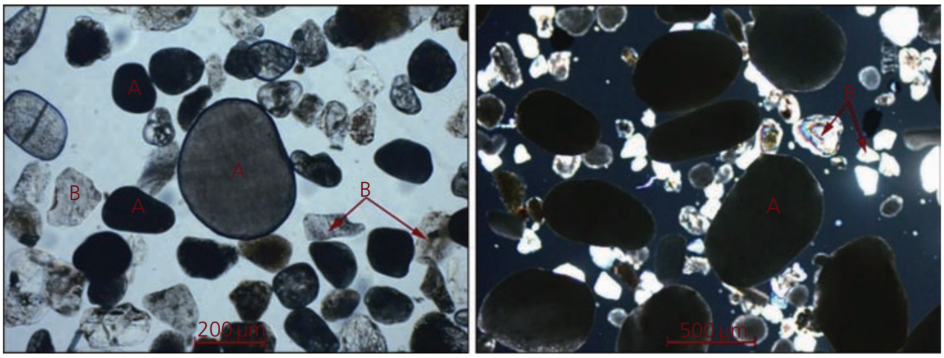
After being blown and sorted by the wind over long periods, aeolian sand is non-plastic and uniformly graded fine sand (ASTM, 2017a). The particles move freely relative to one another, which explains their low mechanical properties. The particles were primarily in the size range of 0.05 to 0.5 mm (Figure 1), which accounted for 99.47% of the total. Within this range, the average content of very fine sand (0.05–0.1 mm) was 7.85%, that of fine sand (0.1–0.25 mm) was 72.37% and that of medium sand (0.25–0.5 mm) was 19.25%. The contents of silt, coarse sand and very coarse sand were very low, and there was no clay. The uniformity coefficient C_u was 1.867, and the curvature coefficient C_c was 0.994 (ASTM, 2017a). Therefore, loose structure, poor grading, large porosity and low strength characterised the aeolian sand at the site, indicating that it was not suitable for use in engineering projects.

According to X-ray fluorescence spectrometer results (MLA650, FEI Co), the most abundant chemical component of aeolian sand in the site was calcium oxide, accounting for 33.94%, followed by silicon dioxide, accounting for 29.23%. The other chemical components, including aluminium oxide, ferric oxide, magnesium oxide, sodium oxide and potassium oxide, had small contributions to the total (Table 1). Compared with aeolian sand in China (Niu *et al*., 2019), the calcium oxide content of aeolian sand in the site was four to six times higher, whereas the silicon dioxide content was only half of that in China. The minerals in the aeolian sand at the site were primarily calcite, quartz, feldspar and calcium carbonate aggregate. The calcium carbonate content of the aeolian sand was between 60 and 90% (Figure 2).

According to the Matcon Testing Laboratory (2018), the cohesion of aeolian sand in the site was zero, and the angle of shear resistance was from 30.0° to 34.4°, with an average of 32.9° ±

Table 1. Chemical composition (%) of aeolian sand, gatch and sandstone in the project site in the United Arab Emirates (UAE) and of aeolian sand in China

Country	Sample	Silicon dioxide	Aluminium oxide	Ferric oxide	Magnesium oxide	Calcium oxide	Sodium oxide	Potassium oxide	Others
UAE	Aeolian sand	29.23	2.51	0.97	1.41	33.94	1.00	0.61	29.95
UAE	Gatch	24.55	2.39	0.81	1.24	39.10	0.86	0.60	30.05
UAE	Sandstone	53.84	2.94	1.00	1.17	17.07	0.90	0.83	21.80
China	Aeolian sand	64.69	8.20	3.48	1.99	6.67	2.48	1.55	10.33



(a) (b)

Figure 2. Polarising micrographs of aeolian sand particles in the project site (100×). (a) Image under plane-polarized light. (b) Image under cross-polarized light. In the images, A indicates rounded or elliptical microcrystalline carbonate aggregate, and B indicates quartz or feldspar clastic mineral

1.6° (mean ± standard deviation, n = 19). The angle of shear resistance is lower than that in aeolian sand in the centre of the Taklimakan Desert (31.9°–36.3°; Yao *et al*., 2001) and in the Mu Us Desert (33°–48°; Zhang *et al*., 2015) in China but is higher than that in the Thar Desert (27.1°–32.0°) in India (Prasad and Purohit, 2017). The value is equivalent to the internal friction angle of aeolian sand in the Baiji region of Iraq and Kuwait (Al-Sanad *et al*., 1993; Fattah *et al*., 2016).

Compaction characteristics of the soils were determined by using standard Proctor's test according to the procedure in ASTM D 698-12e2 (ASTM, 2012). The maximum dry density (MDD) varied from 1.68 to 1.70 g/cm^3 at the optimum moisture content (OMC) from 15.7 to 16.5%. The mean value of MDD was 1.69 g/cm^3, and that of OMC was 16.2%. Compared with the Mu Us Desert (Ren *et al*., 2018), the Horqin Desert (Zhang *et al*., 2013), India's Thar Desert (Tiwari *et al*., 2016), Algeria's Valgra Desert (Cherrak *et al*., 2015) and Saudi Arabia (Rahman and Ahmed, 2017), the MDD was lower and the OMC was higher at the site in the UAE.

Sand fixation materials

According to geological exploration data (Matcon Testing Laboratory, 2018), the underlying stratum of loose Quaternary sediments in the project area was brownish-red sandstone, with clear horizontal or oblique bedding, calcareous cementing and highly weathering. Under the sandstone was white or greyish-white sabkha, which was primarily porous sand debris or silty limestone (locally known as gatch) and gypsum sediments, containing the remains of marine microorganisms.

Sandstone, sandstone–gatch (sandstone mixed with gatch) and sandstone–gypsum (sandstone mixed with gypsum) were used as sand fixation materials to cover the surface layer, and aeolian sand was used as backfill material. Therefore, three samples of those four materials were collected to run geotechnical engineering property tests. The tests included grain size, natural moisture content, specific gravity, standard Proctor's test and a soluble salt test. The test results are shown in Tables 2 and 3.

