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Effect of Permeation Grouting Using Cement Kiln Dust (CKD) On Some Mechanical Properties of Sandy Soil

Faten Alsakr[1,*], Toufik Fayad [1] and Rami Alabdeh[1]
[1]College of Engineering, University of Tishreen, Syria
* Corresponding author: College of Engineering, University of Tishreen, Latakia, Syria. Tel: +963999574032.
ramihashimalabda@tishreen.edu.sy; tawfikabdoallahfiad@tishreen.edu.sy

ABSTRACT

Permeation grouting is a suitable technique to enhance the geotechnical characteristics of granular soils, several researches have proved that permeation grouting using conventional grouting materials has improved the behavior of the treated soils, but the use of conventional materials causes additional costs. Cement Kiln Dust (CKD) is a significant by-product produced in considerable quantities during the production of Ordinary Portland Cement. This study was conducted to assess the effect of permeation grouting using (CKD) grouts on enhancing some mechanical properties of coastal sandy soil in Syria. To achieve the objective of this study; a laboratory grouting model was manufactured. The studied sand has been grouted with suspensions consisting of different percentages of (CKD) (2, 4, 6, 8, 10, and 12%) as a proportion of the dry weight of the treated sand, and various mixing ratios (Water: CKD) (2:1, 4:1, 6:1, 8:1, and 10:1). Then an inclusive laboratory study was carried out before and after grouting for (7 & 28) days of treatment. The results of this study proved the effectiveness of (CKD) grouts; the grouted sand has obtained a high unconfined compressive strength. Also, the values of both shear strength and cohesion increase, and the values of permeability coefficient decrease as (CKD) content and curing period increase.

KEYWORDS: Grouted Sand; By-Products; UCS tests; Shear tests; Permeability tests.

1 INTRODUCTION

The geotechnical properties of weak soils can be modified using soil improvement technologies [1], [2]. Grouting is an advanced technique; it has been extensively applied in various applications of different fields of civil engineering. The main concept of grouting is to pump grouting materials in the form of different viscosity fluids under pressure into the rock fissures or the soil through small diameter tubes, thereby the geotechnical performance of the treated soil is improved. The types of grouting are permeation grouting, compaction grouting, jet grouting, and hydraulic fracturing. To get the best results, it is essential to select the appropriate type of grouting, grouting material, equipment of grouting, and pressure of grouting [3], [4],[5], [6].

The results of many researches have shown that permeation grouting has improved the engineering properties and the bearing capacity of the treated granular soils [5],[6],[7],[8],[9]. The most used grouting materials in previous studies are cement suspensions and chemical solutions. But on the one hand, the use of these materials is expensive. On the other hand, the cement industry causes the emission of 7% of the carbon dioxide (CO2) emitted globally, which is one of the most greenhouse gases contributing to global warming, as the manufacture of one ton of Ordinary Portland Cement reasons the production of a ton of this gas [10], [11]. So, it is preferable to limit the use of (OPC) in construction works. As for chemical solutions, in addition to their high cost, they have a toxic effect on soil, groundwater, and the environment.

Besides, they are low in durability as they lose their strength over time [12], [13], [14]. All the above must be considered when using conventional grouting materials.

In recent years, the use of industrial wastes has received widespread global attention because its accumulation poses an environmental and health hazard. Moreover, the disposal of them by landfilling is costly and requires vast areas. In this context, many researchers have recently been interested in the use of industrial wastes in the field of geotechnical engineering. (CKD) which is manufactured throughout the manufacturing of Portland cement, is one of these industrial wastes, it contains components almost like those in (OPC) such as lime, silica, and many metal oxides. Depending on several factors, e. g. the type of raw materials used in the manufacturing process, plant operation, extracting and disposal practices, (CKD) collection system, and the type of fuel used; chemical composition and physical properties of (CKD) differ significantly [15],[16]. (CKD) can be utilized to improve soil properties, and thereby eliminate its negative impacts on the environment, health, and cement industry [17],[18], [19], [20].

Sandy soils cover the Syrian coast and are considered weak soils due to their loose state at shallow depths, hence their low shear strength and low bearing capacity. Structures in this region are often constructed on deep footings, but this traditional solution is a costly one.

In this research, (CKD) produced in one of the local cement manufacturing plants in Syria was used to improve some mechanical characteristics of coastal sandy soil.

2 MATERIALS AND METHODS

2.1 Materials

Sand: The studied sand in this study was obtained from the beach of Snobar Jbleh town, which is in the southeast of Latakia city; (13 km) from the city center; " Figure. 1 ".

