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Sustainable Stabilization of Poorly Graded Desert Sand by Cement Kiln Dust and Salt Water for Using in Backfilling and Subbase Layers

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Abstract

Effective use of natural materials and industrial by products has a direct impact on economy, sustainable environment, and waste management. Poorly graded desert sand (SP) is widely observed in sand dunes and sand seas. Studies were performed to get beneficial use of cement kiln dust (CKD) in soil improvement. But there is a lack of information concerning using of CKD as an improving material for poorly graded sand with the aid of salt water. Salt water is widely available in Egypt from seas and some deep wells, using it will help in saving drink water which suffers from shortage in many countries. The aim of this research is to study the possibility of improving SP using CKD and salt water to be used in backfilling work and subbase layers of roads and pavements. Mixtures of poorly graded sand and various CKD ratios (10%, 20% and 30%) were classified and tested using grain size distribution, compaction, shear strength and California bearing tests. The results were compared with potable water. The results show that adding CKD improves the characteristic properties of SP even with salt water. The study enhances the using of 20% CKD with optimum water content of 9.12% of salt water to have noticeable improvement for SP and to be used efficiently in backfilling and subbase layers.

Keywords

soil improvement, waste management, cement kiln dust, salt water, sustainability, strength

1 Introduction

Sand accumulations nearly covers whole of Egypt. A large portion of this sand is present in the form of sand dunes and sand seas. Sand dunes are found in deserts and near shores. Sand dunes are mostly composed of poorly graded fine sand. While poorly graded coarse sand are particles which remain behind due to several cycles of high wind speeds which remove finer grains and leave coarser ones. This poorly graded coarse sand is found at the plinths of draa ridges (large sand dunes) [1–3].

Salt water is also widely available in Egypt from seas and deep wells. Using salt water in ground improvement techniques is a prospective trend to encounter global shortage in fresh water specially in Egypt [4]. Sand is involved in many geotechnical aspects; it could be used in backfilling and as a subbase layer for roads and pavements after improving its properties instead of crushed stone [5–10]. The utilization of by products in improving sand geotechnical and bearing properties is of big benefit for any country from the environmental and economical point of view [11–16]. This benefit could be magnified if we add to it the usage of salt water in stabilizing process. Due to buildings construction and road networks are widely spread all over country, using salt water in stabilization could be inevitable in many locations.

Cement kiln dust (CKD) is a by-product produced in massive amounts in the form of fine cementitious powder during cement manufacturing. Unproper disposal of CKD has many environmental hazards [17]. Studies have been performed to get benefit of cement kiln dust in many applications [18, 19]. Some of these studies investigated the improvement of properties of well graded sand in roads and pavements with fresh potable water [20–23]. But there is a lack of information concerning using of cement kiln dust (CKD) as an improving material for poorly graded sand with the aid of salt water.

In this research, CKD was used as a filling and hydraulic binder material, and it was mixed with sand and salt water to enhance sand properties to be used as a sub-base

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material for pavements and road construction. Material properties of this mixture were presented. The main performed laboratory tests concentrate on, grain size distribution, compaction, CBR and direct shear tests which reflect the main properties required for the design of roads and pavements subbase layers.

2 Materials and methods

2.1 Materials

The materials used in this study are sand, CKD, potable water, and salt water. The material properties are as following.

2.1.1 Sand

The sand is imported from a dune land in the western desert in Egypt administratively belongs to the boundaries of 6th of October city. Grain size distribution test was done on the sand soil sample using the sieve analysis method in accordance with the ASTM C136 [24] standard. It is classified coarse to medium sand according to sieve gradation analysis as shown in Fig. 1. The whole sand sample passes from sieve No. 4 and the fines content are about 7.5%, finesse modeless is 2.90 and Coefficient of gradation *Cu* is 4.48 less than 6 so it is classified as poorly graded sand according to Unified Soil Classification System (USCS) as per ASTM D-2487 [25]. Sand is siliceous according to visual classification. Specific gravity test was conducted on three sand samples giving an average *Gs* value of about 2.525. Table 1 summarizes the properties of sand.

2.1.2 CKD

Cement kiln dust is used as a fine, powdery material hydraulic binder, and it is obtained from Al Arabia for Cement (AAC) factory in Ain Sokhna zone in a fresh condition from a single production batch to have constant properties and was isolated in sealed vessel all over the research period to avoid moisture effect. Materials were stored in room temperature at about 23 to 28°C. Chemical analysis was performed on CKD using x-rays test as per ASTM C114 [26]. The chemical composition is presented in Table 2 for a CKD sample. It is observed that CKD consists of four major components: unreacted raw feed, partially calcined feed and clinker dust, free lime, and enriched salts of alkali sulphates, halides, and other volatile compounds. When potable water is added to CKD and dried it is observed a thick layer of salts covering the surface of the sample. Consequently, adding salt water to CKD resulted in more salt content.