The aeolian sand had low contents of chloride and sulfate (Table 3) and therefore no corrosiveness to building materials. The sandstone and sandstone–gypsum had high sulfate contents, 2.15 and 1.99 g/l, respectively, which are corrosive to concrete. However, when used as a sand fixation material, it is on the surface of the site in a relatively thin layer, so the corrosiveness to concrete can be ignored.

Foundation treatment method

Technical requirements for backfilling

According to the owner's technical specification (OTS), the technical requirements for the foundation can be classified into three working conditions.

- Condition I. Backfill materials of road or load area should reach the compaction coefficient of 98% (the MDD and OMC should be measured by the modified effort Proctor's test according to ASTM D 1557-12e1 (ASTM, 2003), with a hammer weight of 4.5 kg and a drop distance of 45.7 mm).
- Condition II. Backfill materials of the ditch under the road should reach the compaction coefficient of 95%.
- Condition III. Backfill materials in other sites (such as embankment and non-load area, among others) should reach the compaction coefficient of 90%.

Backfilling and rolling equipment

According to the backfill technical requirements and relevant engineering experience, a Dynapac SD-200 vibratory roller was selected for rolling. The roller weight was 20 t, and the speed was 2 to 5 km/h. The vibration frequency was 0 to 30.8 Hz, and the amplitude was 0.9 to 1.8 mm. To backfill the site, a loader was used, and to water the site, two water trucks (5000 and 10 000 gallons; 1 gallon = 4.5 litres) were used.

Table 2. Geotechnical characteristics of the backfill and sand fixation materials

Backfill materials		Fine grain ($d \le 0.075$ mm): %	Moisture content: %	Specific gravity	Maximum dry density: g/cm^3	Optimum moisture content: %
Aeolian sand	Sample 1	1.0	0.1	2.65	1.69	16.5
Aeolian sand	Sample 2	3.0	0.6	2.65	1.68	15.9
Aeolian sand	Sample 3	4.0	0.9	2.65	1.70	16.2
Aeolian sand	Max	4.0	0.9	2.65	1.70	16.5
Aeolian sand	Min	1.0	0.1	2.65	1.68	15.7
Aeolian sand	Mean	2.7	0.5	2.65	1.69	16.2
Sandstone	Sample 1	5.0	0.7	2.66	1.79	14.3
Sandstone	Sample 2	5.0	0.6	2.66	1.76	15.2
Sandstone	Sample 3	4.0	0.8	2.65	1.77	15.0
Sandstone	Max	5.0	0.8	2.66	1.79	15.2
Sandstone	Min	4.0	0.6	2.65	1.76	14.3
Sandstone	Mean	4.7	0.7	2.66	1.77	14.8
Sandstone–gatch	Sample 1	16.0	0.9	2.65	1.76	12.9
Sandstone–gatch	Sample 2	7.0	3.3	2.66	1.74	16.4
Sandstone–gatch	Sample 3	14.0	2.4	2.66	1.75	16.0
Sandstone–gatch	Max	16.0	3.3	2.66	1.76	16.4
Sandstone–gatch	Min	7.0	0.9	2.65	1.74	12.4
Sandstone–gatch	Mean	12.3	2.2	2.66	1.75	15.1
Sandstone–gypsum	Sample 1	7.0	1.6	2.65	1.73	16.8
Sandstone–gypsum	Sample 2	12.0	0.6	2.66	1.74	16.4
Sandstone–gypsum	Sample 3	29.0	0.6	2.63	1.74	16.4
Sandstone–gypsum	Max	29.0	1.6	2.65	1.74	16.8
Sandstone–gypsum	Min	7.0	0.6	2.63	1.73	16.4
Sandstone–gypsum	Mean	16.0	0.9	2.65	1.74	16.5

Table 3. Contents of soluble salts and pH of the backfill and sand fixation materials

Materials	Chloride ion content: %	Sulfate content: g/l	pH
Aeolian sand	<0.01	0.07	7.8
Sandstone	0.02	2.15	7.4
Sandstone–gatch	<0.01	0.13	7.5
Sandstone–gypsum	0.01	1.99	7.5

Backfilling and rolling technology

Lift thickness of backfill

According to the recommended standard for rolling in China's 'Guidelines for highway design and construction in sandy desert area', the average thickness of each layer of aeolian sand is 30 to 50 cm (Ministry of Transport of the People's Republic of China, 2008). On this basis, the thickness of the aeolian sand lift in the test was 30 or 50 cm.

Watering of backfill soil

According to exploratory data, the natural moisture content of the aeolian sand varied from 0.1 to 0.9% because of different burial depths. However, owing to the high temperatures and dry and windy conditions, the moisture in the backfill material evaporated easily, and the content decreased significantly to a low level during excavation, transportation and stacking. Therefore, the moisture content of the backfill was considered to be 0%, and the amount of water added to the backfill material was obtained according to the following formula:

$$1.\quad m_{\mathrm{w}} = w_{\mathrm{opt}} \cdot \rho \cdot V$$

where m_w is the water added to the backfill material for rolling; w_{opt} is the OMC; ρ is the density of backfill material before watering; and V is the volume of backfill material.

Two sites were designed for the backfill rolling test, and each site was divided into four blocks according to the thickness of the backfill layer, the thickness of the sand fixation material and moisture content (Table 4 and Figure 3). Each block was approximately 6 × 20 m.

Backfill and rolling process

Backfilling and rolling processes for aeolian sand and sand fixation materials were summarised in a flow chart (Figure 4). The number of rolling passes was adjusted according to the dry density and compaction coefficient test results.

Test results

According to the requirements of the rolling test program, the moisture content, lift thickness, compaction coefficient and CBR of backfill material were monitored during the rolling process.