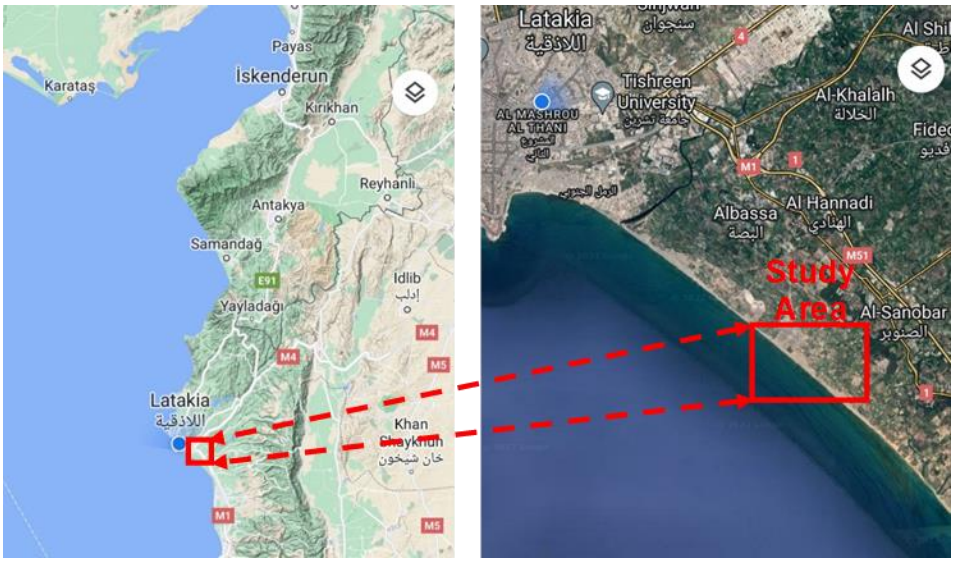

Figure 1. Location map and satellite image of the studied area

To obtain the properties of the sand, standard laboratory tests were performed. The physical and mechanical properties of the used sand are tabulated in "Table.1", and all tests were conducted according to (ASTM) Specifications [21]. The curve of the grain size distribution of the studied sand is illustrated in " Figure. 2".

Table 1. Properties of the studied Sand

Property	Value	Specification	Property	Value	Specification
Specific gravity, Gs	2.73	ASTM D854	Sand equivalent (%)	97.9	ASTM D2419
Moisture content (%)	2.6	ASTM D2216	e_{max}	0.88	ASTM D4254
Total unit weight (KN /m^3)	15.73	ASTM D7263	e_{min}	0.64	ASTM D4253
Maximum dry unit weight (KN /m^3)	16.7	ASTM D4253	Permeability K (cm/sec)	0.0013 3	ASTMD4234
Minimum dry unit weight (KN /m^3)	14.5	ASTM D4254	Coefficient of uniformity Cu	1.72	ASTM D2487
Relative density ID	41.67	ASTM D4254	Coefficient of curvature Cc	0.82	ASTM D2487
Angle of internal friction ø°	38.69°	ASTMD3080	Classification (USCS)	SP	ASTM D2487

Cement Kiln Dust (CKD): The used (CKD) in this study was obtained from a Tartous cement factory. The chemical analysis results are listed in "Table.2", while the physical and mechanical properties of (CKD) are listed in "Table.3", tests were done in the Tartous cement factory laboratory. The curve of the grain size distribution of (CKD) is illustrated in " Figure. 2".

Table 2. Chemical analysis results of the used cement kiln dust (CKD)

Chemical Composition	CaO	SiO2	Al_2O_3	Fe_2O_3	MgO	SO_3	Na_2O	K_2O	L.O. I
Percentage (%)	61.88	21.25	4.6	4.1	2.71	3.05	0.61	0.18	1.03

* L. O. I: Loss of ignition

Table 3. Properties of the used (CKD)

Property	Value
Specific gravity	3.1
Blaine's specific surface (cm^2/g)	3330
Initial setting time (min)	196
Final setting time (min)	287
Compressive strength (N/mm^2) (7 days)	34
Compressive strength (N/mm^2) (28 days)	41

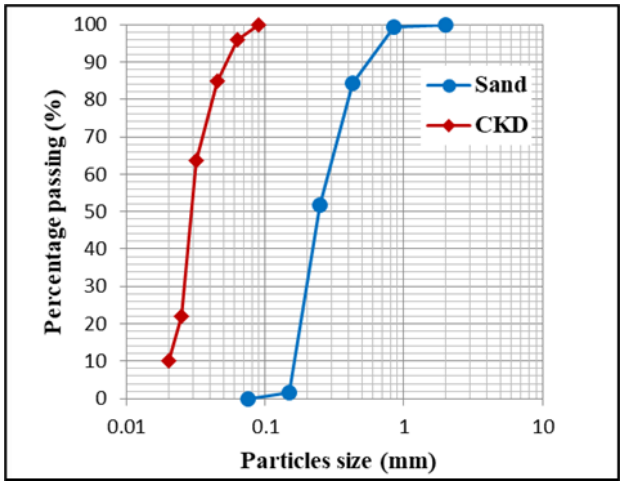

Figure 2. The curves of the grain size distribution of the used materials

2.2 Grouting Equipment

The permeation grouting process was performed using a laboratory model shown in " Figure. 3 ".