Particles size distribution test was done according to ASTM D422 [27] on CKD using the (151-H) hydrometer. The grain size distribution curve for CKD represents a generally fine material with almost 90% in silt size (0.002 > *D* > 0.06) as shown in Fig. 2. The specific gravity of CKD is 2.738 based on ASTM D854-92 [28]. CKD is used

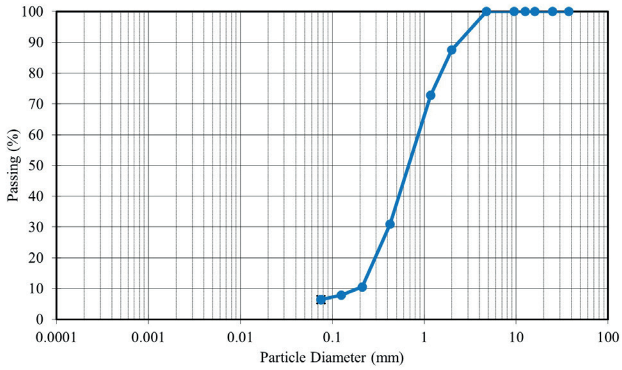

Fig. 1 Grain size distribution curve for the utilized sand

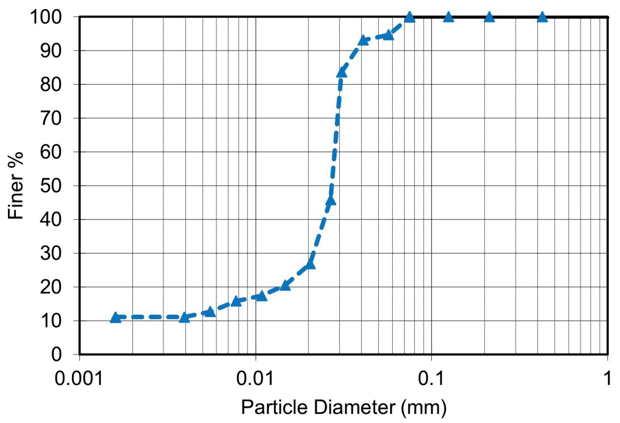

Fig. 2 Grain size distribution curve for the CKD sample

Table 1 Physical properties of sand

Sample	Fines % < 80 μm	Fineness modulus, FM	*D*10 (mm)	*D*30 (mm)	*D*60 (mm)	Coefficient of gradation *Cu*	Coefficient of curvature *Cc*	Specific gravity
Sand	7.5	2.9	0.19	0.412	0.865	4.486	1.021	2.525

Table 2 Chemical composition of CKD

Chemical composition	Silicon Dioxide, SiO_2	Aluminum Oxide, Al_2O_3	Iron Oxide, Fe_2O_3	Calcium Oxide, CaO	Magnesium Oxide, MgO	Sodium Oxide, Na_2O	Potassium Oxide, K_2O	Sulphur Trioxide, SO_3	Loss of Ignition
Percentage	13.857	4.528	2.986	56.909	2.966	1.488	5.515	2.18	2.112

as hydraulic binder to improve the properties of the poorly graded sand widely spreading in the stated zone. Small-scale soil structure and chemical tests studying the effect of CKD as a filling and binder material aren't included in this study as tests were performed immediately after mixing. Their effects are studied from the geotechnical point of view using geotechnical tests.

2.1.3 Water

Potable water (PW) and salt water (SW) are used as lubricants in compaction process. Potable water was gotten from ordinary tap water purified from Nile River. Saltwater salinity was 35 parts per thousand of normal table salt and composed mainly of sodium chloride (NaCl).

2.2 Methods

This research deals with the effect of CKD and water type on poor graded sand. Four groups of tests were carried out on the Sand-CKD mixtures consists of grain size distributions, compaction tests, California bearing ratio, and direct shear tests. Tests were conducted to investigate the effect of CKD percentage in CKD-Sand mixtures on the geotechnical mixture properties. Table 3 summarizes the experimental program including testing groups and variables [24, 29–31]. The tests for the last three groups were performed using potable water and salt water as a mixing lubricant to study the impact of water salinity on results. Three different mixtures of 10%, 20% and 30% of CKD were mixed with sand by weight to form the Sand-CKD blends.

2.2.1 Grain size distributions

The sand used is classified as poorly graded sand, accordingly it was essential to know the effect of adding CKD on the grain size distribution. Fig. 3 shows the grain size distribution of Sand-CKD mixtures. Adding CKD shifts the gradation curve upward and decreases the curve inclination. This change indicates a decrease of large particles with the increase of fine particles fraction. To check the grain size improvement, coefficient of gradation *Cu* and coefficient of curvature *Cc* were calculated for the mixtures and compared with limits according to Unified Soil Classification System (USCS) according to the following criteria for well graded sand:

$$Cu = D60 / D10 > 6; \;\; Cc = (D30)2 / (D60 \times D10), \;\; 1 \le Cc \le 3 \quad (1)$$

*D*10, *D*30, and *D*60 are particles diameters (mm) corresponding to passing percentage of 10, 30, and 60, respectively.

Table 3 Experimental testing program

Group No.	Test No.	Test Type	Mixing Fluid Type	Sample Components
G1	1-1	Grain size distribution ASTM C136 [24]	Dry State	Sand
	1-2			Sand + 10% CKD
	1-3			Sand + 20% CKD
	1-4			Sand + 30% CKD
G2	1-1	Compaction Standard Proctor Method AASHTO T-99 [29]	Fresh Water	Sand
	1-2		Salt Water	
	1-3		Fresh Water	Sand + 10% CKD
	1-4		Salt Water	
	1-5		Fresh Water	Sand + 20% CKD
	1-6		Salt Water	
	1-7		Fresh Water	Sand + 30% CKD
	1-8		Salt Water	
G3	2-1	Un-soaked California Bearing Ratio ASTM D1883-21 [30]	Fresh Water	Sand
	2-2		Salt Water	
	2-3		Fresh Water	Sand + 10% CKD
	2-4		Salt Water	
	2-5		Fresh Water	Sand + 20% CKD
	2-6		Salt Water	
	2-7		Fresh Water	Sand + 30% CKD
	2-8		Salt Water	
G4	3-1	Direct Shear ASTM D 3080 [31]	Fresh Water	Sand
	3-2		Salt Water	
	3-3		Fresh Water	Sand + 10% CKD
	3-4		Salt Water	
	3-5		Fresh Water	Sand + 20% CKD
	3-6		Salt Water	
	3-7		Fresh Water	Sand + 30% CKD
	3-8		Salt Water	