Change in moisture content

To achieve better compaction, the backfill soil and sand fixation materials should be watered before rolling (Rogers *et al*., 1994). To meet the requirements of the backfill and the rolling test, the moisture content of backfill and sand fixation materials was controlled within

Table 4. Backfill rolling test blocks and working condition combinations

Test site		Backfill material	Lift thickness (cm) × layers	Rolling passes	Controlled moisture content: %
I	A	Aeolian sand	30 × 1	2, 4, 6, 8, 10	Not watered
I	B	Aeolian sand	30 × 3	2, 4, 6, 8, 10	w_{opt} + 5
I	B	Sandstone–gypsum	15 × 1	2, 4, 6, 8, 10	w_{opt} + 5
I	C	Aeolian sand	30 × 3	2, 4, 6, 8, 10	w_{opt} + 5
I	C	Sandstone–gatch	15 × 1	2, 4, 6, 8, 10	w_{opt} + 5
I	D	Aeolian sand	30 × 3	2, 4, 6, 8, 10	w_{opt} + 5
I	D	Sandstone	15 × 1	2, 4, 6, 8, 10	w_{opt} + 5
II	A	Aeolian sand	50 × 1	4, 6, 8, 10, 12	Not watered
II	B	Aeolian sand	50 × 3	4, 6, 8, 10, 12	w_{opt} + 5
II	B	Sandstone–gypsum	30 × 1	4, 6, 8, 10, 12	w_{opt} + 5
II	C	Aeolian sand	50 × 3	4, 6, 8, 10, 12	w_{opt} + 5
II	C	Sandstone–gatch	30 × 1	4, 6, 8, 10, 12	w_{opt} + 5
II	D	Aeolian sand	50 × 3	4, 6, 8, 10, 12	w_{opt} + 5
II	D	Sandstone	30 × 1	4, 6, 8, 10, 12	w_{opt} + 5

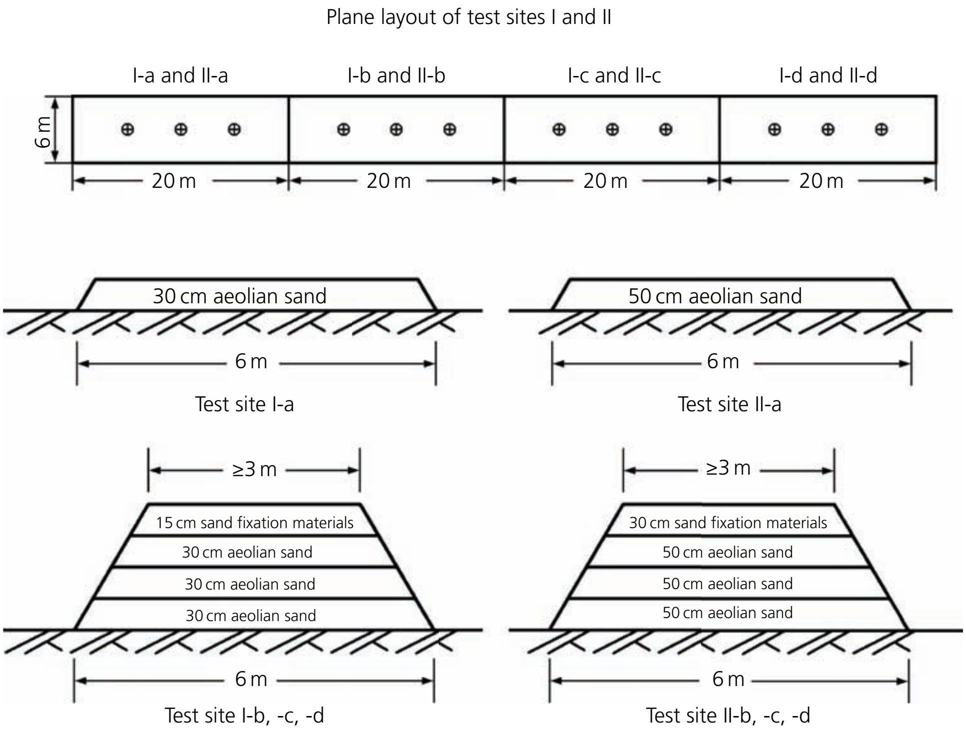


Figure 3. Plane layout and profile layouts of the two sites used for backfill rolling tests. Note: (*a*) the thickness of the backfill is loose laying depth; (*b*) ⊕ is the top elevation measurement spot

the range of OMC+5% (Figures 5 and 6). With the increase in the number of rolling passes, the moisture content of the backfill gradually decreased. In cohesionless materials such as aeolian sand, water plays a lubricating role between soil particles during the compaction process, which is more conducive to rearrangement and compaction of soil particles in vibration rolling (Munkholm and Kay, 2002). Because the project site was in a tropical desert area, the water evaporated easily. Therefore, the moisture content was controlled at the limit of OMC+5% when watering. Backfilling and rolling performed better at this level, and supplemental watering during the rolling process was reduced or avoided. However, because moisture was lost during loading, transporting and unloading, the initial moisture content did not reach OMC+5%.

Backfill layer deformation

During the rolling process, with the increase in the number of rolling passes, the deformation settlement of backfill materials increased continuously. The deformation process of the backfill material layer is shown in Figure 7.

There was a considerable decrease in the thickness of the dry aeolian sand layer with the increase in the number of rolling

