




Effect of adding cement kiln dust on the effective geotechnical properties of sand dunes in Najran–Sharourah, Kingdom of Saudi Arabia: a laboratory study

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Abstract

Sand dunes are one of the most common soil types all over the world, particularly in North Africa and the Arabian Peninsula. These dunes, with their regional extensions, are considered the main natural resource for fine aggregates being used in construction purposes. To use dune sands as a road construction material, suitable treatment is necessary. Sand dunes have typically been stabilized using a cement material, however, though extremely costly and consuming a substantial amount of energy, it is not particularly effective. Therefore, this study has investigated the potentiality of adding cement kiln dust (CKD) for enhancing the strength and durability of dune sands in Najran–Sharourah, SW Saudi Arabia. Twenty-seven specimens have been mixed with 0%, 10%, 20%, and 30% CKD plus 2% cement and then examined and assessed using macro-characterization techniques. Results indicated that the strength of the sand dune samples, treated with an enhanced mixture of 30% CKD and 2% cement, improved the minimum dry density from 1.652 at 0% to 1.854 g/cm³. The soil became more qualified as a construction material. This enhanced mixture can serve as a high-quality sub-base for both flexible and rigid pavements. Besides, micro-characterization techniques, including X-ray diffraction (XRD), back-scattered electron imaging (BEI), and scanning electron microscopy (SEM) supported by energy-dispersive X-ray (EDX), were applied to identify the various phases of the treated dune sands. Finally, the implementation of adding the CKD to the dune sands geomechanical parameters has been modeled, and a series of highly reliable mathematical equations have been introduced ($0.938 \leq R^2 \leq 1.0$).

Keywords Sand dunes · Cement mixture · Cement kiln dust · Geomechanical parameters

Introduction

Saudi Arabia has the world's largest sand sheet areas with intricate and extensive geomorphic settings [1, 2]. About 30% of the Arabian Peninsula is covered by sandy dunes, and the Rub'al Khali is one of the world's largest continuous

sand deserts (Fig. 1). It is considered a broad depression that extends for about 650,000 km² in Saudi Arabia and extends across Yemen, Oman, United Arab Emirates, and Qatar [3, 4]. As an extension of the Rub'al Khali sand desert, nearly one-third of the kingdom of Saudi Arabia (K.S.A) is covered by many other big active moving sand dunes, representing the most extensive continuous desert of aeolian sand on the earth's surface (800,000 km²) [5, 6]. Figure 1 shows the regional extension of sand deserts and sand dunes in Saudi Arabia. The majority of unconsolidated sandy soils in these deserts are granular in shape, and their gradations are the main controlling factor for their final geomechanical properties [7, 8]. In eastern Saudi Arabia, the sand dunes are active and in continuous drift by windy currents, with an annual movement rate reaching up to 15 m/year.

Due to the worldwide development, urbanization exerts remarkable stresses on the construction industry to build more houses and infrastructure. Although the industrial applications of dune sands are growing continuously, dune

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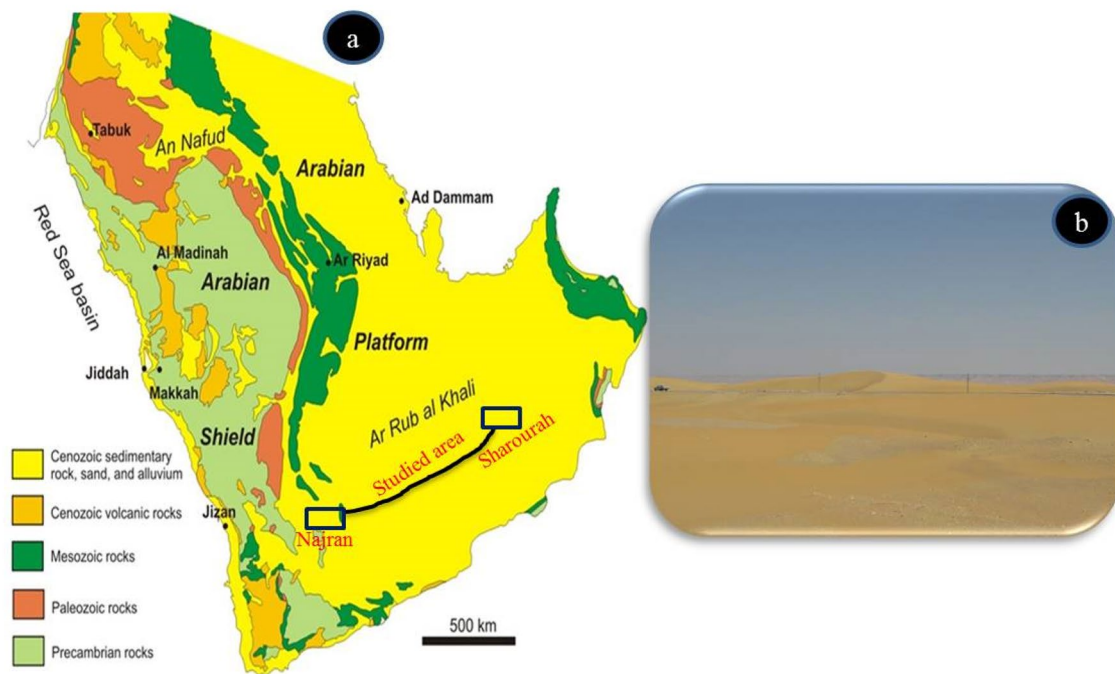


Fig. 1 a A geologic map shows the sand dunes terrains in the Arabian Peninsula, and b A field photograph illustrates the sand dunes along the studied area (Najran–Sharourah)

sands are often difficult to be compacted to serve as a building and/or filling material or as a sub-base for roads and infrastructures, even with chemical treatment due to lack of fine particles and to their poor sorting [9–13]. Consequently, dune sands with their natural conditions are not suitable to serve as bedrock materials and should be treated and enhanced before being used for construction applications [14, 15].

Najim et al. [16] investigated the use of cement kiln dust (CKD) as a replacement for cement in high-performance/self-compacting concrete. Concrete specimens with up to 30% CKD, used as a replacement for cement, were prepared, and their rheological and key mechanical properties were evaluated. Sadique and Coakley [17] used CKD as an activator in high-fly ash cement concrete. It was reported that the particle fineness, the chemical composition of fly ash, and the quantity of calcium oxide and sulfur trioxide in CKD influenced the compressive strength gain. Also, the migration of sand dunes toward these recently constructed infrastructures causes more problems, limiting cities expansion, further roads construction, power stations, and communication lines. In K.S.A., the movable sand dunes extend along the coastal shorelines as collapsible soil, which needs some stabilization using chemical treatments. Portland cement mostly serves as a stabilization material for this type of soil. Furthermore, the growth of the cement industry has resulted in the production of

large amounts of industrial waste and other by-products. It is highly expensive to treat or recycle this waste material due to the restricted environmental conditions. Consequently, there was more potential to use these by-products and waste materials for other construction purposes.

In Saudi Arabia, there are many cement factories that produce millions of tons of cement annually, besides large quantities of CKD as a by-product material at rates reached in 1998 of up to 1.4 million ton/year. In a previous study in the UK, it was reported that over 200,000 tons a year of landfill space could be saved if CKD could be recycled or if alternative uses could be found in 2021. The CKD causes air and soil pollution, and it should be disposed of properly with increasing the restrictions applied to pollution [18]. Cancer incidences cannot ultimately be attributed to pollution from cement manufacturing. There is more than enough data to link it to skin and eye irritation, as well as respiratory illnesses. There are so many variables to consider, and cement pollution's contribution is still unclear. As more studies are conducted in this area, the magnitude of its contribution will become clearer. Retrospective cohort studies should evaluate the varied health implications for retired or long-serving professionals. They make excellent subjects because of their ongoing exposure over the years. As a soil cement by-product, CKD is considered a waste material; it should be the main task to be used for stabilizing soils. Generally, for each ton

of clinker, around 0.06–0.07 ton of CKD is generated by a typical kiln [18].

During the last decades, many authors worked on the use of cement, lime, and industrial waste by-products to enhance soil properties e.g., [19–21]. Al-Homidy et al. [22] studied the stabilization of sand dunes using Electric Arc Furnace Dust (EAFD). They stated that the stabilized sand dune samples had been enhanced and became more qualified as filling materials and construction sub-bases in both flexible and rigid pavements.

The present study is considered a further application and modeling of this technique that has been initiated in KSA by Al-Homidy [22] on 27 sand dune samples from the Rub'al Khali, Najran, and Sharourah in SW K.S.A. (Fig. 1). In these areas, the quartz sand grains are mostly ferruginated, coated with an iron oxide rim, and fine to medium-grained. The large granite batholiths that underlie the Arabian Shield are thought to be the primary source of these sand grains [23, 24] Also, the ability to enhance the geomechanical properties of dune sands in the study areas will be checked using the native industrial by-product CKD, as well as the mechanism by which the CKD affects the properties of the dune sands in the study area. The thickness of pavement layers is designed by the designers according to traffic flow, utilizing the proper material that fulfills the minimum strength and durability requirements. This research studied whether dune sands met the requirements to be used as a material for pavement layers.

Materials and applied techniques

The studied sand dunes samples were collected from Narjan-Sharourah Road, Najran Province, in the Rub'al Khali, SW K.S.A., while the CKD samples were collected from the location of the Saudi Arabian Cement Company in Jeddah. Besides, the chemical composition (XRD analysis) and physical properties of the dune sands and CKD have been imported from Al-Homidy et al. [25]. Also, some additional data has been imported from Al-Homidy [22].

In the present study, percentages of the added materials were estimated as a function of the dry weight of the studied soil. Due to the cost of the cement material, it is planned to optimize the percentage of the waste material that can replace the cement that is required to stabilize the sandy soil to enhance its geomechanical properties such as UCS (kPa), soaked California Bearing Ratio, and durability test [13, 26]. The percentage of the waste material used as stabilizer depends mostly on the important physical and chemical properties of sand dune samples.