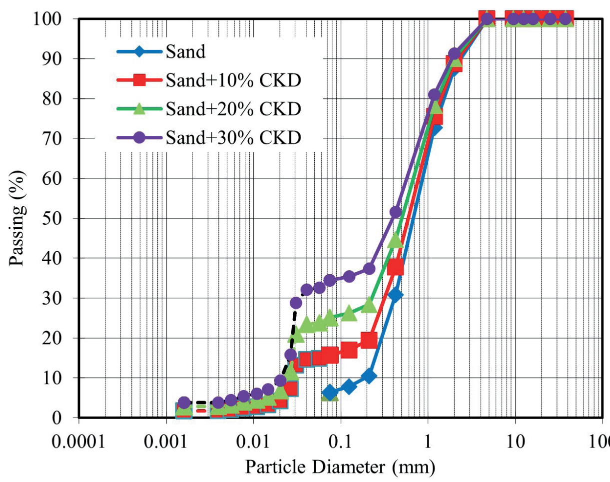

Fig. 3 Grain size distribution curve for the Sand-CKD mixtures

It is recommended that the last criteria should be used for fines content less than 5%, but it is used as an indication for improvement of the mixture gradation in many studies [8, 32, 33]. Hence, it was used as a sign of improvement in addition to the following experiments in the research. Table 4 shows the results of *Cu*, *Cc* and fineness modulus. According to criteria, sand mixed with 20% CKD is the nearest mixture to well graded condition and consequently it is expected to give the highest density and strength properties.

2.2.2 Compaction tests

The compaction is used to improve the densify of loose soil. It depends on decreasing the voids ratio in the soil to improve its strength capacity and decrease its settlement. In this test the sand-CKD mixtures were compacted to different water contents using standard proctor test according to AASHTO T-99 [29]. Compaction curves were graphed to specify the optimum water content and maximum dry density for each mixture. Tests were executed using potable water and salt water. Fig. 4 and Fig. 5 present the standard proctor curves for fresh water and salt water for Sand-CKD blends, respectively. Table 5 presents the results of the maximum dry density and its corresponding optimum water content for the three sand-CKD blends mixed with fresh water and salt water. The effect of water type on the maximum dry density of sand-CKD blends is shown in Fig. 6 and its effect on optimum water content is shown in Fig. 7.

Table 4 Mixtures grain properties

Mixture Type	coefficient of gradation *Cu*	coefficient of curvature *Cc*	Fineness Modulus of Sand
Sand + 0% CKD	4.486	1.021	2.9
sand + 10% CKD	27.19	4.52	2.61
sand + 20% CKD	27.66	3.1	2.33
sand + 30% CKD	27.12	0.098	2.03

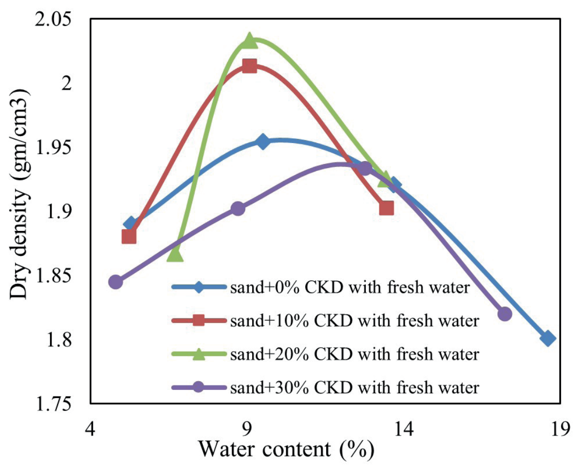

Fig. 4 Standard proctor curves for sand-CKD blends mixed with fresh water

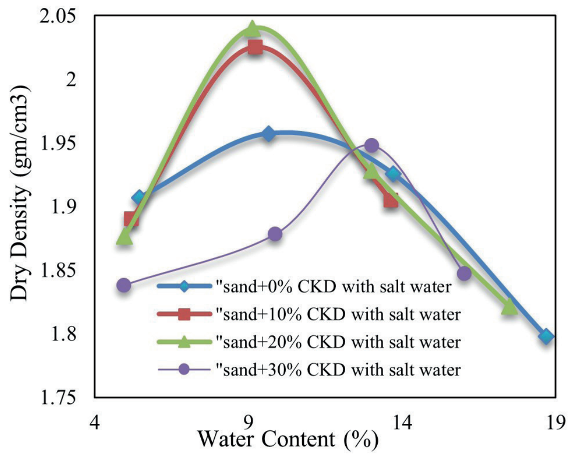

Fig. 5 Standard proctor curves for sand-CKD blends mixed with salt water

Table 5 Results of maximum dry density and its corresponding optimum water content for different sand-CKD mixtures

Tested Materials	Standard proctor test			
	Fresh water		Salt water	
	γ_d (gm/cm^3)	w_c (opt.) (%)	γ_d (gm/cm^3)	w_c (opt.) (%)
Sand + 0% CKD	1.954	9.508	1.957	9.664
sand + 10% CKD	2.013	9.088	2.025	9.22
sand + 20% CKD	2.033	9.077	2.04	9.125
sand + 30% CKD	1.933	12.756	1.948	13.006

The percentage of improvement of maximum dry density was calculated and shown in Fig. 8 for sand-CKD blends with respect to natural sand. And the deviation percentage of optimum water content of sand-CKD blends with respect to natural sand was shown in Fig. 9.