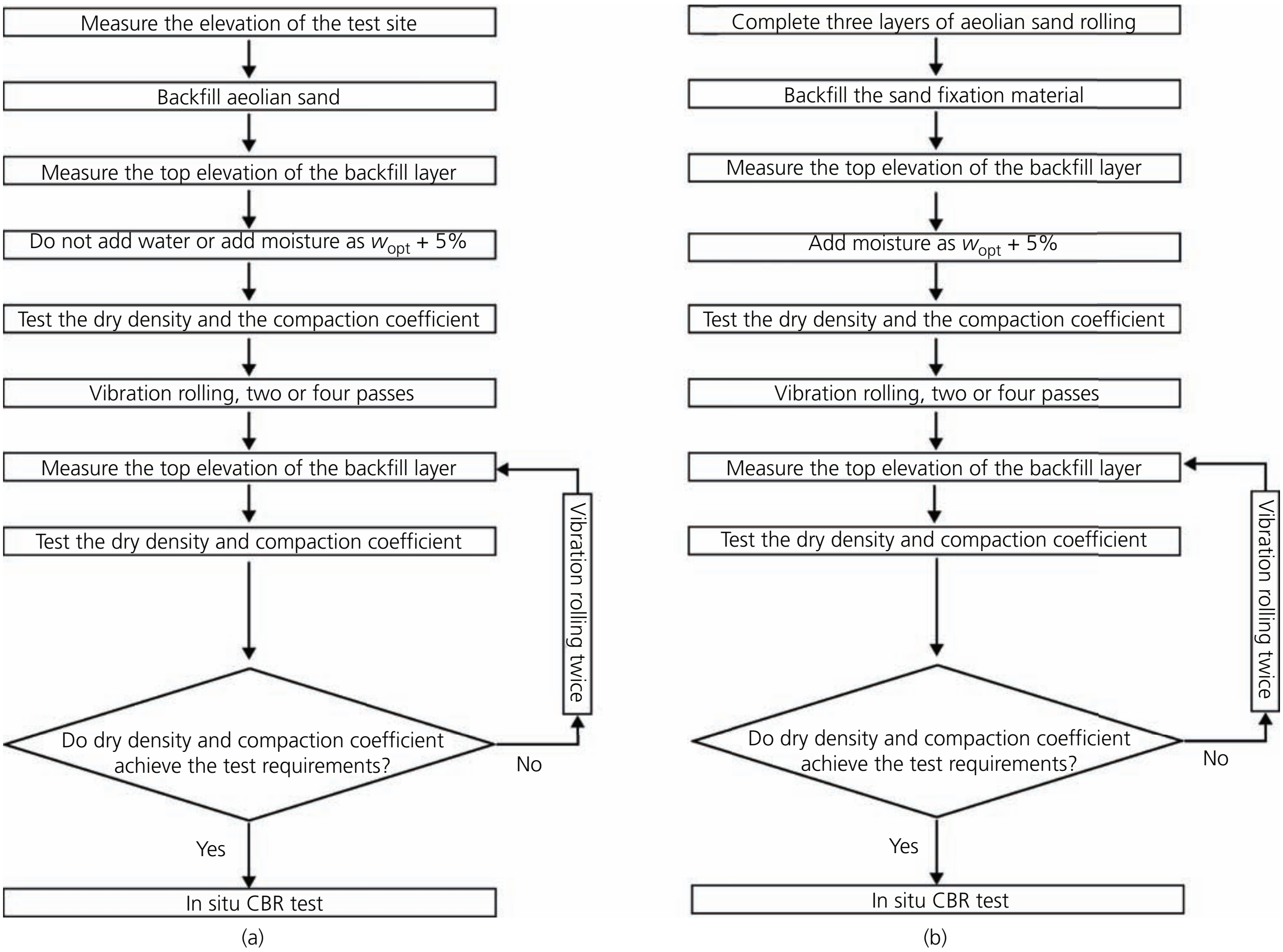


Figure 4. Flow chart of the backfill and rolling process. (a) Aeolian sand backfilling and rolling processes; (b) sand fixation material rolling processes

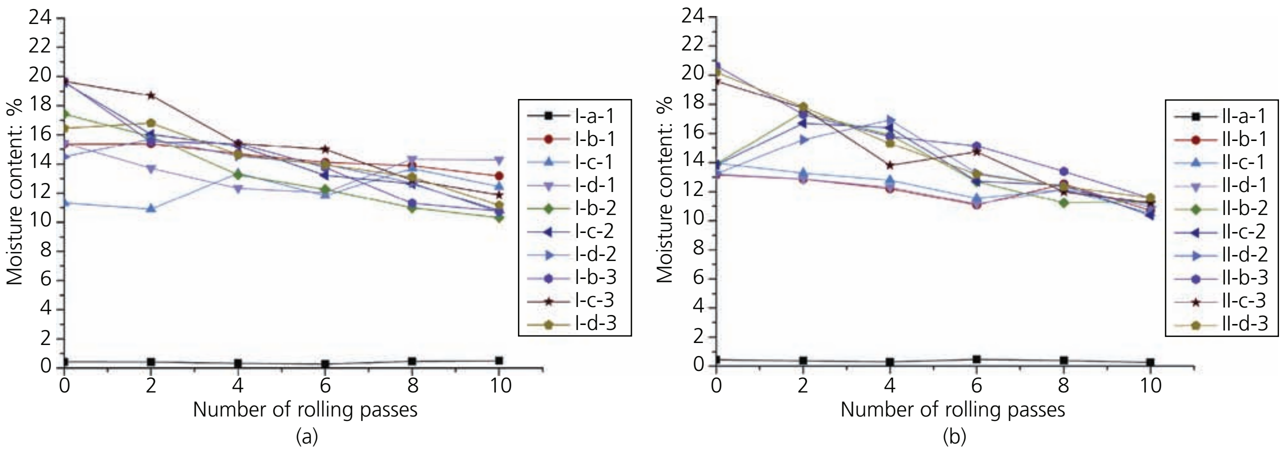


Figure 5. Changes in moisture content (%) of aeolian sand during rolling. (a) Test site I (30 cm thickness); (b) test site II (50 cm thickness)

passes. The cumulative compression deformation of the 30 cm dry aeolian sand layer was 4.8% (I-a-1), and that of the 50 cm dry aeolian sand layer was 2.9% (II-a-1), indicating that dry aeolian sand was not easily compacted. When the 30 cm wet aeolian sand layer was rolled twice, the compression deformation increased rapidly by an average of 4.73%. During the next rolling, the