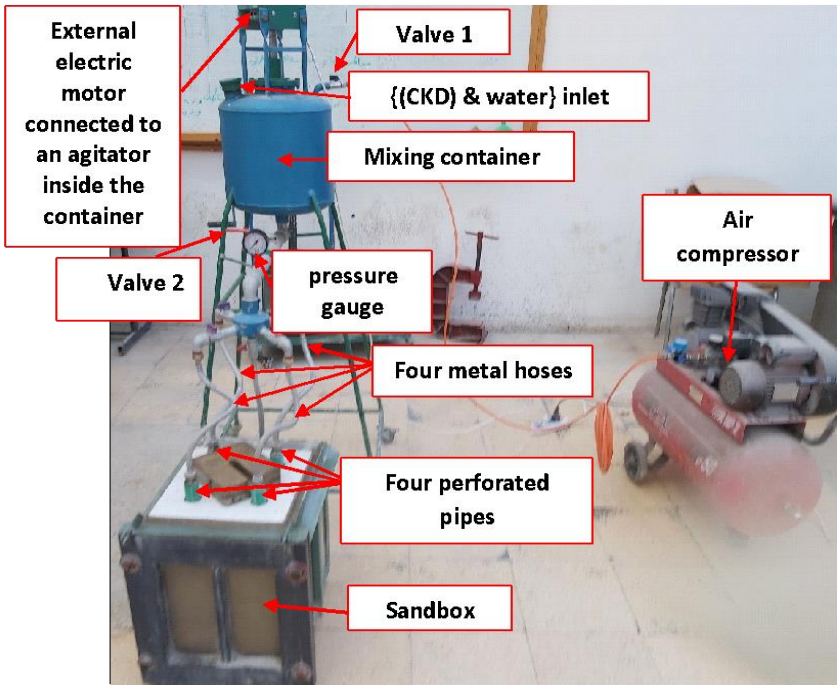

Figure 3. The laboratory grouting model

2.3 Grouting Process

The process of permeation grouting was performed according to the following: Firstly, the sand was dried for (24 hours) in an oven at (105° C) before conducting grouting.

Next, a metal frame was placed at the top of the box to maintain the place of the pipes and their vertical position, and the grouting pipes were placed at a height of 5 cm from the bottom of the box, " Figures. 4", the diameter of each pipe is 20 mm, on the surface of each pipe there are 64 perforations each one with a diameter of 3mm.

Then, the dried sand was filled in the box; the sand bed was prepared at a loose state by pouring the dried sand through a funnel placed at the top of the box.

After that, the suspension consisting of ((CKD) and clean tap water) was prepared in the mixing container, it was well mixed for 10-15 minutes before grouting, the mixing continued during the grouting process to get a uniform suspension and to avoid separation of water from (CKD). Then, the suspension was pumped under pressure into the four pipes uniformly, the grouting pressure was (1.5 - 2) bar and the pressure gauge was used to measure the grouting pressure, so the suspension was flowed and placed within the pores of the sand bed.

Finally, after the grouting process was completed, the four pipes were pulled quietly and carefully, filling their place with dry sand, " Figure. 5".

The sand bed was grouted with a suspension consisting of different percentages of (CKD) (2,4,6,8,10, and12%) as a proportion of the dry weight of the treated sand, and different mixing ratios (Water: CKD) (W: CKD=2:1, 4:1, 6:1, 8:1, and 10:1). The procedure was repeated for each percentage of (CKD) and the different ratios of (Water: CKD).

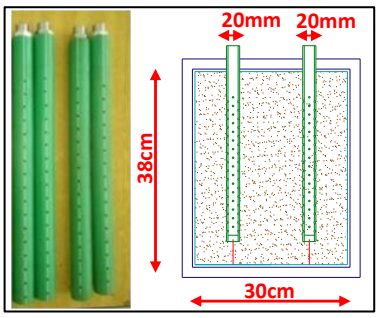

Figure 4. The perforated pipe

Figure 5. After the grouting process is completed

The effectiveness of permeation grouting mainly relies on the infiltration of the grouting material into the sand pores [5]. " Figure. 6" shows the penetration of (CKD) suspension between the pores of the grouted sand using a Polarizing Microscope, the range of magnification is 40x.