The following results could be observed from the presented figures:

1. Poorly graded sand mixed with CKD percentage of 10% and 20% gives higher maximum dry density and lower optimum water content compared to natural sand values. This improving behavior is due to adding CKD increases the fines content in the sample mixture to an adequate limit. Accordingly, it fills the voids in poorly graded sand and makes the whole sample much denser, this agrees with the results from grain size distribution.

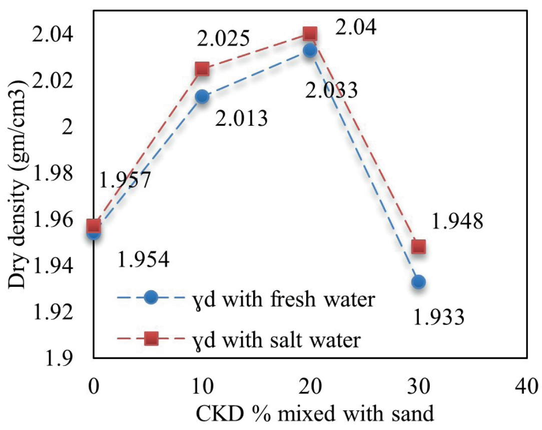

Fig. 6 Water type effect on the maximum dry density for sand-CKD blends

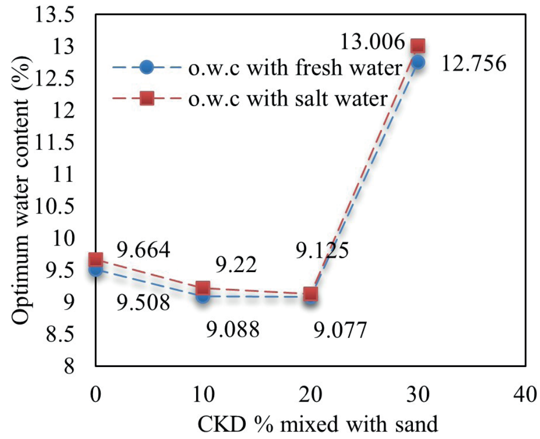

Fig. 7 Water type effect on the optimum water content for sand-CKD blends

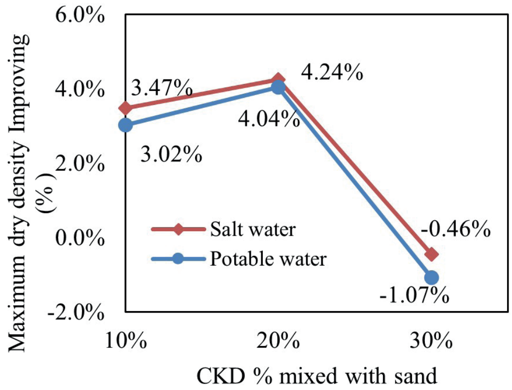

Fig. 8 Improving percentage of maximum dry density of sand-CKD blends with respect to natural sand

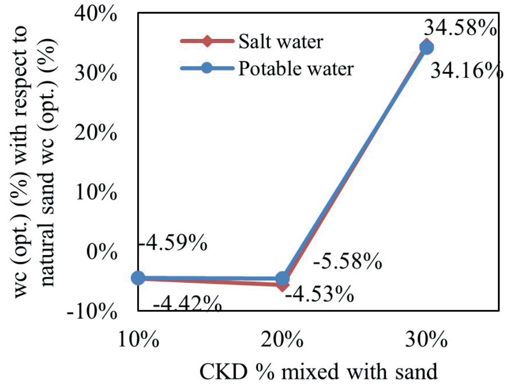

Fig. 9 Deviation percentage of optimum water content of sand-CKD blends with respect to natural sand

2. Adding 30% of CKD to sand resulted in decreasing of the maximum dry density γd(max) of sand and increasing the wc(opt.) required for compaction with a very high value (34% increase). This is due to increasing the CKD percentage leads to increase of the optimum water content, as it needs much water for compaction due to its powdery composition causing more water voids in sample. This causes a lower density on drying.
3. Mixing with saltwater gives a slight increase in maximum dry density than potable water as in Fig.6 with almost the same optimum water content as in Fig. 7 for all mixtures.
4. The improving percentage of 10% CKD is almost near to that from 20% CKD accordingly using 10% CKD has a noticeable effect on improving density.
5. Adding 30% of CKD is uneconomic in water consumption due to its high optimum water content required for compaction.
6. The values agrees with [8] in terms of compaction properties for improvement of dune sand.

2.2.3 Direct shear test

Direct shear tests were performed on both natural sand and mixtures of sand with CKD to investigate the effect of CKD content and mixing water type on the soil shear parameters. Direct shear tests were done according to ASTM D 3080 [31]. All samples were compacted statically in the shear box at the standard proctor maximum dry density. The test is performed using three normal stresses (0.5, 1 and 2 kg/cm^2) with a fast speed of 1 mm/sec.

Table 6 presents the results of direct shear test of mixtures with potable and salt water. Fig. 10 to Fig. 15 show the effect of CKD percentage mixed with potable water and salt water on the shear behavior of sand CKD mixtures subjected to different normal stresses. It is observed from the figures that the shear stress of the mixtures increases with the increase of CKD percentage in the sample.