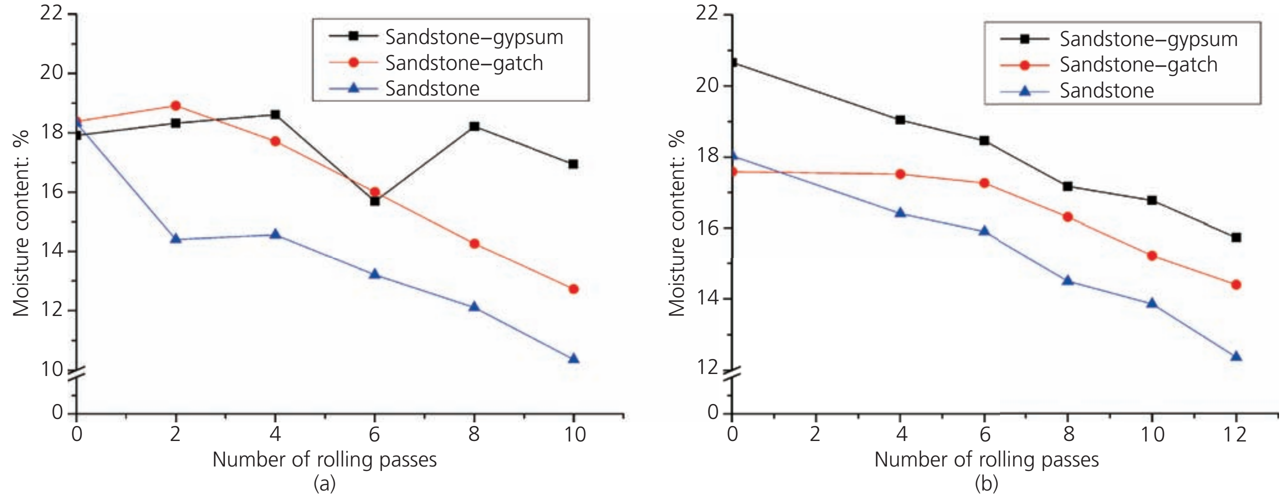


Figure 6. Changes in moisture content (%) of sand fixation materials during rolling. (a) Test site I (15 cm thickness); (b) test site II (30 cm thickness)

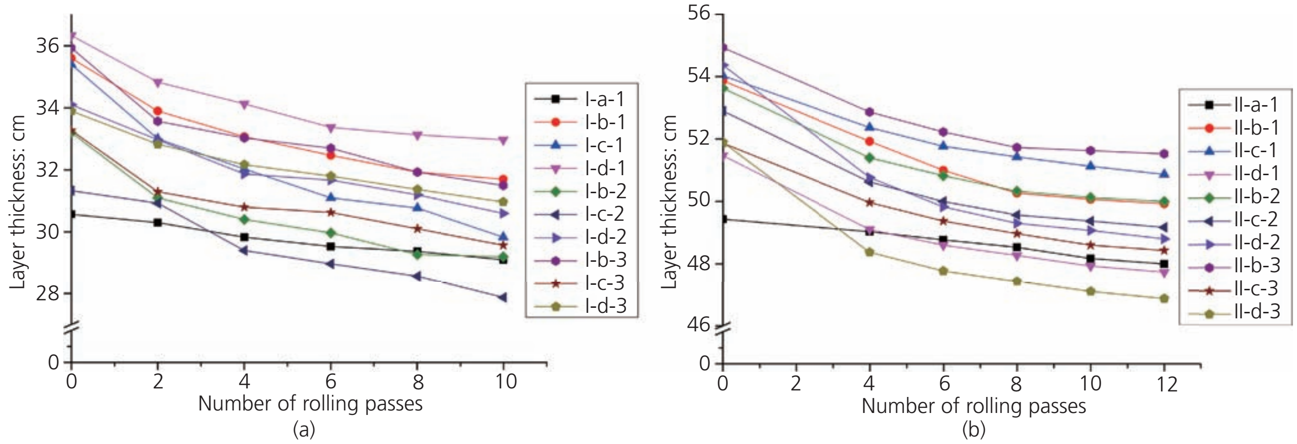


Figure 7. Deformation of the aeolian sand layers with the number of rolling passes. (a) Test site I (30 cm thickness); (b) test site II (50 cm thickness)

compression deformation increased slowly. With ten rolling passes, the cumulative compression deformation was 8.65% to 15.73%, with an average of 11.28%. In the first several rolling passes, the compression deformation of the 50 cm wet aeolian sand layer increased rapidly. With four rolling passes, the average compression deformation reached 4.50%. However, deformation increased very little with additional rolling passes. With 12 rolling passes, the cumulative compression deformation was 5.86% to 10.24%, with an average of 7.44%.

With the increase in the number of rolling passes, the thickness of sand fixation layers gradually decreased (Figure 8). The average compression deformation of the sandstone–gypsum layer was 14.33%, that of the sandstone–gatch layer was 11.94% and that of the sandstone layer was 17.21%, which were values positively related to the compressive strength of the three sand fixation materials.

Variation in compaction coefficient

The sand filling method and a nuclear density hygrometer (Seaman Nuclear Corporation) were used to measure the density of backfill material (ASTM, 2017b). Using the density and moisture contents measured by the above methods, the dry density and compaction coefficient of the backfill material were calculated using the following formulas:

$$\rho_{\mathrm{d}} = \frac{\rho}{1 + 0.01w} \quad (2)$$

$$\lambda_{\mathrm{c}} = \frac{\rho_{\mathrm{d}}}{\rho_{\mathrm{dmax}}} \quad (3)$$