Therefore, 27 representative sand dune specimens were maintained with their maximum dry density and optimum moisture content for each soil sample in their natural state to

serve as reference samples to the stabilized soil specimens that have been treated with varying dosages of CKD. For the present study, tests were performed on sand dune samples with 2% cement and varying amounts of CKD (0, 10, 20, and 30% of the dry sand weight). The sand samples were mixed first with 2% cement and the CKD in the dry state for about 2 min, and thereafter, water content was added and mixed continuously for an additional 3 min to obtain a homogeneous mixture.

Atterberg limits and sieve analyses of 27 representative dry sand dune samples were determined using Sieve #4 (ASTM) [27] to remove the lumped coarse particles (greater in size than 4.75 mm) from the soil materials, then the CKD (10, 20, and 30%, by weight of the dry dune sands), and 2% of the used cement were mixed up. The final mixture was dried and stored in 27 plastic containers until testing time, following the international standards (ASTM D422-63) [28]. The optimum required water content was estimated following the modified Proctor compaction test (ASTM D1557-12) [29] to achieve the optimum geomechanical properties. The determination of the optimum moisture and dry density values of the suggested mixtures was carried out in addition to the estimation of the unconfined compressive strength (UCS) and the soaked California Bearing Ratio (soaked C.B.R.) for the prepared sand mixtures that satisfy the required strength limits.

The UCS was estimated following the procedures that have been listed in ASTM D2166 [30]. The treated sand dunes samples were mixed and compacted at their optimum moisture content, which had been mixed in the geomechanical mixer for 3 min. The mixture was then pressed in a mold of 10.0 cm diameter and 20.0 cm height ($H/D=2$) in 3 layers, and the auto-compactor was adjusted at 69 blows for each layer to reach the optimum dry density (2710.5 kJ/m^3) following the Proctor compaction energy. The specimens were chipped after compaction and wrapped with three layers of plastic sheets to minimize the evaporation of moisture content. The wrapped specimens were cured for 7 days under ambient conditions ($22 \pm 3 \text{ }^\circ\text{C}$) until assessing the UCS. According to ASTM D559M-15 [31], 7 days are required to reach the optimum period for stabilizing the soil.

Finally, the soaked C.B.R. test was performed according to ASTM D1883 [39] on the 7-day stored samples and those immersed in water for 4 days to simulate the natural field conditions (e.g., fluctuation of the groundwater table, septic tanks, flooding by rain, etc.). Finally, wet and dry durability tests have been performed for mixtures that satisfied strength and C.B.R. following ASTM D559M-15 [31] on the stored 7-day samples. The time after 7 days don't have any curing affect, because no chemical reaction tack pale like as the concrete (ASTM C192/C192M-19) [32]. The studied specimens were exposed to a total of twelve alternate dry and wet cycles. The loss in weight

of the measured samples (due to wetting and drying) was then evaluated as the wet and dry durability measure.

Results and discussion

The identity of the treated sand dune samples and the used cement is described in detail in the following section, where the mineral and chemical compositions are discussed.

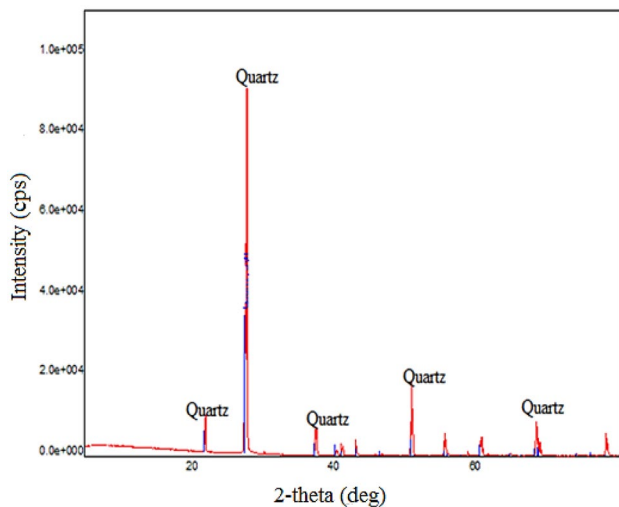


Fig. 2 X-ray diffraction analysis (XRD) for Sand Dune samples [25]

Mineral composition and identity of sand dune samples

The XRD studies indicated that the studied sand dune samples are composed of 100% pure quartz grains (SiO_2) of the silica tetrahedral group that has strongly bonded ions in its structure (Fig. 2) and is of relatively high hardness. The predominance of quartz in dune sands is mostly attributed to its stability and resistance against corrosive factors [14].

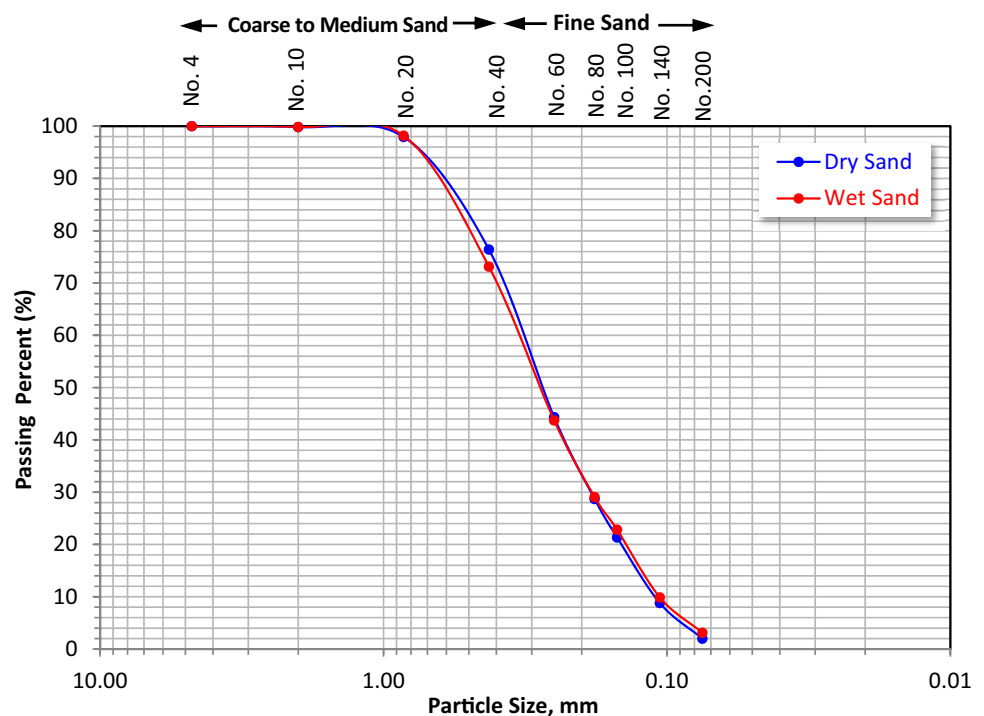
The bulk samples of the studied dune sand lack well gradation; therefore, the quality is not adequate for commercial applications in routine concrete construction as filler. Following the Unified Soil Classification System (USCS), most of the studied sand dunes samples are ranked as poorly sorted sand and as A-3 type following the American Association of State Highway and Transportation Officials (ASSHTO) system [15].

The sieve analyses were conducted following ASTM D422-63 [28] using the dry and washed techniques. Results show no differences in the sieved weight (Fig. 3), which indicates that no soluble materials are present in the studied soil [15]

The sand dune samples have specific gravity values in the range of 2.62–2.70 g/cm^3 and particle sizes in the range of 0.075–1.0 mm with an average of 0.3 mm (about 75% are in the range of medium sand size and 25% are considered fine sand).

Sands in Najran Province (the core of the present study) have a fineness modulus that varies between 0.9 and 3.0; the median is 1.8. The uniformity coefficient, C_u , varies

Fig. 3 Grain Size Distribution of the Investigated Sand Dune Samples in the dry and wet state



from 2.0 to 4.0, while the curvature coefficient, C_c , varies from 0.94 to 1.27 [33]. Tests of the Atterberg limits indicated that the sand samples were in the range of non-plastic materials. It is difficult to compact the studied sand dune samples to serve as filling material due to their poor sorting and the absence of fine particles that serve as hardening material. However, the tested sand samples are not collapsible and are not affected by water washing during flow. Therefore, the sand dune samples are not suitable for construction purposes in their natural state and still need special treatments to be suitable for construction and industrial applications [34].

Types of cement

In the present study, common Portland cement Type-I, with a specific gravity of 3.15 g/cm^3 (following ASTM C150 [35]), has been used as an additive in this investigation. Besides, CKD as a by-product and waste material has been used as a main component and as a stabilizer for the sand dunes (ASTM C150/C150M-18) [35].

The specific gravity of the studied CKD is 2.79 g/cm^3 , which is composed of 49.3% CaO, 17.1% SiO_2 , 4.24% Al_2O_3 , 3.84% Na_2O , 2.18% K_2O , 1.14% MgO, and 3.56% SO_3 (Table 1). Also, the loss on ignition (L.O.I.) of the CKD is 15.78% (under alkalis in CKD 750°C or 950°C), which is considered relatively high in comparison with the ranges of the L.O.I. values of the common CKD. This could be attributed to its high content of CaCO_3 . However, it is worth mentioning that lower L.O.I. results are better for CKD performance [36]. Finally, the studied CKD contains 6.9% chloride, in addition to 5.27% alkalis (Table 1), which is about four times the alkali content of the common Portland cement. The overall chemical composition of these materials is summarized in Table 1.