Figs. 16 and 17 present the relationship between shear strength and the normal stress for blends mixed with potable water and salt water. The results show that mostly the blends of sand mixed with CKD and saltwater gives high shear strength than that mixed with potable water except

Table 6 Direct shear test results of sand-CKD blends with potable water and salt water

Sand -CKD blends	Sample no.	potable water				Salt water			
		Max vertical stress (*s*)	Max shear stress (*τf*)	Cohesion (*c*)	Angle of internal friction (*φ*)	Max vertical stress (*s*)	Max shear stress (*τf*)	Cohesion (*c*)	Angle of internal friction, (*φ*)
		kg/cm²	kg/cm²	kg/cm²	Degrees	kg/cm²	kg/cm²	kg/cm²	Degrees
	1	0.5	0.57	0.189	37.6	0.5	0.6	0.327	30.77
Sand + 0% CKD	2	1	0.97			1	0.96		
	3	2	1.73			2	1.51		
	1	0.5	0.78	0.215	44.55	0.5	0.88	0.34	44.3
Sand + 10% CKD	2	1	1.09			1	1.24		
	3	2	2.22			2	2.32		
	1	0.5	1.12	0.613	42.61	0.5	1.25	0.905	41.02
Sand + 20% CKD	2	1	1.47			1	1.91		
	3	2	2.48			2	2.6		
	1	0.5	1.45	0.496	62.9	0.5	1.27	0.658	53.16
Sand + 30% CKD	2	1	2.49			1	2.07		
	3	2	4.39			2	3.3		

for 30% CKD. A noticeable difference in stress appeared in the mix of 30% CKD between potable water and salt water compared with other mixtures. This decrease of results in mixing 30% of CKD with salt water could be attributed to the high content of salts in CKD as shown previously in chemical analysis. This high salt and dust content pushes the mixture to absorb more water as appeared in compaction results and results in increasing of voids ratio thus decreasing of shear strength. Also mixing sand with CKD and saltwater affects its hydration for high CKD percentages than lower and gives a high variance in results than for potable water as shown in 30% CKD results.

It is observed from results that using of salt water instead of fresh water resulted in increasing of mixture cohesion (c) for all samples as in Fig. 18. The increasing percentage in cohesion is 73.01% for natural sand without CKD, 58.14% for sand mixed with 10% CKD, 47.63% for sand mixed with 20% CKD and 32.66% for sand mixed with 30% CKD. Also, it is noted from results the increasing of CKD percentages for both types of water results in an increase in cohesion up to 20% of CKD then it decreases at 30% CKD.

While Fig. 19 shows that using of salt water resulted in decreasing of the angle of internal friction (Φ) for all samples. The decreasing percentage in internal friction is 18.16% for natural sand without CKD, 0.56% for sand mixed with 10% CKD, 3.73% for sand mixed with 20% CKD and 15.48% for sand mixed with 30% CKD. It is observed that the internal friction angle increases with the increase of CKD percentage except in 20% CKD a decrease appeared in friction angle and a high increase appeared in cohesion. These values agree with [8] in friction for CKD percentages of 10% and 20%.

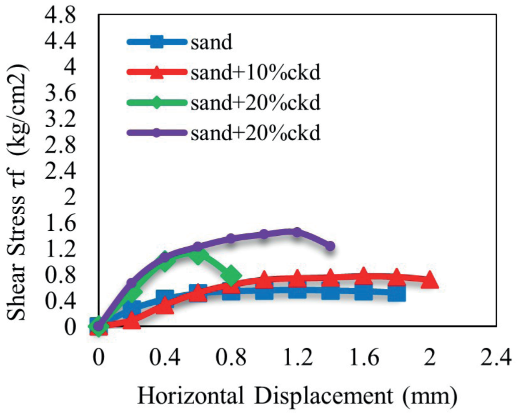

Fig. 10 Shear stress versus horizontal displacement for mixtures with potable water at normal stress = 0.50 kg/cm²

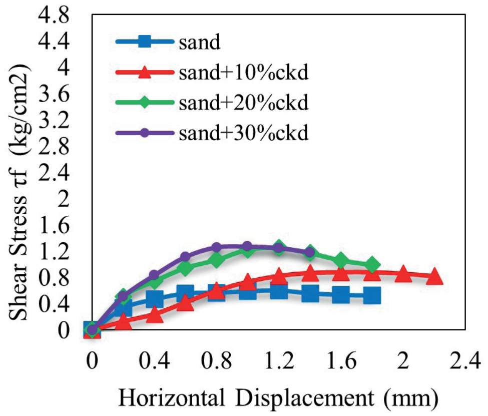

Fig. 11 Shear stress versus horizontal displacement for mixtures with salt water at normal stress = 0.50 kg/cm²

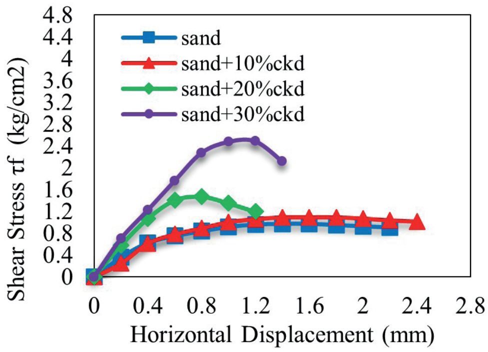

Fig. 12 Shear stress versus horizontal displacement for mixtures with potable water at normal stress = 1.00 kg/cm^2

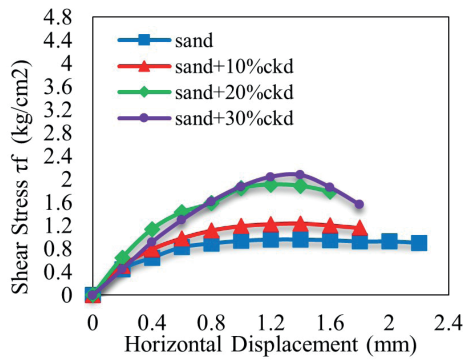

Fig. 13 Shear stress versus horizontal displacement for mixtures with salt water at normal stress = 1.00 kg/cm^2