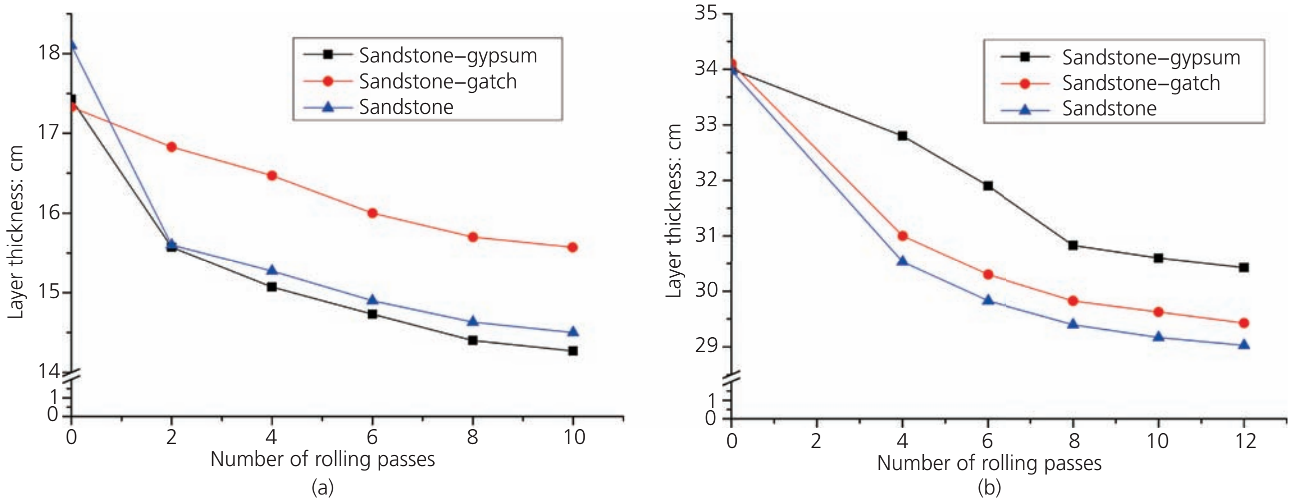


Figure 8. Deformation of the sand fixation material layers with the number of rolling passes. (a) Test site I (15 cm thickness); (b) test site II (30 cm thickness)

where ρ_d is the dry density of backfill (kg/m^3); ρ is the density of backfill (kg/m^3); w is the moisture content of backfill material (%); λ_c is the compaction coefficient of backfill material; and ρ_{dmax} is the MDD of backfill material (kg/m^3).

Figure 9 shows the changes in the compaction coefficient of aeolian sand during rolling. The compaction coefficient of the dry sand layer increased slowly with the increase in the number of rolling passes but remained lower than that of the wet sand layers. When the 30 cm dry sand layer was rolled ten times, the compaction coefficient reached 0.90. When the 50 cm dry sand layer was rolled 12 times, the compaction coefficient also reached 0.90. Therefore, the dry sand could not be easily compacted. The field vibration rolling test showed that the dry density at 0% moisture content was less than that at the OMC. Hence, the vibration rolling method of dry sand is not suitable for the project.

Wet sand is more easily compacted than dry sand. When the 30 cm wet sand layer was rolled twice, the compaction coefficient was 0.89 to 0.94, with a mean of 0.92, which is close to or exceeds the OTS' requirement of 0.90. When the 30 cm wet sand layer was rolled ten times, the compaction coefficient was 0.96 to 0.98, with a mean of 0.97, which is close to or meets the OTS' requirement of 0.98.

When the 50 cm wet sand layer was rolled four times, the compaction coefficient was 0.90 to 0.95, with a mean of 0.92, which reaches or exceeds the requirement of 0.90. After 12 rolling passes, the compaction coefficient of the 50 cm wet sand layer was 0.96 to 0.99, with a mean of 0.97, which is close to or meets the requirement of 0.98.

The compaction coefficient of dry sand increased only after watering (without rolling), especially in the 50 cm thick aeolian

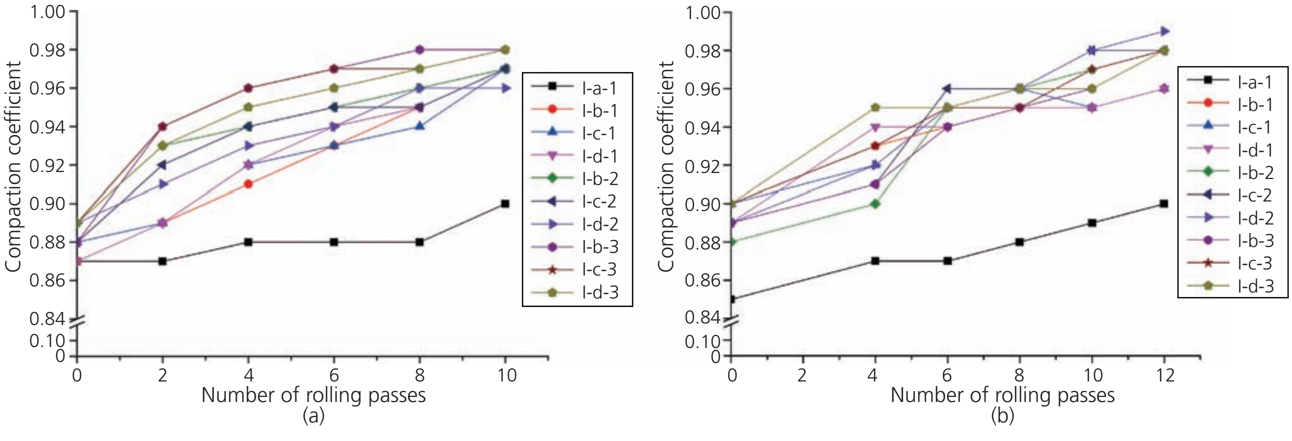


Figure 9. Changes in the compaction coefficient of aeolian sand layers with the number of rolling passes. (a) Test site I (30 cm thickness); (b) test site II (50 cm thickness)

sand, and the compaction coefficient of some test sections reached 0.90. This result was related to the addition of water. In this test, large amounts of water were sprinkled on the top of the 50 cm dry sand layer, with the water penetrating freely, which is equivalent to the hydro-compaction method (Munro, 2017). The aeolian sand in the top layer was more likely to reach the compaction coefficient of 0.90 in a short time, which indirectly showed that water played an important role in backfill compaction.