Table 1 Chemical composition of the used Cement Kiln Dust (CKD) and the Ordinary Portland Cement (OPC)

Components	CKD weight (%) present study	OPC weight (%)
CaO	49.3	64
SiO_2	17.1	22
Al_2O_3	4.24	5
Fe_2O_3	2.89	3
K_2O	2.18	< 1
MgO	1.14	1
Na_2O	3.84	< 1
SO_3	3.56	3
Chloride	6.90	< 0.1
Loss of ignition, L.O.I	6.7	1

Effect of adding cement to the compacted sand

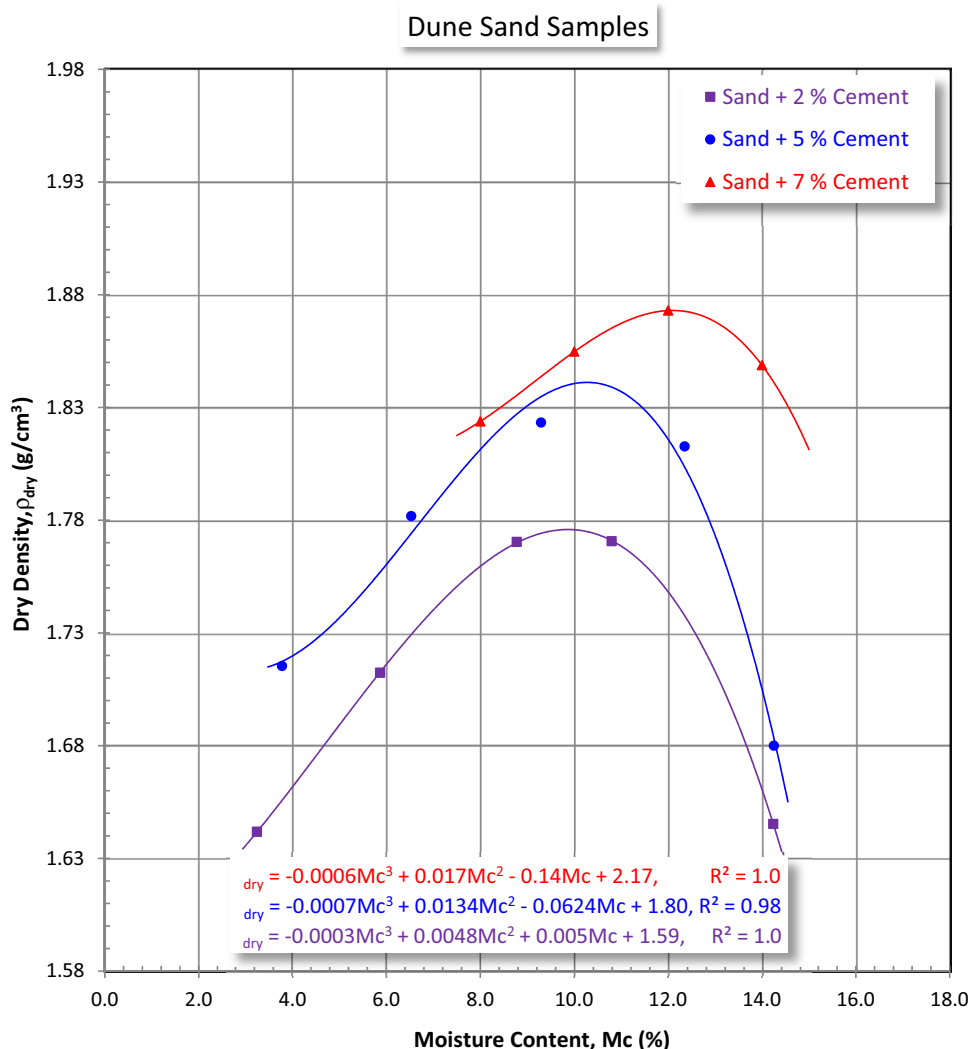
Compaction tests were carried out on 27 sand and cement mixtures in different dosages (2–7% cement, Table 2) to study the effect of its cement content on its maximum dry density and its optimum moisture content. The results of the moisture content were plotted as a function of the dry density, as shown in Fig. 4. It is revealed that both the optimum moisture content and the maximum dry density of the sand and cement mixtures increase with increasing the cement content till an optimum point is reached, which is represented by hyperbola behavior (Fig. 4). The maximum values of the dry density for the sand mixtures with cement contents of 2, 5, and 7% equal 1.652, 1.681, and 1.824 g/cm^3 , respectively (Table 3). The increasing maximum dry density values could be attributed to the higher specific gravity of the mixed cement (3.15 g/cm^3) than the specific gravity of the studied sand (2.65 g/cm^3). Also, increasing the cement content causes an increase in the optimum moisture content of the sand–cement mixtures (Table 3). This can be explained by the fact that the mixed cement is composed of very fine particles that need more water for lubrication, because they are hydrophilic. Consequently, the required water content increases with increasing the cement content [25]. Similarly, filling up the interstitial pore spaces in between the sand grains of the studied samples with CKD cement will cause their specific gravity to increase, reaching an optimum point in a hyperbola behavior. Results of moisture content were also plotted as a function of the dry density for 27 sand samples stabilized with different percentages of CKD (0, 10, 20, and 30% CKD) (Fig. 5).

On increasing the CKD content, the minimum dry density of the sand samples increases until the optimum point, as shown in Fig. 5. The measured minimum dry densities of the studied samples of sand with 0, 10, 20, and 30% CKD are 1.836, 1.812, and 1.825 g/cm^3 , respectively. Similar to Fig. 4, the increase in the minimum dry density values could be explained by the high specific gravity of the CKD (2.79 g/cm^3), which is relatively higher than that of the pure sand grains (2.65 g/cm^3). Furthermore, when the CKD content increases, the optimum moisture content decreases due to filling up the interstitial pore spaces with the CKD, which reduces the required amount of water to lubricate the mixture [37]. The maximum dry density values of the prepared

Table 2 Dosages of the Investigated Stabilizers

Stabiliser	Dosage (by dry weight of soil)
Cement	2%, 5% and 7%
Cement kiln dust (CKD)	(i) 10%, 20% and 30% (ii) 2% cement plus 10%, 20% or 30% CKD

Fig. 4 Moisture-Dry density relationship for Sand Dune samples stabilized with cement content [25]



sand grains, cement, and CKD mixtures were plotted as a function of their moisture contents (Fig. 6). It indicates that the minimum dry density values of the sand dune sample that stabilized with 2% cement and 0, 10, 20, and 30% CKD are 1.652, 1.788, 1.797, and 1.854 g/cm³, respectively. This could be explained again by the relatively higher specific gravity of the CKD (2.79 g/cm³) than that of the sand dune samples (2.65 g/cm³). Also, Fig. 6 shows that decreasing quantity of CKD causes increasing the optimal moisture content, which could be attributed to the very fine constituents of the CKD content that fill the pore spaces between sand grains and reduce the bulk pore space volume, i.e., to reduce the amount of water required for lubrication. Because of its high alkaline content, CKD acts as an efficient accelerator for compounds with latent hydraulic qualities, which enhances their mechanical properties.

The hyperbola behavior of the dry density–moisture content relationships of the different CKD-cement-dune sand

mixtures has been mathematically modeled through a series of third-order polynomial equations as shown in Table 4.

Unconfined compression tests

The U.C.S. is the most common method that has been applied in most codes and standards for evaluating stabilized soils (ASTM D2166/D2166M-16) [30].

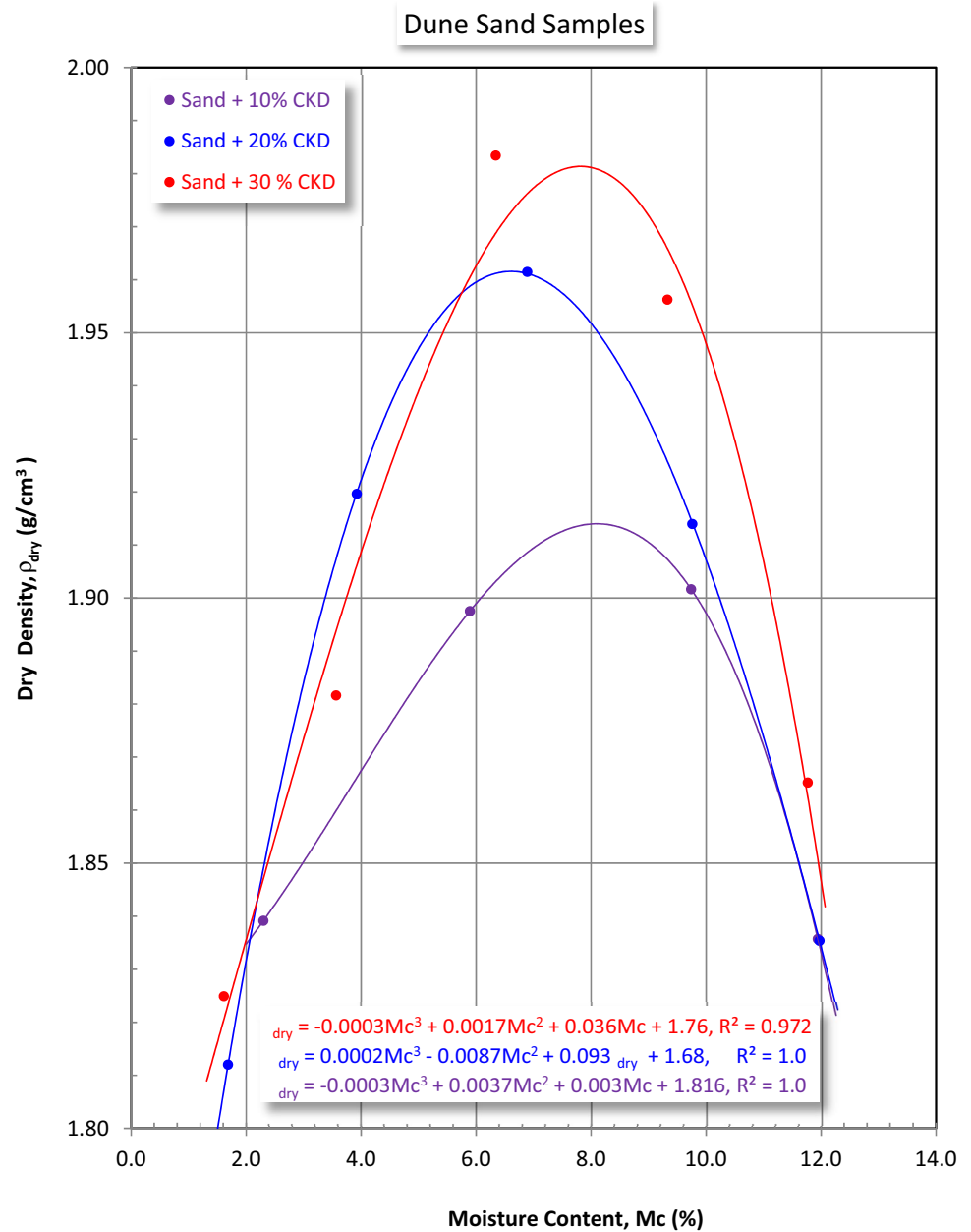
Effect of cement on U.C.S.