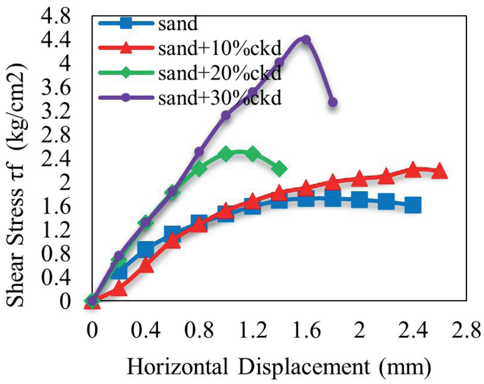

Fig. 14 Shear stress versus horizontal displacement for mixtures with potable water at normal stress = 2.00 kg/cm^2

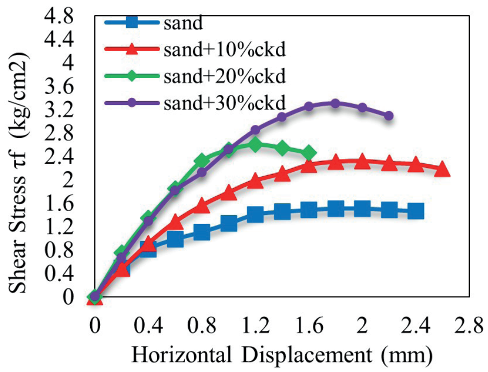

Fig. 15 Shear stress versus horizontal displacement for mixtures with salt water at normal stress = 2.00 kg/cm^2

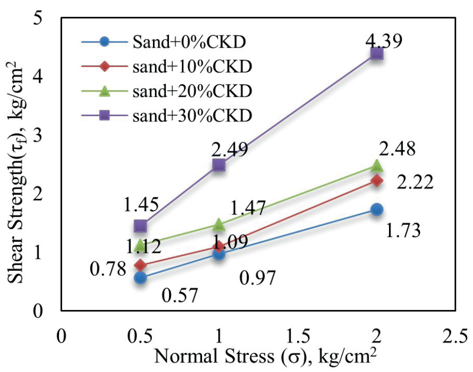

Fig. 16 Shear strength versus normal stress for mixtures using potable water

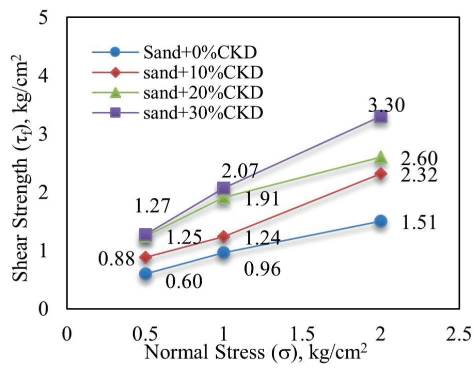

Fig. 17 Shear strength versus normal stress for mixtures using salt water

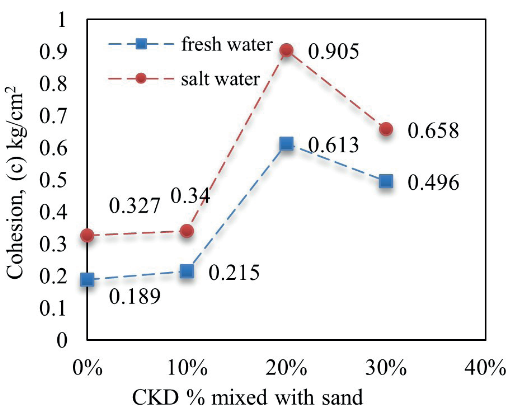

Fig. 18 Effect of water type on cohesion for sand-CKD mixtures

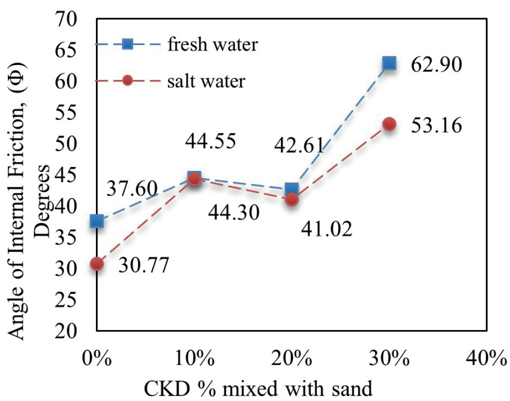

Fig. 19 Effect of water type on the angle of internal friction for sand-CKD mixtures

2.2.4 California bearing ratio tests (CBR)

Un-soaked CBR tests were performed on compacted samples of natural sand and mixtures of sand with CKD. The utilized mixtures were tested with potable water and salt water. The performed CBR tests were conducted in accordance with ASTM D1883-21 [30] standards. The tests were performed directly after compaction to decrease the CKD hydration effect to get more critical values and to simulate rapid construction stages of subgrades. Soaked tests weren't included in this study as soaking in water will cause CKD mixtures to hydrate, harden, and loose its plasticity according to CKD setting time. And the study is focusing on short term behavior of CKD added to poorly graded sand. In each test the mixture is inserted in the mold on three layers, each layer was compacted by 55 blows with a rammer of weight 2.6 kg dropping from 310 mm height. Each sample were tested two times, on the top face and on the bottom face. These two times were averaged at the end to get a CBR value with minor errors. In some graphs the CBR value was corrected as per standards to have the concave curve shape of the CBR.

Figs. 20 and 21 show the CBR relationship between load and penetration for sand mixed with 30% CKD as an example for the relationships showing top and bottom test results depending on type of mixed water. CBR test was performed for different mixtures with potable water and salt water and the CBR relationships for top face and bottom face are shown in Figs. 22 to 25 according to type of mixing water. General view on these results indicates that the CBR values increased with respect to increasing of sample penetration. And the resistance of the bottom face for penetration is higher than top face for all cases. Fig. 26 shows that natural sand has the minimum CBR value then the 30% CKD mixture, then it is followed by 10% CKD and the highest improved CBR% is for the 20% CKD mixture.