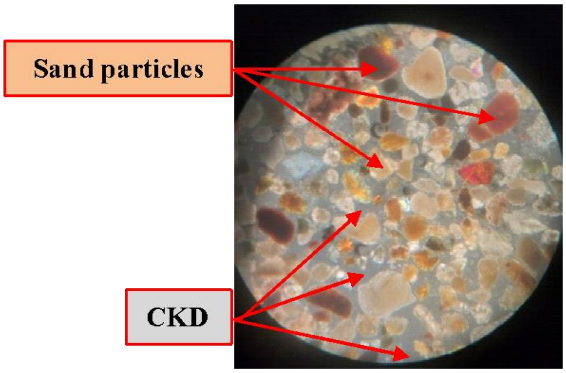

Figure 6. Microscopy photo of the grouted sample after 28 days

3 EXPERIMENTAL PROGRAM

To study the influence of (CKD) permeation grouting, a wide laboratory study was performed on the sandy soil before and after the grouting process for (7&28) days of curing, which included:

- Unconfined Compressive tests.
- Direct shear tests.

- Permeability tests.

3.1 Unconfined Compressive tests

Directly after the implementation of a grouting process for each case, the samples for unconfined compressive tests were extracted from the grouted sand bed; using cylindrical plastic molds with internal dimensions of (D=5cm) and (H=10cm); where (H/D=2) " Figure. 7", the extracted samples were kept in the laboratory for (7&28) days for curing.

(a) (b) (c)

Figure 7. (a) Internal dimensions of the used cylindrical plastic mold
(b) Some of the extracted samples after the grouting process
(c) Some samples after removal from the cylindrical plastic mold

Unconfined compressive tests were performed according to the procedure given in ASTM D4219, using the digital apparatus. The axial compressive force was applied on each sample with a constant velocity of 1 mm/min until the sample failed. Three samples were tested to obtain the values for each studied case, and the average result of the three tests was adopted.

3.2 Direct Shear tests

To prepare the grouted samples for the direct shear test, the samples were extracted from the grouted sand bed; by inserting circular plastic molds with the same diameter and height of the standard circular shear mold as shown in " Figure. 8", the extracted samples were stored in the laboratory for (7&28) days for curing.

(a) (b) (c)

Figure 8. (a) Internal dimensions of the used shear mold
(b) Some of the extracted samples immediately after the grouting process
(c) Placing the grouted samples in the direct shear box

Direct shear tests were performed on the soil samples before grouting to determine the shear strength and shear strength parameters of the untreated sand, and after grouting to determine the shear strength and shear strength parameters of the grouted sand for each case after (7&28) days of curing. After each curing period for each case, the extracted grouted samples were placed carefully in the steel shear box to carry out direct shear tests. Direct shear tests were performed according to the procedure given in ASTM D 3080, using a fully digital and computational control direct shear apparatus. The shear was applied at a constant

rate of 5mm/ min [22]; because the natural sand was completely dry when the shear tests were conducted, the grouted sand was also dry after a curing period of 7 or 28 days. Three specimens were tested to obtain the values for each studied case, three samples were subjected to the same procedure, each one subjected to different vertical loads, and the normal stresses applied were: (100, 200, and 300) kPa.

3.3 Permeability Tests

Permeability tests were performed using the constant head method on natural sand before grouting to determine the value of the permeability coefficient of the ungrouted sand, and after grouting to determine the values of the permeability coefficient of the grouted sand for each case after (7&28) days of curing. To prepare the grouted samples for the Permeability tests, the samples were extracted from the grouted sand bed using permeability molds. The extracted samples were kept in the laboratory for (7&28) days for curing. Permeability tests were performed according to the procedure given in ASTM D4234, using a permeability apparatus under an applied constant water pressure of 0.5 bar.

4 RESULTS

4.1 The Results of Unconfined Compressive Tests

Unconfined compressive tests were done for the grouted sand for all cases after (7&28) days of curing, during the unconfined compressive test; the magnitudes of vertical forces and vertical deformations were recorded simultaneously. " Figure. 9" shows the influence of (CKD) content on unconfined compressive strength for all (W/CKD) ratios after (7 & 28) days of curing. " Figure. 10" presents the effect of (W/CKD) ratio on unconfined compressive strength for all (CKD) percentages after (28) days of curing.