To determine impacts of cement and the CKD content on the U.C.S. of the sand dune samples, additional U.C.S. data (of the stabilized sand dune samples using electric arc furnace dust) was imported from Al-Homidy et al. [25] to compare impacts of the CKD content and cement content on sand samples with impacts of the electric arc furnace dust and cement on the sand dune samples (Fig. 7).

Table 3 The dry density (ρ_{dry} , g/cm³), moisture content (Mc, %), the unconfined compressive strength (U.C.S., kPa), and the soaked California Bearing Ratio (C.B.R., %) data of the studied mixed samples. Additional data were imported from Al-Homidy et al. [25]

	Mc (%)	ρ_{dry} (g/cm ³)	U.C.S. (kPa)	C.B.R. (kPa)	Mc (%)	ρ_{dry} (g/cm ³)	U.C.S. (kPa)	C.B.R. (kPa)	Mc (%)	ρ_{dry} (g/cm ³)	U.C.S. (kPa)	C.B.R. (kPa)
Sand+2% cement	3.24	1.652			2.3	1.839			5.01	1.841		
	5.86	1.712		Sand+10% CKD	5.89	1.898		Sand+2% cement+10% CKD	8.83	1.923	424	198
	8.77	1.770			9.74	1.902	107		11.12	1.885		
Sand+5% cement	10.8	1.771	378	183	11.94	1.836			13.9	1.788		
	14.24	1.655			1.68	1.812		Sand+2% cement+20% CKD	4.44	1.882		
	6.53	1.782		Sand+20% CKD	3.92	1.921			7.46	1.957	805	286
Sand+7% cement	9.29	1.823	1060	266	6.89	1.961	402		11.18	1.887		
	12.35	1.813			9.76	1.914			13.02	1.797		
	14.25	1.681			11.97	1.835		Sand+2% cement+30% CKD	4.34	1.914		
Sand+5% cement	8.1	1.824			1.61	1.825		Sand+2% cement+30% CKD	6.78	1.983	1390	404
	10.2	1.855		Sand+30% CKD	3.56	1.882			9.24	1.964		
	12.3	1.873	1728	448	6.34	1.983	752		12.33	1.854		
Al-Homidy et al. [25] Sand+2% cement	14.1	1.849			9.33	1.956						
					11.77	1.865						
								Sand+2% cement+10% CKD			412	180
Sand+5% cement			360	159			99					
								Sand+2% cement+20% CKD			792	280
Sand+7% cement			950	250			398					
								Sand+2% cement+30% CKD			1372	388

Fig. 5 Moisture-dry density relationship for Sand Dune samples stabilized with different CKD values



Data in Fig. 7 indicate that increasing the cement content causes an increase in the U.C.S. of the sand and cement mixtures in a directly proportional relationship. The U.C.S. values of the sand samples mixed with 2, 5, and 7% cement are 370, 1060, and 1728 kPa, respectively. Data in Fig. 7 indicate the presence of a very high, directly proportional relationship between the U.C.S. values of the cement-stabilized sand samples and their cement content, as follows:

$$\text{U.C.S.} = 228.2 \times \text{Cement } R^2 = 0.973, \quad (1)$$

where U.C.S. (in kPa) of the cement-stabilized sand dune samples was sealed and stored for 7 days, and C is the cement content in %.

Adding the different percentages of cement enhanced the U.C.S. of sand, but only the 7% cement content has a U.C.S. value (1728 kPa) that exceeds the minimum specified value of the sub-base materials in rigid pavement (1380 kPa, A.C.I.) [38]. Consequently, only the sand dunes samples that have been stabilized with 7% cement are characterized by the U.C.S. value, which is acceptable as a sub-base material in the rigid pavements, while the other values are not accepted.

Fig. 6 Moisture-dry density relationship for Sand Dune samples with 2% cement and different contents of CKD

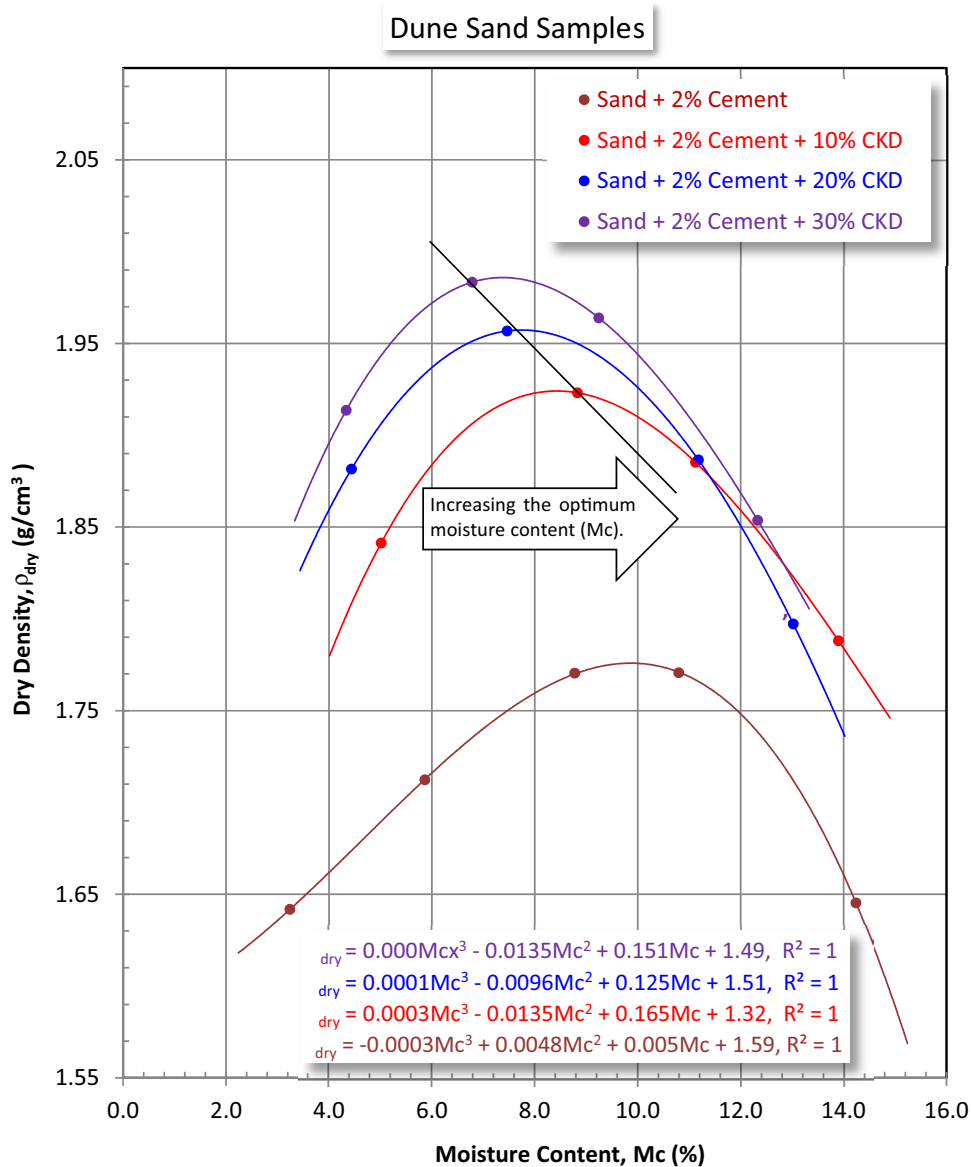
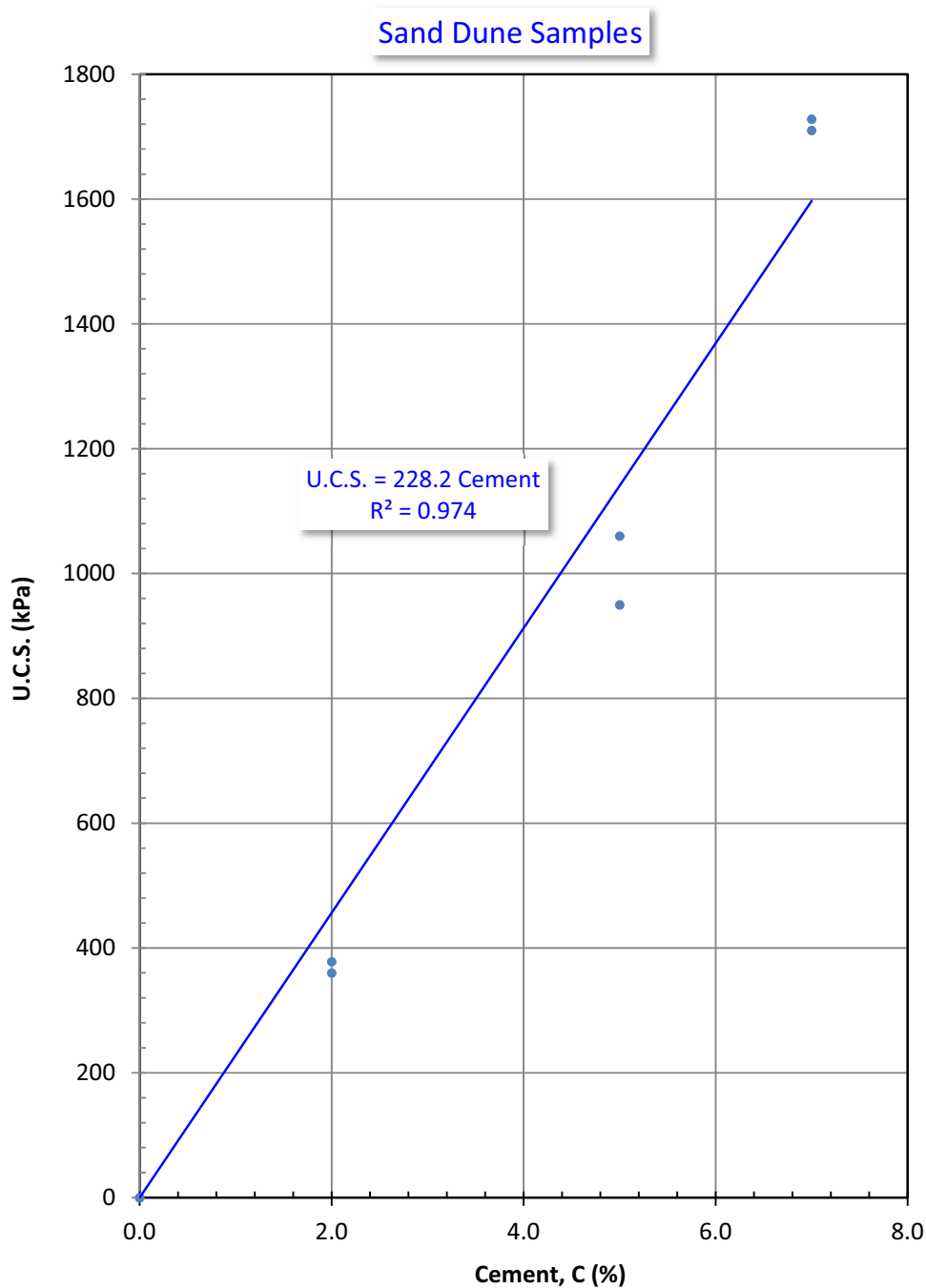