Sand-CKD blends with potable water resulted in high CBR values compared to salt water. Accordingly using salt water in mixing instead of potable water will cause decreasing of CBR ratio with 67.9% for natural sand without CKD, 50.7% for sand mixed with 10% CKD, 11.5% for sand mixed with 20% and 64.68% for sand mixed with 30% CKD. Otherwise improving of poorly graded sand

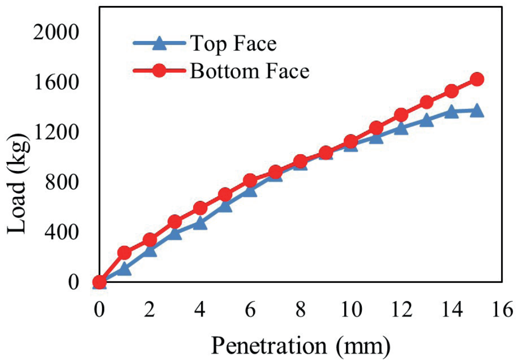

Fig. 20 Relationship between stress and penetration for CBR test on Sand-30% CKD mixed with potable water

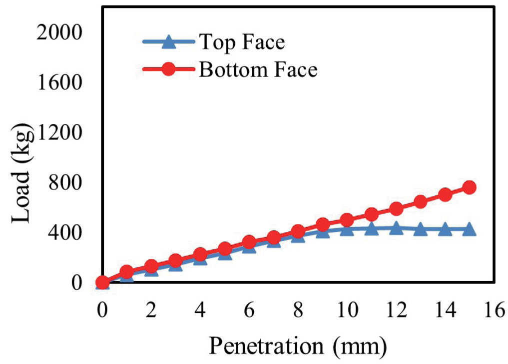

Fig. 21 Relationship between stress and penetration for CBR test on Sand-30% CKD mixed with salt water

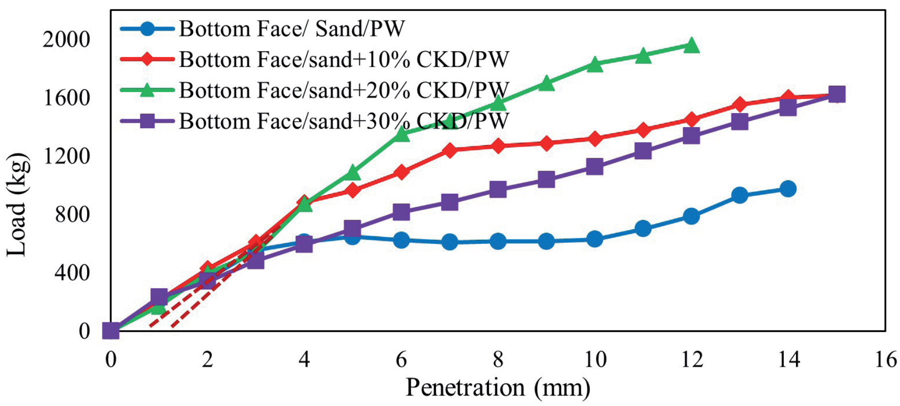

Fig. 22 Relationship between stress and penetration for CBR test on the bottom face for Sand-CKD blends mixed with potable water

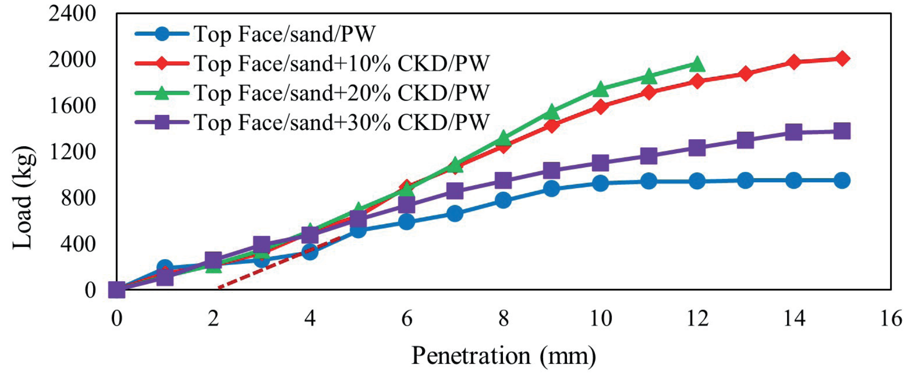

Fig. 23 Relationship between stress and penetration for CBR test on the top face for Sand-CKD blends mixed with potable water

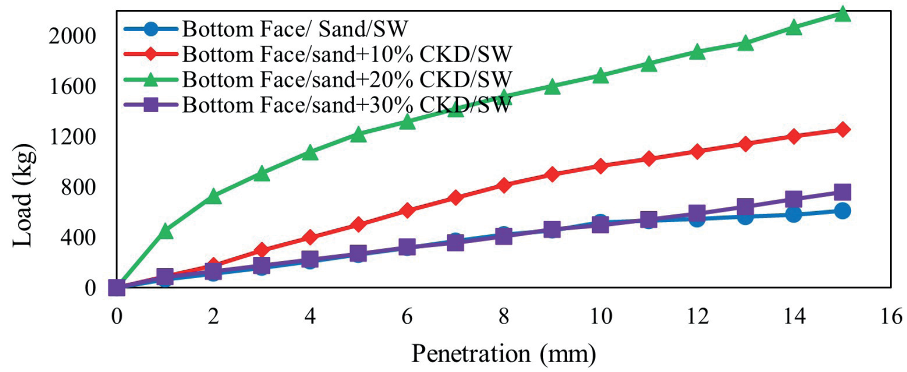

Fig. 24 Relationship between stress and penetration for CBR test on the bottom face for Sand-CKD blends mixed with salt water