Figure 10 shows the changes in the compaction coefficient of sand fixation materials during rolling. In the initial stage of rolling, the compaction coefficient of the three materials in a 15 cm thickness increased rapidly with the increase in the number of rolling passes. After six rolling passes, the compaction coefficient could exceed 0.92. In the later stage of rolling, the coefficient of compaction increased slowly. When rolled ten times, the coefficient of compaction reached or exceeded 0.97. However, the compaction coefficient of the three materials in a 30 cm thickness increased slowly with the increase in the number of rolling passes in the initial stage of rolling. When rolled ten times, the compaction coefficient reached 0.92. After 12 rolling passes, the compaction coefficient increased rapidly and reached or exceeded 0.97. When the three materials in a 15 cm lift thickness were rolled ten times, the compaction coefficient met the engineering requirements. However, the three materials in a 30 cm lift thickness required 12 rolling passes in order for the compaction coefficient to meet the engineering requirements.

CBR field tests

The in situ CBR test results are summarised in Table 5 (ASTM, 2009).

The mean CBR values of compacted sandstone–gypsum in test area I (15 cm thickness) and test area II (30 cm thickness) were nearly equal, at 24.5% and 22.0%, respectively, indicating that they both had high bearing capacity. However, the mean CBR values of compacted sandstone–gatch in test area I and test area II were different, at 30.0% and 23.0%, respectively. In test area I, the CBR values of both sandstone–gypsum and sandstone–gatch were greater than those in test area II. Both sandstone and aeolian sand had smaller CBR values that ranged from 5% to 9%, which were much lower than those of sandstone–gypsum and sandstone–gatch, indicating that both had low bearing capacity.

The CBR values were greater than 20% for sandstone–gypsum and sandstone–gatch, indicating their suitability for subgrade and

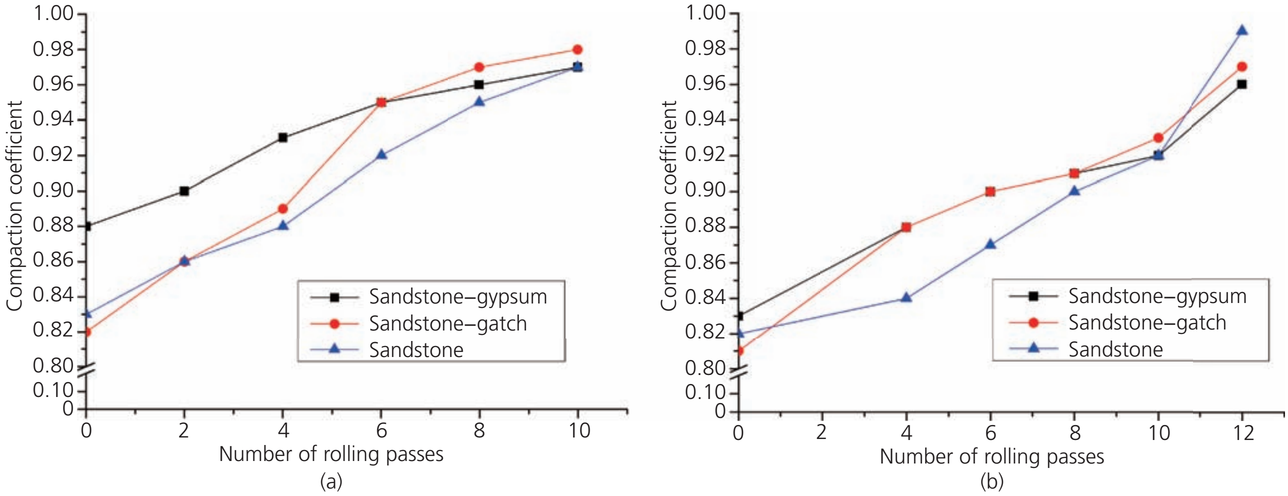


Figure 10. Changes in the compaction coefficient of sand fixation material layers with the number of rolling passes. (a) Test site I (15 cm thickness); (b) test site II (30 cm thickness)

Table 5. Summary of CBR field test results

Backfill material	Field CBR value: %					
	Test area I			Test area II		
	Max.	Min.	Mean	Max.	Min.	Mean
Aeolian sand	8.0	6.0	6.8	7.0	5.0	6.3
Sandstone–gypsum	25.0	24.0	24.5	23.0	21.0	22.0
Sandstone–gatch	34.0	26.0	30.0	24.0	22.0	23.0
Sandstone	7.0	7.0	7.0	9.0	8.0	8.5

pavement filling materials for various roads in the site. With CBR values of 7% to 9%, the sandstone is suitable as sand fixation material and subgrade filling material in the heliostats area. With CBR values of 5% to 8%, the aeolian sand is suitable as site backfilling material.

Wind erosion resistance

After completion of the backfill rolling test on 12 July 2018, iron bars with a sign ring were inserted into the surface layer of the sand fixation material to monitor the wind erosion depth. After almost half a year of observation, on 19 January 2019, the surface layer of the sandstone–gatch remained in good condition, and the wind erosion depth was zero, indicating strong resistance against wind erosion (Figure 11). Blown sand weakly eroded the surface of the sandstone–gypsum. The wind erosion depth was 2 to 3 mm, and an uneven surface formed. These results indicated that the sandstone–gypsum had moderate resistance against wind erosion. The surface of sandstone eroded approximately 13 mm, forming a raised gravel surface and indicating weak resistance against wind erosion.

Wind erosion resistance tests were conducted on 20 January 2019. Each erosion plot was 1.5 × 2 m and was enclosed by wood strips (Figure 12). The time of wind erosion was 10 min, and the wind speed was 16 to 18 m/s, based on the highest wind speeds recorded at the local meteorological station. The wind was produced with an AJS-MH58 portable pneumatic extinguisher. The eroded materials were collected and weighed in the laboratory. The sandstone–gatch layer had a strong resistance to wind erosion, and the eroded weight of the surface layer was 4.57 g/(min·m^2). The sandstone–gypsum layer had moderate resistance to wind erosion, and the eroded weight was 23.73 g/(min·m^2). The sandstone layer had a weak resistance to wind erosion, and the eroded weight was 111.36 g/(min·m^2). The results of the wind erosion tests were consistent with those of 6-month monitoring of natural wind erosion.