Table 4 A mathematical model for estimating the dry density and moisture content of the different dune sand mixtures that were supported with cement and different CKD content proportions

Composition	Model	Coefficient of determination
Sand + 2% cement	$\rho_{dry} = -0.0003M_c^3 + 0.0048M_c^2 + 0.005M_c + 1.59$	$R^2 = 1.0$
Sand + 5% cement	$\rho_{dry} = -0.0007M_c^3 + 0.0134M_c^2 - 0.0624M_c + 1.80$	$R^2 = 0.98$
Sand + 7% cement	$\rho_{dry} = -0.0006M_c^3 + 0.017M_c^2 - 0.14M_c + 2.17$	$R^2 = 1.0$
Sand + 10% CKD	$\rho_{dry} = -0.0003M_c^3 + 0.0037M_c^2 + 0.003M_c + 1.816$	$R^2 = 1.0$
Sand + 20% CKD	$\rho_{dry} = 0.0002M_c^3 - 0.0087M_c^2 + 0.093\rho_{dry} + 1.68$	$R^2 = 1.0$
Sand + 30% CKD	$\rho_{dry} = -0.0003M_c^3 + 0.0017M_c^2 + 0.036M_c + 1.76$	$R^2 = 0.97$
Sand + 2% cement + 10% CKD	$\rho_{dry} = 0.0003M_c^3 - 0.0135M_c^2 + 0.165M_c + 1.32$	$R^2 = 1.0$
Sand + 2% cement + 20% CKD	$\rho_{dry} = 0.0001M_c^3 - 0.0096M_c^2 + 0.125M_c + 1.51$	$R^2 = 1.0$
Sand + 2% cement + 30% CKD	$\rho_{dry} = 0.000M_cx^3 - 0.0135M_c^2 + 0.151M_c + 1.49$	$R^2 = 1.0$

ρ_{dry} is the dry density (g/cm^3), M_c is the moisture content (%), and the CKD is the cement Kiln Dust

Fig. 7 Effect of cement content on the U.C.S. of Sand Dune samples that have been sealed for 7 days (blue circles), red solid circles refer to data imported from [25]



Effect of cement kiln dust (CKD) on the U.C.S.

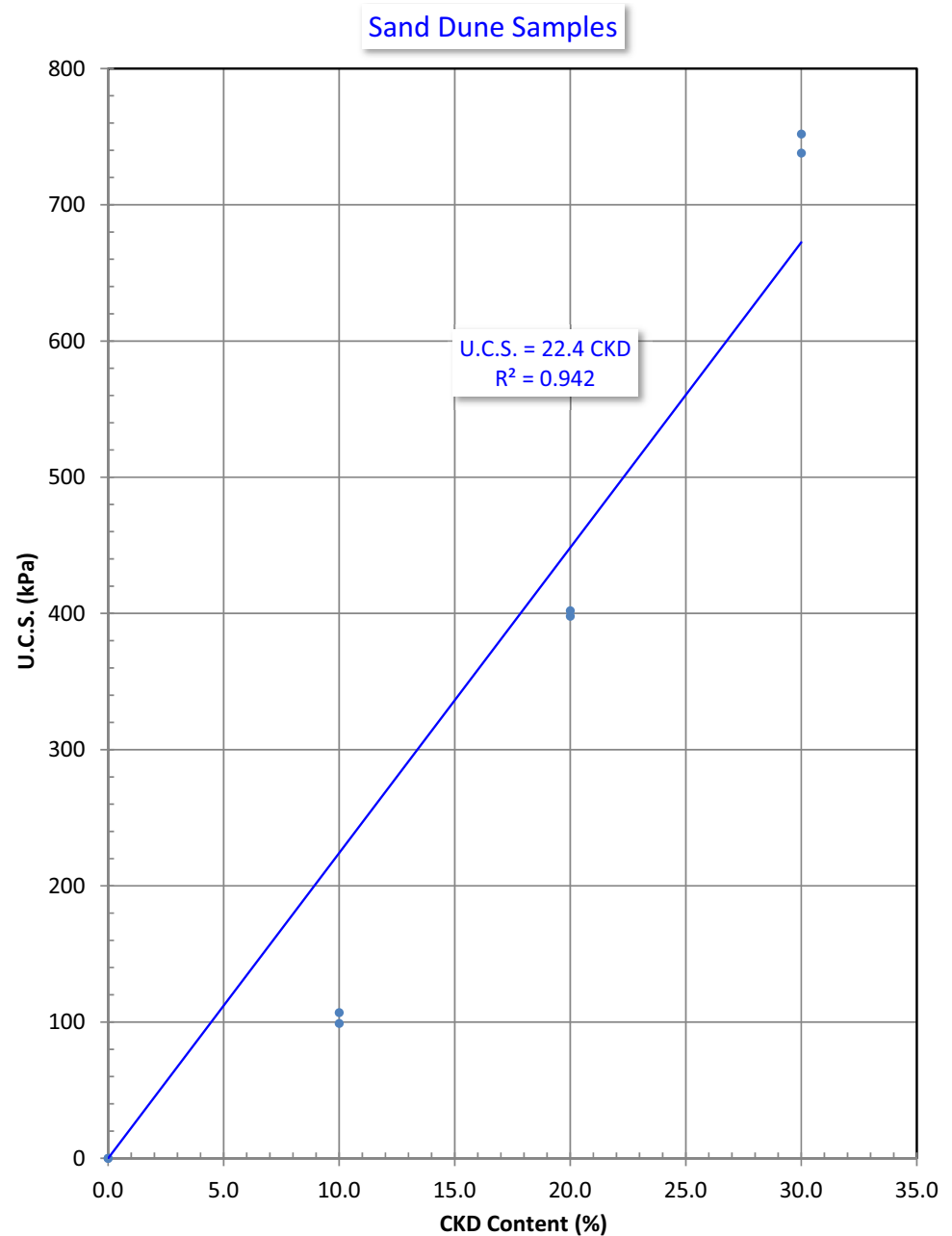
The U.C.S. was conducted on the sand specimen with 10, 20, and 30% of CKD mixtures after sealing and storing for 7 days, and the obtained U.C.S. values were plotted as a function of the CKD content (Fig. 8). It is indicated that the U.C.S. values increase with increasing CKD content in a directly proportional relationship. The U.C.S. values of the sand samples mixed with 10, 20, and 30% are 107, 402,

and 752 kPa, respectively. The U.C.S. can be calculated in terms of the CKD content as follows:

$$U.C.S. = 22.4 \times CKD R^2 = 0.942, \quad (2)$$

where U.C.S. of sand stabilized with different CKD contents (kPa), and CKD is the CKD content (%). For the present study, the measured U.C.S. values of the sand grains mixed with the different ratios of the CKD contents are relatively

Fig. 8 Effect of CKD content on the U.C.S. of Sand Dune samples (7-day sealed curing)