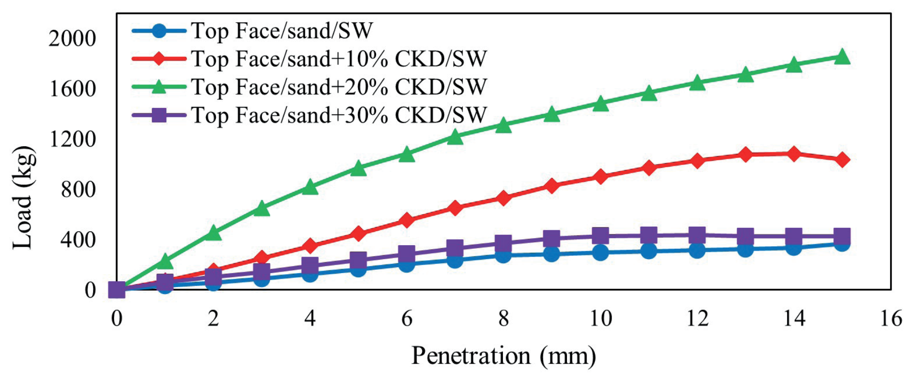

Fig. 25 Relationship between stress and penetration for CBR test on the top face for Sand-CKD blends mixed with salt water

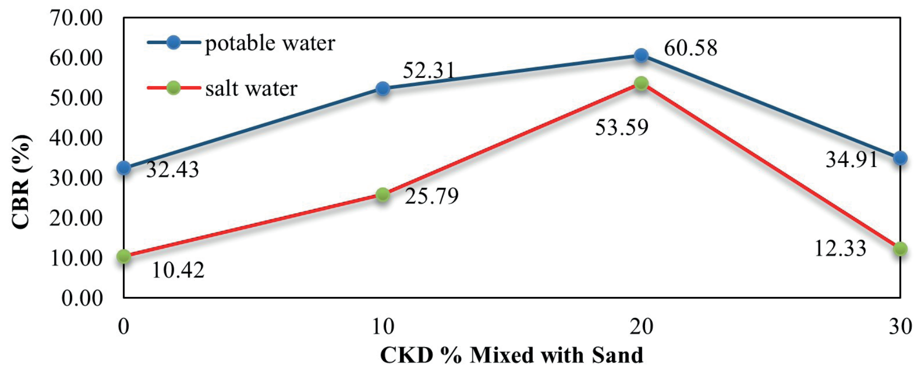

Fig. 26 Relationship between mixing CKD (%) with sand and average CBR (%) for Sand -CKD samples mixed with potable and salt water

of CBR value of 10.42% with 10% CKD reached a CBR value of 25.79% and 53.59% with 20% CKD. These are very promising results. The CBR value agree with [8] and as it is recommended for subbase layers to have CBR not less than 20–25% according to design loads. Accordingly, it is recommended to use 20% CKD in case of using salt water in mixing.

3 Conclusions

The utilization of by products in improving of poorly grade sand is of big benefit for any country from the environmental and economical point of view. Shortage of fresh water and regulations limiting its use, leads to the usage of salt water in improvement techniques. CKD is a byproduct affected by the type of water due to its rich in salt content. Salt water is widely available in Egypt. In this research, poorly graded sand was mixed with ratios of CKD and salt water. A series of geotechnical tests were performed to investigate the mixtures properties and evaluate its sufficiency to be used in backfill and subbase layers of roads and pavements. The studied mixtures were examined by the grain size distribution, compaction, direct shear, and California bearing tests. The conclusions can be drawn as follows:

1. Sand mixed with 20% CKD is the nearest mixture to improve the grain size gradation then 10% CKD, while 30% CKD is not recommended due to it decreases the coefficient of curvature *Cc* aggressively below allowed limits.
2. Poorly graded sand mixed with CKD percentage of 10% and 20% gives higher maximum dry density and lower optimum water content compared to natural sand values. While adding 30% of CKD resulted in decreasing of the maximum dry density γd(max) of sand and increasing of *wc*(opt.) with a very high percentage. It was observed in compaction that mixtures with saltwater gives a slight increase in maximum dry density than potable water with almost the same optimum water content for all mixtures. This enhances the use of salt water in compaction with 10% or 20% of CKD with optimum water content of about 9 % of salt water.
3. The direct shear results show that blends of sand mixed with CKD and saltwater gives high shear strength than that mixed with potable alt water except for 30%CKD. A noticeable difference in stress appeared in the mix of 30% CKD between potable water and salt water compared with other mixtures. Using salt water instead of fresh water resulted in increasing of cohesion (*c*) for all samples and the best value was for 20% CKD. While using of salt water instead of fresh water resulted in decreasing of the angle of internal friction (Φ) for all samples. The direct shear results enhance the using of salt water with 10% or 20% of CKD.
4. Sand-CKD blends mixed with potable water resulted in high CBR values compared to salt water. The least noticeable decrease is 11.5% for sand mixed with 20% other blends decreased much. These CBR results recommends the using of 20% CKD in case of using salt water rather than other CKD percentages.
5. According to results, the research enhances the using of salt water in improving of poorly graded sands with a CKD percentage of 20% with optimum water content of 9.12% of salt water.

Conflict of interest

The authors wish to confirm that there is no conflict of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

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