Conclusions

The aeolian sand in the MBR Solar Park Phase IV project in Dubai was fine, loose, poor in grading, high in porosity, low in strength and high in fluidity and needed treatment to meet the requirements of various projects. With aeolian sand used as backfill material and with sandstone, gatch and gypsum excavated during site levelling used as sand fixation materials, rolling tests were conducted to monitor the changes in moisture content, backfill layer deformation, compaction coefficient and CBR. The test results showed the following.

- When dry aeolian sand in 30 and 50 cm lift thicknesses was vibration rolled, the compaction coefficient increased slowly, and the final compaction coefficient was close to or reached 0.90. Thus, the dry aeolian sand was not easily compacted, and therefore, the dry sand vibration rolling method was not suitable for the project site.
- Rolling had a good effect on the wet sand. In a 30 cm lift thickness of wet sand, the compaction coefficient reached 0.96 to 0.98, with an average of 0.972, after ten rolling passes. In a 50 cm lift thickness of wet sand, the compaction coefficient reached 0.96 to 0.99, with an average of 0.974, after 12 rolling passes. The values of both thicknesses were close to or reached the requirement of 0.98 for the compaction coefficient. Therefore, according to the test results, wet aeolian sand in 30 and 50 cm lift thicknesses can achieve the requirements of OTS as backfill materials.
- When the three types of sand fixation materials in a 15 cm thickness were rolled ten times, the compaction coefficient reached 0.97 to 0.98. However, 12 rolling passes were needed for the three types of sand fixation materials in a 30 cm thickness to reach compaction coefficient values of 0.96 to 0.99.
- Because the site was in the desert, the moisture in the backfill material easily evaporated when excavated, transported and stacked. Therefore, the water content was controlled at OMC +5% to account for the evaporation loss and to maintain moisture at the OMC during rolling.
- The CBR values of sandstone–gypsum and sandstone–gatch were higher than 20%, indicating that both had high bearing capacity. The CBR values of sandstone and aeolian sand were 5% to 9%, indicating that both had low bearing capacity.
- Monitoring resistance to wind erosion and test results showed that the sandstone–gatch layer had the strongest resistance against wind erosion. The resistance of the sandstone–gypsum layer to wind erosion was moderate, whereas the sandstone layer had the weakest resistance against wind erosion.

(a) (b) (c)

Figure 11. Resistance of the sand fixation layers to wind erosion (after 6 months on 19 January 2019). (a) Sandstone–gypsum; (b) sandstone–gatch; (c) sandstone

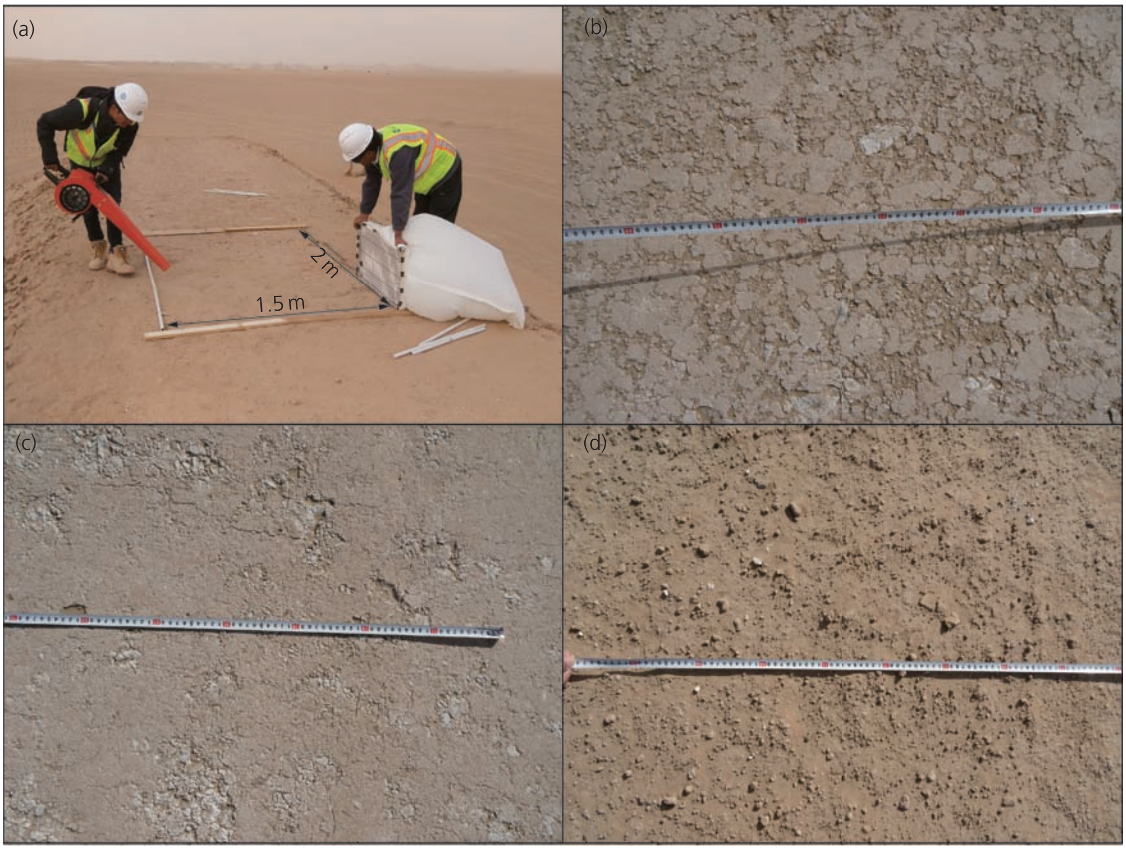


Figure 12. Sand fixation layers after wind erosion tests. (a) In situ wind erosion test; (b) sandstone–gypsum; (c) sandstone–gatch; (d) sandstone

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