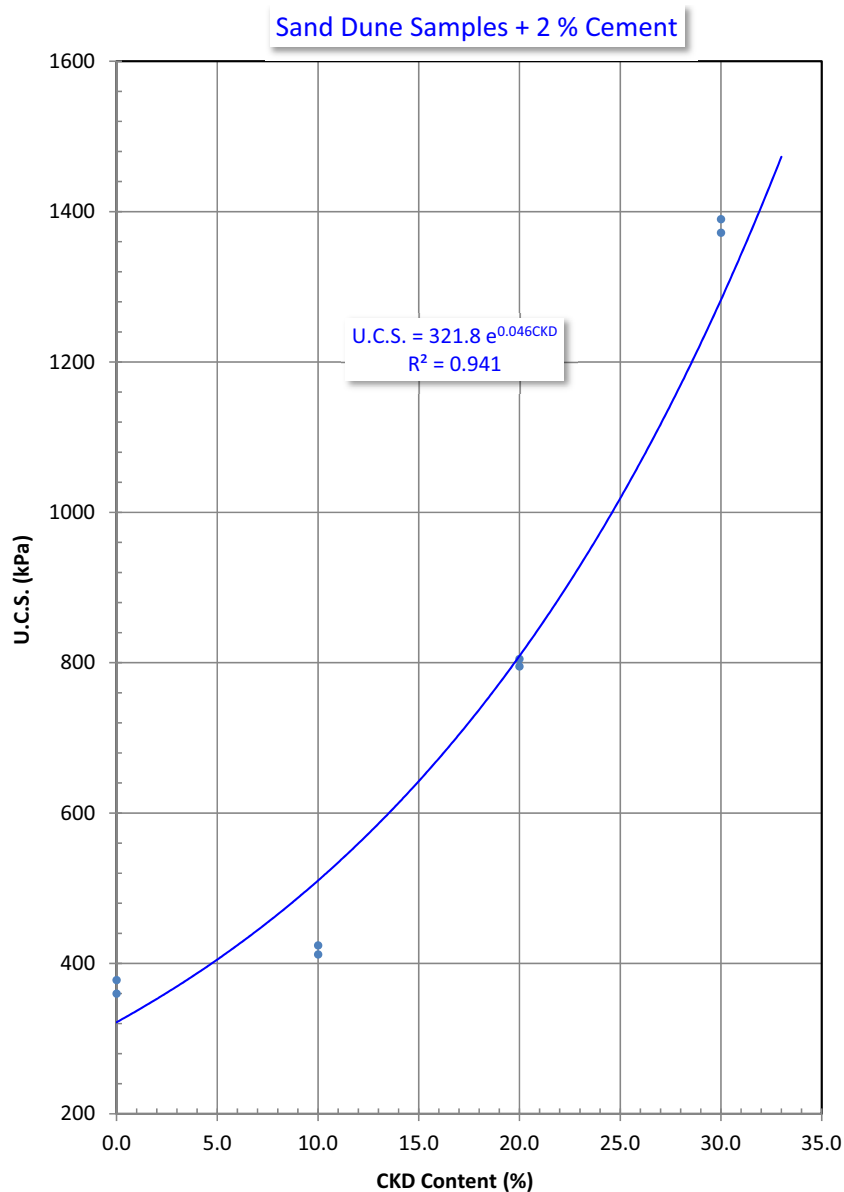
low. The U.C.S. values of the sand samples mixed with up to 30% CKD (Fig. 8) do not satisfy the minimum U.C.S. value (1380 kPa) that has been referred by A.C.I. [38] for sub-base application in rigid pavements. Therefore, properties of the obtained mixtures due to adding the CKD alone to the sand grains without cement do not fulfill the minimum A.C.I. requirements needed for the stabilization process. This could be attributed to the poor sorting of sand samples and the high L.O.I. and alkalis in the CKD additives. Therefore, adding some amounts of cement is required to enhance the U.C.S. of the sand and CKD mixtures to fulfill the A.C.I. requirements.

Effect of both cement and CKD on the U.C.S.

A U.C.S. test was then conducted on 27 sand dune samples that were enhanced with 2% cement, in addition to those with CKD scores of 10, 20, and 30% (Fig. 9).

The U.C.S. values of the enhanced sand samples increase with increase the amount of the added CKD, where adding the CKD caused increasing the U.C.S. values from 370, 420, 804 to 1383, respectively. The obtained data indicate a direct experiential relationship between the U.C.S. values and the CKD content, which can be modeled as follows:

Fig. 9 Effect of different CKD contents on the U.C.S. of Sand Dune samples with 2% cement that has been sealed for 7 days (blue circles), red solid circles refer to data imported from Al-Homidy et al. [25]



$$\text{U.C.S.} = 321.8 e^{0.046\text{CKD}} R^2 = 0.941, \quad (3)$$

where U.C.S. in kPa is the unconfined compressive strength of the sand samples that were stabilized with 2% cement and different CKD contents, and CKD is the CKD content in %.

Adding 30% CKD and 2% cement enhanced the U.C.S. values of the sand samples (1383 kPa) to fulfill the minimum required strength (1380 kPa) that has been referred to by A.C.I. [38] for the sub-base materials in the rigid pavements. This enhancement in the U.C.S. by adding 30% CKD and 2% cement was mostly explained by the fact that adding the 2% cement satisfied the requirement for cementing paste, whereas the CKD content served as a filling material.

It is shown that all the sand samples with 2, 5, or 7% cement plus 30% CKD met the A.C.I. strength

requirements, whereas adding the 30% CKD reduced the required cement to reach the minimum accepted U.C.S. (1380 kPa, following the A.C.I., [38]) from 7 to 2%. This reduction in the required amounts of cement will reasonably reduce the cost of stabilizing the sand samples.

Results of soaked C.B.R. tests

Specimens of sand dune samples have been treated with the 2% cement and stabilized with the CKD content that satisfies the estimated strength limit following ASTM D1883-16 [39] recommendations. The impacts of each stabilizer additive on the soaked C.B.R. of sand samples are discussed as follows:

C.B.R. of cement-stabilized dune sands

The obtained results of the soaked C.B.R. of the dune samples were correlated with the data imported from Al-Homidy et al. [25] to compare the impacts of cement content on sand dune samples with the impacts of electric arc furnace dust and cement on the sand samples (Fig. 10).

From the present study, it is apparent that the soaked C.B.R. values of the studied sand dunes samples increase with increasing added amounts of cement (Fig. 10). The soaked C.B.R. values are 183, 266, and 448% for the sand dune samples after adding the cement as 2, 5, and 7% of the bulk sample, respectively. This result is similar to those mentioned by Abdullah [37], who mentioned that the

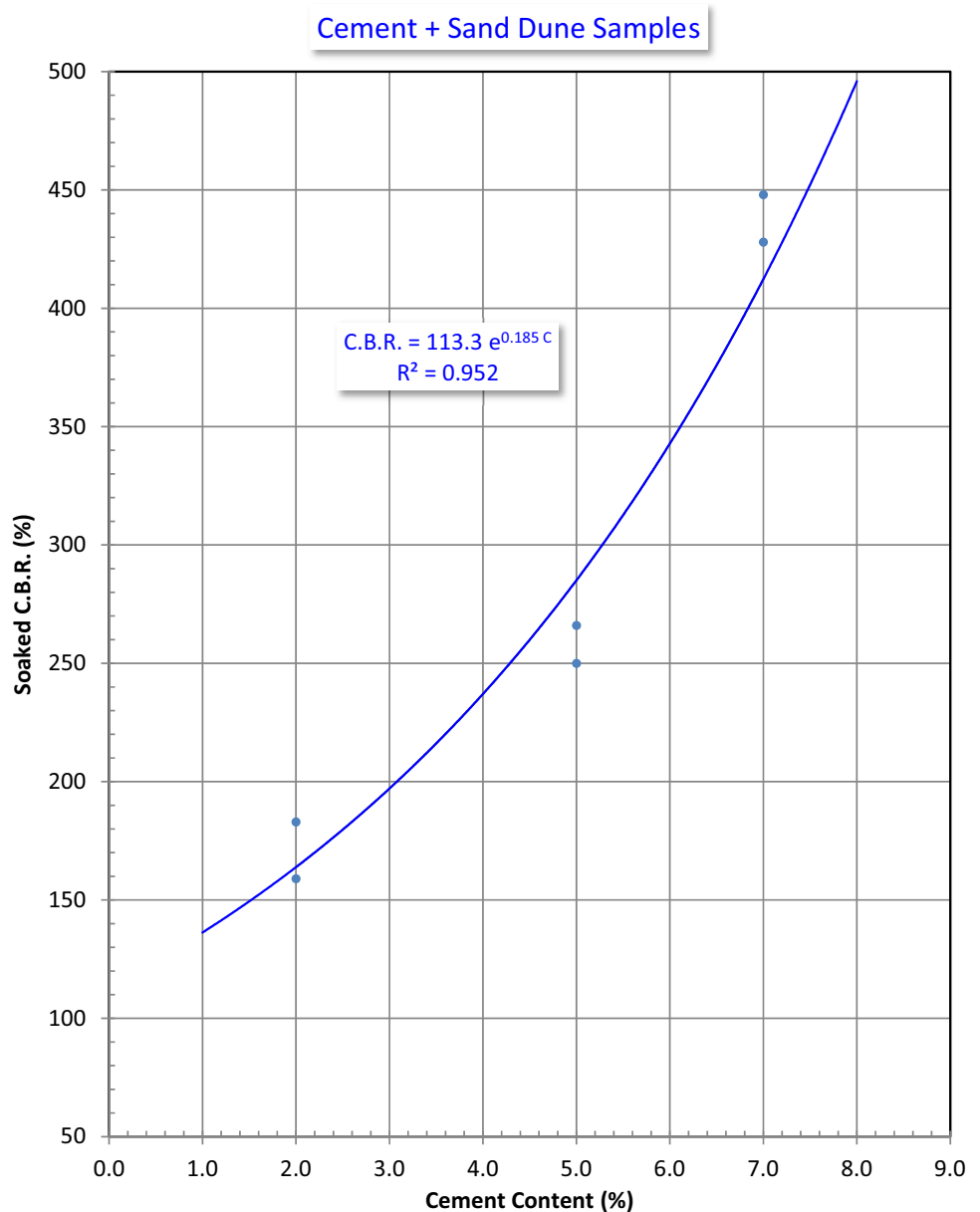
soaked C.B.R. of sand dunes with 2 and 5% cement has been enhanced from 181 to 273%. This similarity could be attributed to the stability of the sand dune samples, which are not sensitive to water.

Plotting the soaked C.B.R. as a function of the cement content indicated that the amount of added cement and the soaked C.B.R. values are closely related in an empirical relationship of high reliability as follows:

$$\text{Soaked C.B.R.} = 113.3 e^{0.185C} R^2 = 0.952, \quad (4)$$

where C.B.R. in % is the California Bearing Ratio of the sand dune samples with added cement (sealed and stored for 7 days), and C is its cement content (%). The obtained

Fig. 10 Effect of cement content on soaked C.B.R. of Sand Dune samples that have been sealed for 7 days (blue circles), red solid circles refer to data imported from Al-Homidy et al. [25]



C.B.R. results support and confirm the obtained U.C.S. results, which indicate that 2–7% cement increases the quality of the sand dunes as a basal course.