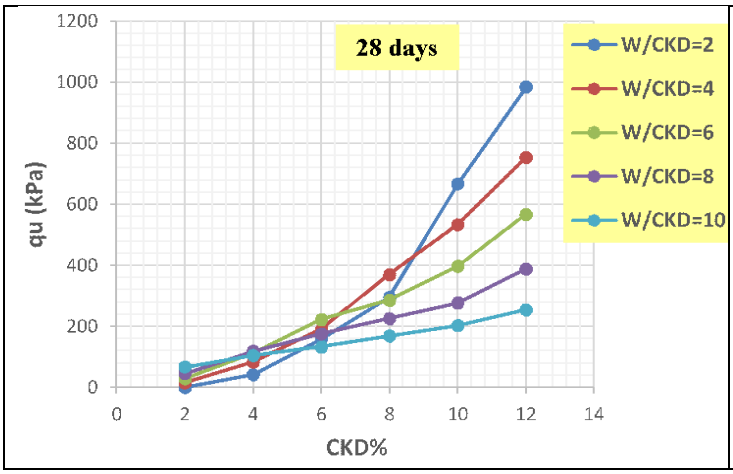

Figure 9. Unconfined compressive strength variation with (CKD) content

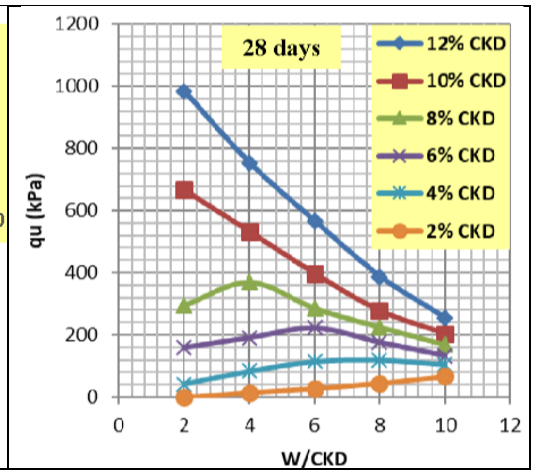

Figure 10. Unconfined compressive strength variation with (W/CKD) ratio

From " Figure. 9" it can be easily noticed that for each (W: CKD) ratio the unconfined compressive strength increases with the increase in (CKD) content, and with higher percentages of (CKD) than at lower percentages, unconfined compressive strength is very high. Moreover, the effect of water content varies according to (CKD) content, for example, when (CKD=2%) the unconfined compressive strength increases with the increase in (W: CKD) ratio and its value is maximum at (W: CKD=10) which gives the best viscosity of the suspension. When (CKD=12%) the unconfined compressive strength increases with the decrease in the (W: CKD) ratio and its value is maximum at (W: CKD=2) which gives the best viscosity of the suspension. Also, it was observed that the unconfined compressive strength increases with the increase in the curing period. From " Figure. 10" it can be noticed that for each (CKD) percentage there is an optimum (W/CKD) ratio that results in the maximum value of unconfined compressive strength. The

optimum (W/CKD) ratio which leads to the maximum unconfined compressive strength for each case is tabulated in "Table.4", it can be noted that the unconfined compressive strength increases with the increase in (CKD) content. " Figure. 11" shows some of the failure types after unconfined compressive tests.

Table 4. Unconfined compressive strength values for (CKD) percentages at the corresponding optimum (W/CKD) ratio after (28) days of curing

CKD%	2%	4%	6%	8%	10%	12%
W:CKD	10:1	8:1	6:1	4:1	2:1	2:1
qu (kPa)	67.75	119.21	222.62	369.84	666.84	984.72
$qu_{(i\%)}/qu_{(2\%)}$	----------	1.76	3.29	5.46	9.84	14.53

Figure 11. Some of the failure types after unconfined compressive tests

4.2 Direct Shear Tests Results

Direct shear tests for the natural sand were first performed. Then, direct shear tests were done for the grouted sand for all cases after (7&28) days of curing. During the direct shear test, the magnitudes of shear forces, horizontal deformations, and vertical deformations are recorded simultaneously. The shear stress versus horizontal displacement curves were plotted; for natural sand without grouting and with grouting at various percentages, from which the values of maximum shear stress at failure were obtained in each case. Using the direct shear tests; the shear strength parameters (the cohesion (C) and the internal friction angle (Ø) for each case) were defined according to Mohr- Coulomb's failure criteria; from the relation between maximum shear stress versus normal stress, and best fit straight line through 3 points resulting from 3 tests. "Figure .12" illustrates the effect of (CKD) content on the cohesion of grouted sand, while "Figure .13" presents the influence of (W/CKD) ratio on the cohesion of cured sand.

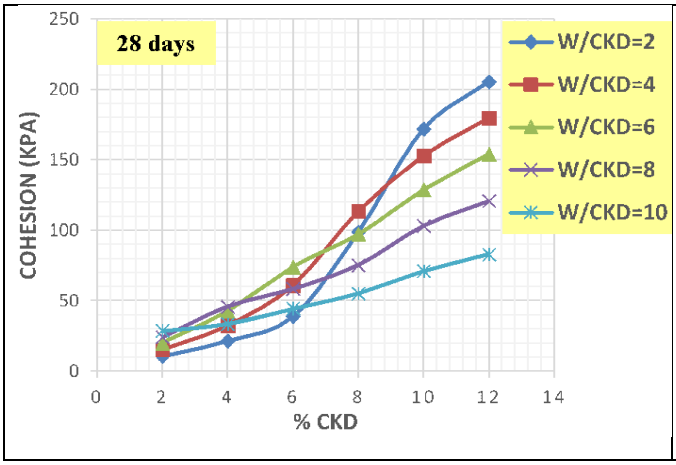

Figure 12. Cohesion variation with (CKD) content

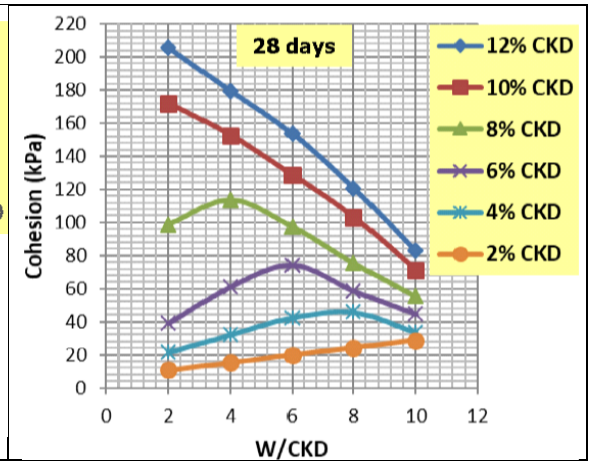

Figure 13. Cohesion variation with (W/CKD) ratio

"Figure. 12" shows that the cohesion of the grouted sand increases with the increase in (CKD) content, and the increase in cohesion is very high at higher percentages of (CKD) than at lower percentages. Moreover, the effect of water content varies according to (CKD) content, for example, when (CKD=2%) the cohesion increases with the increase in (W: CKD) ratio and its value is maximum at (W: CKD=10) which gives the best viscosity of the suspension. When (CKD=12%) the cohesion increases with the decrease in the (W: CKD) ratio and its value is maximum at (W: CKD=2) which gives the best viscosity of the suspension. This is evident in " Figure. 13"; from the relation between (Water/CKD) ratio and cohesion (C) shown in " Figure.13", it can be noted that:

- The cohesion (C) varies with the (W/CKD) ratio, it rises to a certain limit of (W/CKD) ratio, which is the maximum value of cohesion (C) and corresponding to the optimum (W/CKD) ratio for each case. For example: at a constant (CKD) content (8%) the increase in cohesion is up to (W/CKD=4) and beyond that a reduction in cohesion is noted with the increase in (W/CKD) ratio, before and beyond the optimum ratio there is a clear reduction in the values of cohesion.
- The effect of (W/CKD) is greater if the (CKD) content is more i.e., at a higher percentage of (CKD) the decrease in cohesion is more significant with the increase in (W/CKD).
- The maximum value of cohesion at the corresponding optimum (Water: CKD) ratio for each studied case was obtained and tabulated in "Table.5".

Table 5. Values of cohesion (C) for the studied (CKD) percentages at the optimum (W/CKD) ratio

CKD%	0%	2%	4%	6%	8%	10%	12%
W: CKD	---------	10:1	8:1	6:1	4:1	2:1	2:1
C (kPa)	2.08	28.75	45.72	74.06	113.5	171.9	205.4
$C_{grouted}/C_{natural}$	---------	13.82	21.98	35.61	54.57	82.64	98.75

From "Table. 5" the cohesion of the grouted sand has a value ranging from 28.75 kPa to 205.4 kPa. As the percentage of (CKD) content increases from 2% to 12%, the increase of cohesion is from (13.82 to 98.75) times of natural sand. It can be noted that at higher (CKD) contents the influence of grouting on the value of cohesion is remarkable. Also, it was observed that the cohesion increases with the increase in the curing period.