Soaked C.B.R. of cement and CKD-stabilized sand dune samples

The soaked C.B.R. values of the sand dune samples that were mixed with 2% cement and 10–30% CKD are plotted as a function of the CKD content as shown in Fig. 11. Similar to the U.C.S. values, it is indicated that the soaked C.B.R. values increase with an increasing CKD percentage. The C.B.R. values are 198, 286, and 404% for the different samples, whereas the soaked C.B.R. of sand dunes with 2% cement and no CKD is 183% (Fig. 11). All the added contents of CKD and 2% cement significantly enhanced the soaked C.B.R. values of the sand dune samples (C.B.R. > 50%) to make it a suitable material as the base course in pavement.

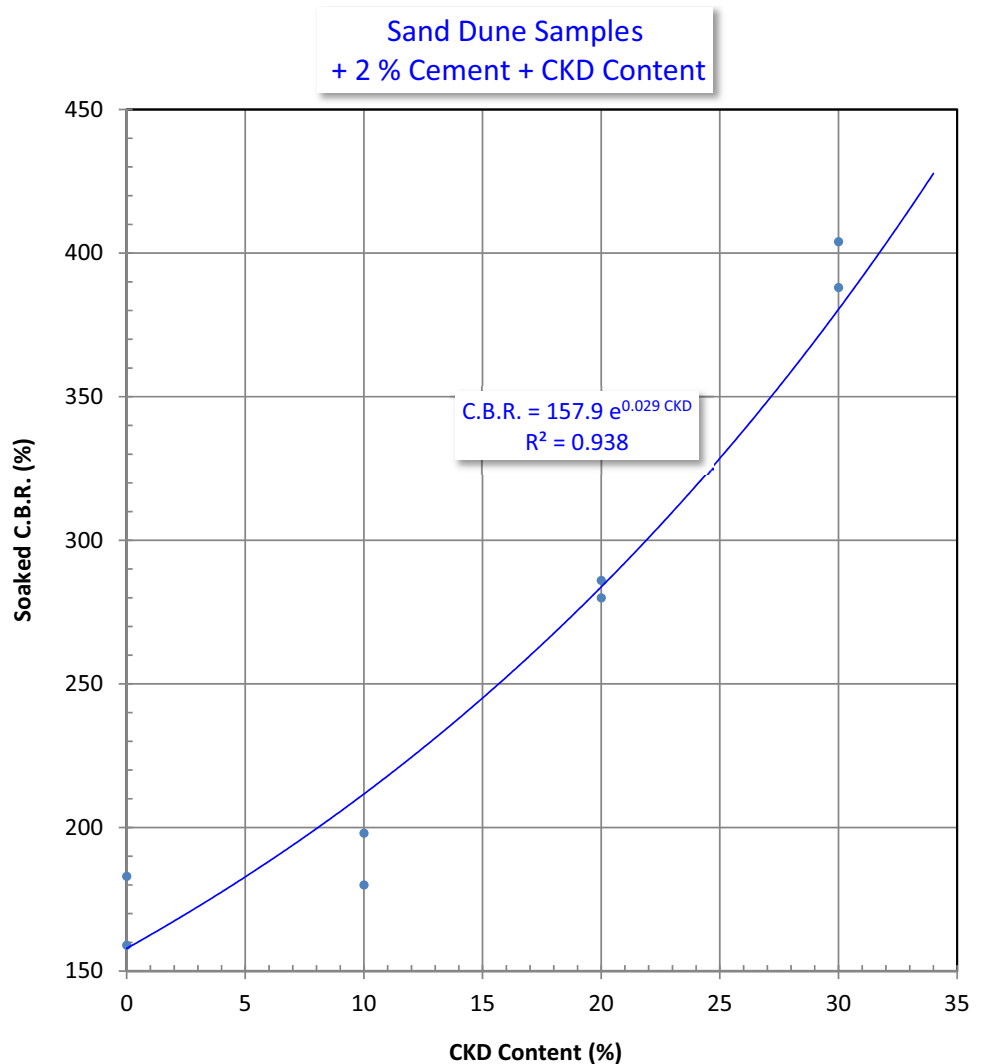
Abdullah [37] mentioned that adding 10 and 20% CKD and 2% cement enhanced the CBR values of the stabilized sand samples by 353 and 486%, respectively. Differences in the obtained data between the present study and that by Abdullah [37] are attributed to the differences in the applied optimum moisture contents in the two studies.

The obtained data of the soaked C.B.R. of the final mixture indicate an exponential relationship with high reliability between the soaked C.B.R. of dune sand with 2% cement and the added amounts of CKD ($R^2 = 0.938$, Fig. 11). This relationship can be expressed as a mathematical model as follows:

$$\text{Soaked C.B.R.} = 157.9 e^{0.029 \text{CKD}} R^2 = 0.938, \quad (5)$$

where C.B.R. in % is the California bearing ratio of sand dune samples mixed with 2% cement and different quantities of CKD (sealed and stored for 7 days).

Fig. 11 Effect of CKD content on soaked C.B.R. of Sand Dune samples with 2% cement that has been sealed for 7 days (blue circles), red solid circles refer to data imported from Al-Homidy et al. [25]



Also, the obtained data indicates that the soaked C.B.R. values of sand samples with 2% cement and 10, 20, and 30% CKD are higher than 50% (Fig. 11), which makes the stabilized sand dune samples more adequate for application in rigid pavement.

Durability tests

The wet and dry durability test was applied to declare whether the stabilized sand dune samples (that satisfy the minimum strength values) will retain its stability and behavior after long-term exposure to arid or wet environments. For the present study, an ASTM D559 [31] wet and dry durability test was carried out on the sand dune samples that were stabilized by the proposed stabilizers in the optimum quantities that satisfy the minimum U.C.S. values reported by the A.C.I. [38]. After preparing two samples of each of the studied mixtures, they were stored at room temperature in plastic bags for 7 days. The obtained samples were subjected to a total of 12 wet and dry cycles. The least weight loss percentage (6.3%) was assigned for the sand dunes that were stabilized with 7% cement, whereas the weight loss increased to 6.9% in the sand dunes samples that were stabilized by 2% cement and 30% CKD. The later loss of weight value (6.9%) is relatively lower than that stated by others (e.g., [37]; 8.2%). In general, the measured weight loss is lower than the limit of weight loss (11%), which has been mentioned by the U.S.A. Corporation of Engineers for soils of poorly sorted sand (as in the present study), and the 14% that was reported by the Portland Cement Association (P.C.A.). Therefore, the current stabilized sand samples could be used for construction purposes as sub-base materials for inflexible and rigid pavement because of the weight loss of stabilized sand is 6.7%. The weight loss was 6.7% in sand stabilized with 30% CKD plus 2% cement (Table 3).

Micro-characterization of the proposed stabilized sand dune mixtures

In this study, the enhanced U.C.S. values of the proposed stabilized sand dunes samples were obtained by mixing them with 2% cement and 10–30% CKD, which were studied and explained by using micro-characterization techniques. For this purpose, scanning electron microscopy (SEM), supplied with energy-dispersive X-ray analysis (EDX), and back-scattered electron image (BEI) were applied to identify the various phases and mineral composition of the prepared mixtures.

The grain arrangement of the obtained mixtures was examined and investigated using the SEM and BEI images (Fig. 12). The comparison between the BEI micrographs of the stabilized 2% and the stabilized 7% sand dunes (Fig. 12a, b) showed that voids in dunes sands stabilized with 2%

cement are larger than voids in dunes sands stabilized with 7% cement. Therefore, sand samples that were stabilized with 7% cement are denser than samples with 2% cement, which supports the higher dry density and U.C.S. of sand dunes stabilized with 7% cement. The SEM micrograph of sand dunes stabilized with 2% cement indicated the presence of a few bright spots of cement coating the sand grains and micro-sized pore spaces in between the grains, presented by darker, smaller spots (Fig. 12c). Besides, there are additional white fibrous bodies of the cementing gel that were developed by the 2% cement. The SEM for sand samples with 7% cement shows a denser morphology compared to the sand samples with 2% cement, with no pore spaces and more fibrous cement gel (C–S–H) bodies (Fig. 12d).

The EDX analysis of the sand dune sample stabilized by 2% cement mixture shows that the studied samples contain Si and Ca as major components (16.68 and 17.70%, respectively), and Al, Fe, K, and Zn as minor components (1.60, 1.25, 1.22, and 0.04%, respectively). The presence of Ca and Si as major components refers to the C–S–H component that was developed due to adding the 2% cement (Fig. 12e).

In similar to the sand dune sample stabilized by 2% cement mixture, Fig. 12f indicates that the prepared sand samples that were strengthened with 7% cement contained Ca and Si as major components but in higher amounts (20.65% and 19.03%, respectively) and Mg, Al, and Fe as minor components (0.80, 1.87, and 1.56%, respectively). The increased amounts of calcium and silicon are due to the presence of higher amounts of cement (7%) in the sand samples in comparison with the sand samples that were strengthened with 2% cement. Consequently, the enhancement in the U.C.S. values is higher due to the increased cementing gel.

On the other side, the BEI micrograph of the sand dune samples strengthened by 30% CKD and 2% cement declares the presence of a dense micro-structure and indicates a decrease in the number of pore spaces (Fig. 13a) in comparison with the BEI images of the sand dune samples that were stabilized with 2% cement (Fig. 12a). Also, the SEM image of the sand samples that were strengthened by 30% CKD and 2% cement shows a dense micro-structure with much more cement C–S–H gel (Fig. 13b). Finally, the EDX data of the proposed sand dune mixture show the presence of Si and Ca as major components (15.25 and 27.05%, respectively), and Al, Cl, and Fe as minor components (1.50, 0.99, and 0.98%, respectively) (Fig. 13c). As mentioned before, increasing the Si and Ca content indicates increasing the C–S–H fibrous bodies.