The angle of internal friction (Ø) was determined for natural sand, and then for grouted sand. The relation between the angle of internal friction and (CKD) content was deduced, also the relation between the internal friction angle and (W/CKD) ratio was deduced.

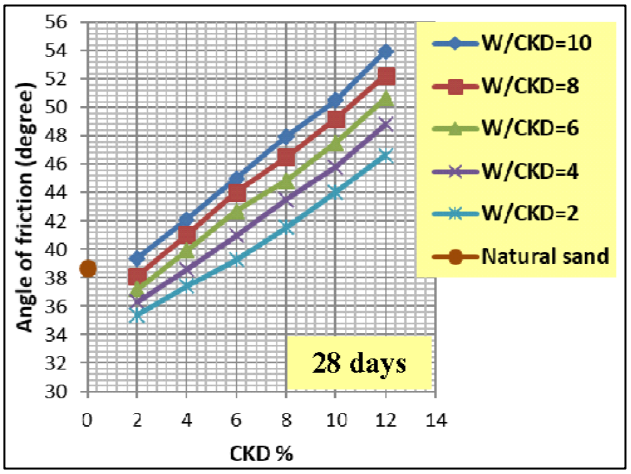

Figure 14. Variation of Ø with (CKD) content

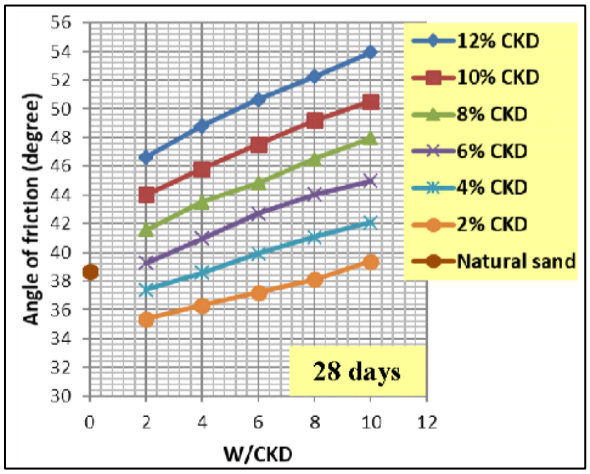

Figure 15. Variation of Ø with (W/CKD) ratio

It is clear from " Figure. 14" that the internal friction angle (Ø) increases with the increase of (CKD) content. The results presented in " Figure. 15" show that the internal friction angle (Ø) increases with the increase of the (W/CKD) ratio and curing period. The rate of the increase in internal friction angle between grouted sand and untreated sand for each studied case at the corresponding optimum (Water: CKD) ratio is tabulated in "Table.6".

Table 6. Values of internal friction angle for studied (CKD) percentages at optimum (W/CKD) ratio

CKD%	0%	2%	4%	6%	8%	10%	12%
W: CKD	---------	10:1	8:1	6:1	4:1	2:1	2:1
Ø°	38.69	39.39	41.06	42.71	43.53	44.04	46.64
$Ø_{grouted}/Ø_{natural}$	---------	1.018	1.061	1.104	1.125	1.138	1.205

4.3 Results of Permeability Tests

Permeability tests for the untreated natural sand were first performed. Then, permeability tests were done for the grouted sand for all cases after (7 and 28) days of curing. "Figure. 16" shows the permeability coefficient variation with the (W/CKD) ratio.

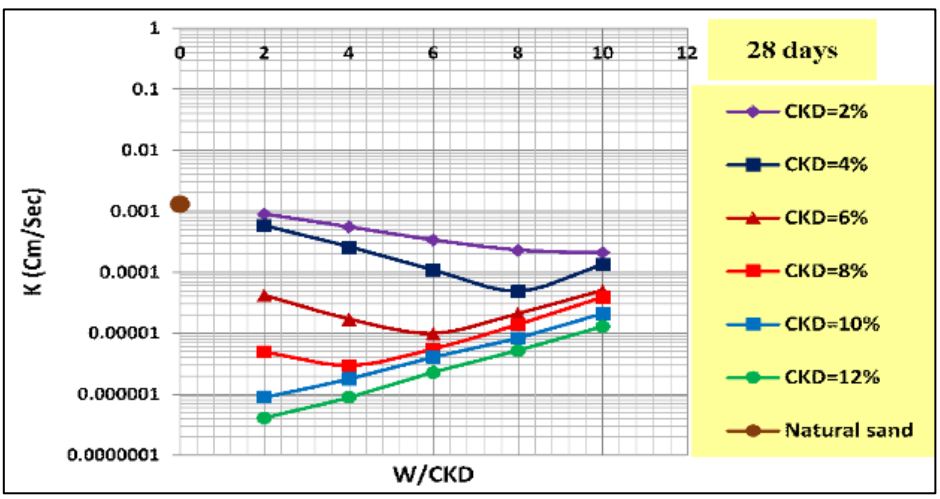

Figure 16. Variation of permeability coefficient with (W/CKD) ratio

From " Figure. 16" it can be noticed that for each (CKD) percentage there is an optimum (W/CKD) ratio that results in the minimum value of the permeability coefficient. The optimum (W/CKD) ratio which leads to the minimum value of the permeability coefficient for each case is tabulated in "Table. 7".