Therefore, the strength and chemical properties of the obtained sand dune stabilized by 2% cement and 30% CKD mixture have the optimal properties and cost compared with the 7% cement sand dune sample, which shows better properties. As the most widely used conventional soil stabilizing material, cement is well known to be both

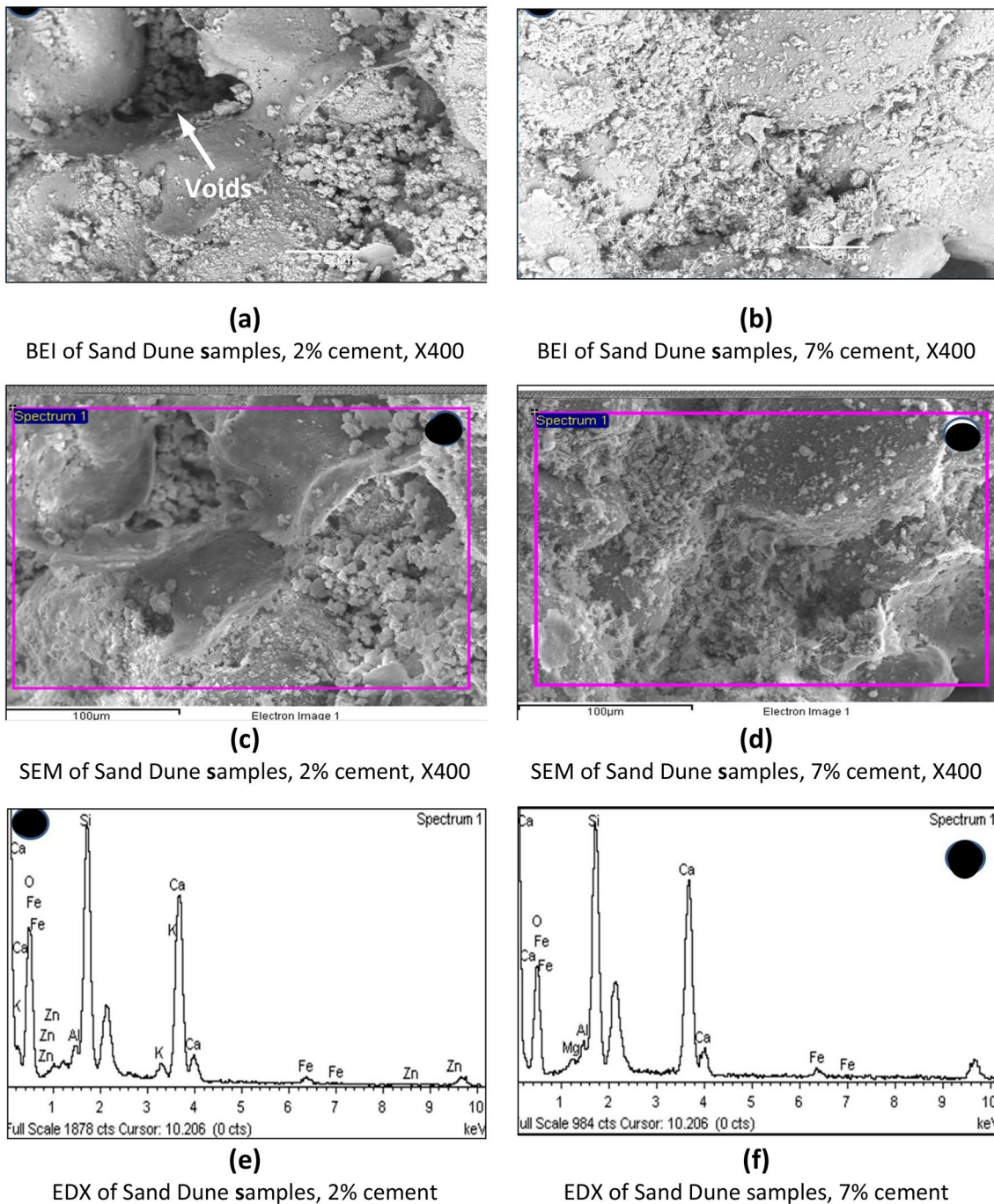
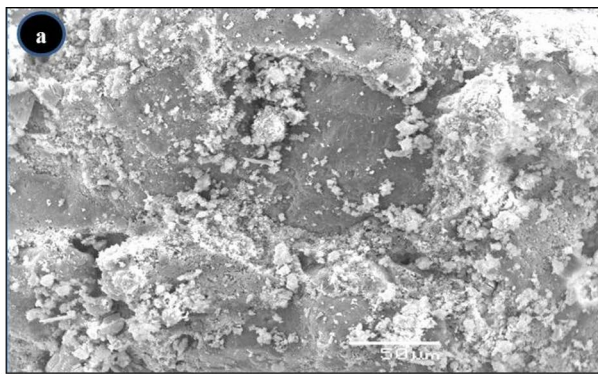


Fig. 12 BEI (a, b), SEM (c, d), and EDX (e, f) of Sand Dune samples stabilized with 2 and 7% cement (7-Day sealed curing) [25]

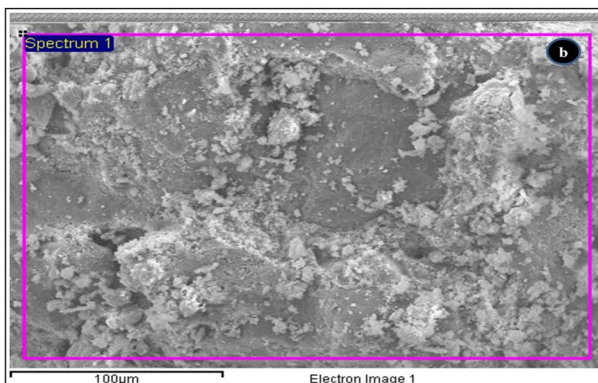
expensive and energy intensive to produce. Additionally, the production of cement produces greenhouse gases that are bad for the environment. As a result, there are widespread efforts to employ materials other than cement in construction. However, the materials must be economical and environmentally friendly. On the other hand, the price

of one ton of cement was assumed to be SR 300. Other materials, such as CKD, were regarded free (as waste materials), with a loading cost of 5 SR/ton and a shipping cost of 10 SR/ton. The transportation cost of material from Najran to the site was projected to be SR 300 for a truck with a capacity of 30 tons, which is economically feasible.



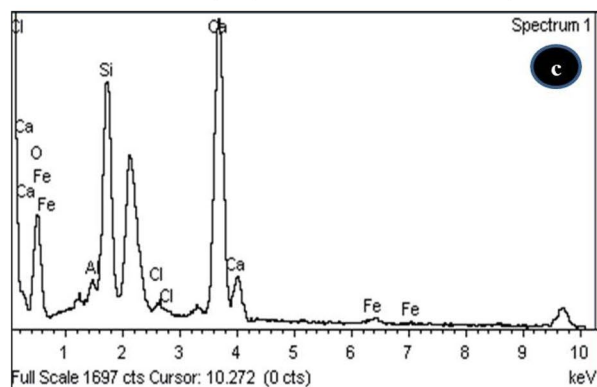
(a)

BEI of Sand Dune samples, 2% cement and plus 30% CKD, X400



(b)

SEM of Sand Dune samples, 2% cement and 30% CKD, X400.



(c)

EDX of Sand Dune samples, 2% cement and 30% CKD.

Fig. 13 BEI, SEM, and EDX of Sand Dune samples stabilized with 2% cement and 30% CKD (7-Day Sealed Curing)

Conclusions

This study focused on evaluating the enhanced effect of adding 2% cement and 30% cement kiln dust (CKD) to stabilize sand dune soils that were classified as A-3 types and poorly sorted soils following the AASHTO and USCS classification systems, respectively. From the obtained experimental

results of the studied mixtures, the following achievements could be concluded:

The U.C.S. of dune sands mixed with 2% cement and different percentages of CKD (10, 20 and 30%) increases with increasing the CKD percentage according to the exposure relationship and could be calculated in terms of each other using a mathematical model of very high significance and very high correlation coefficients ($R=1$). Using the CKD content alone without adding cement is not effective in stabilizing sand dunes.

Adding the 30% CKD and 2% cement increased the U.C.S. of the sand dune samples and their soaked C.B.R. values as well.

The soaked C.B.R. values of samples that were mixed with 2% cement and 10, 20, or 30% CKD are highly enhanced over those of untreated samples (0% cement, 0% CKD) and are preferably used as a base course in pavements.

Sand samples with a 30% CKD ratio and 2% cement indicate the optimum C.B.R. and U.C.S. values.

The dune sands treated with 7% cement with no CKD content or with 30% CKD plus 2% cement satisfy the A.C.I. strength.

Using 30% CKD reduced the amount of cement required for stabilizing the sand dunes from 7 to 2% (about 75% of cement), and therefore it is more economical.

Modeling the impact of adding cement and CKD content to the dune sand in different proportions enabled a precise prediction ($0.938 \leq R^2$) of these additives' impact on the final geomechanical properties of the dune sand.

Finally, the project site (where the pavement was assumed to be constructed) was located in the Dhahran area. The price of one ton of cement was assumed to be SR 300. Other materials, such as CKD, were considered free (as waste materials), with a loading cost of 5 SR/ton and a transportation cost of 10 SR/ton. The transportation cost of material from Najran to the site was estimated to be SR 300 for a truck of 30 tons capacity, which is economically feasible.

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Declarations

Conflict of interest The authors hereby declare that they have no conflict of interest. They received a grant no. (NU/RCP/SERC/12/7) from the deanship of Scientific Research in Najran University, K.S.A., and under the supervision of the scientific Research Centre at Najran University under the Research Centers Funding program, to support the financial fund for carrying out the present experiments. The authors also confirm that they did not receive a speaker honorarium from any companies and do not own stock in companies. Besides, all the authors are not committee members in any organizations that may cause a conflict of interest.

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