Table 7. Values of permeability coefficient for studied (CKD) percentages at optimum (W/CKD) ratio

CKD%	0%	2%	4%	6%	8%	10%	12%
W: CKD	---------	10:1	8:1	6:1	4:1	2:1	2:1
K (cm/sec)	$1.33x10^{-3}$	$2.1x10^{-4}$	$4.9x10^{-5}$	$9.9x10^{-6}$	$3x10^{-6}$	$9x10^{-7}$	$4.1x10^{-7}$

From "Table.7" it can be observed that there is a clear reduction in the permeability of the treated soils beyond (CKD=8%). " Figure. 17" shows the effect of (CKD) content on the permeability coefficient of grouted sand, at (W/CKD=4) and (W/CKD=6) after (7 and 28) days of

curing. It is evident that the permeability coefficient values of the grouted sand decrease with the increase in (CKD) content and curing period.

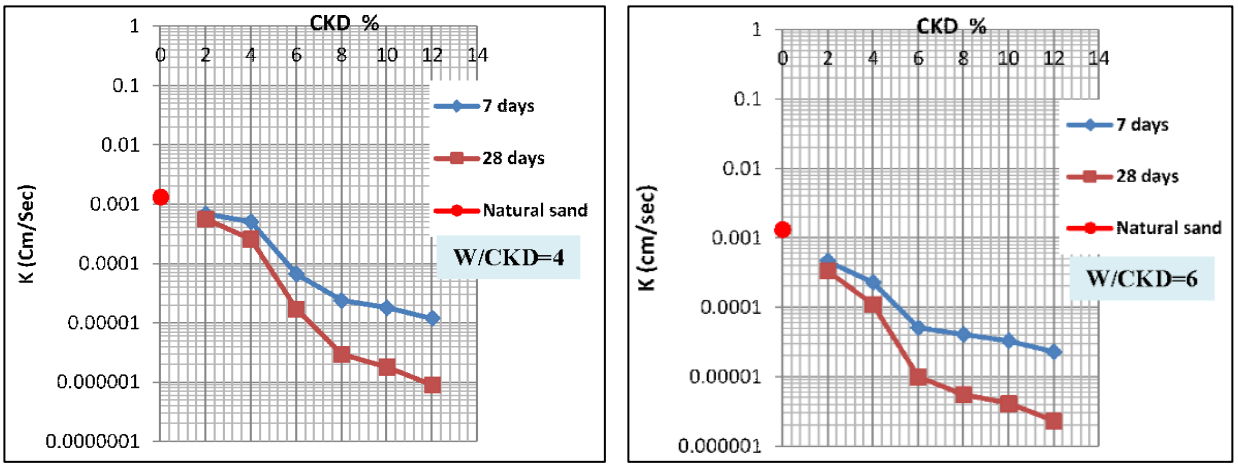

Figure 17. Variation of permeability coefficient with (CKD) content

5 DISCUSSION

Based on the results of this experimental study, it has been concluded that the application of permeation grouting on coastal sandy soil (at a loose state) improves the behavior and bearing capacity, as a result of the infiltration of (CKD) grouts into the voids between soil particles under pressure (1.5 - 2) bar. The increase in (CKD) content results in a decrease in the permeability coefficient and an increase in the values of shear strength, shear strength parameters (the cohesion (C) and the internal friction angle (Ø)), and unconfined compressive strength of the grouted sand, this is due to the chemical reaction between (CaO) and (SiO_2) and water, this chemical reaction results in a bonding material, Calcium Silicate Hydrate (C-S-H), which binds soil particles, so the more (CKD) content the stronger bonding material [17],[23]. Also, the increase in the curing period leads to a decrease in the permeability coefficient and an increase in the values of shear strength, shear strength parameters, and unconfined compressive strength of the grouted sand, this can be explained by the completeness of the chemical reaction, where (CKD) is similar to cement; it needs a period to complete the chemical reaction process and produce a cementation material [24],[25]. While the values of permeability coefficient increase and the values of shear strength, shear strength parameters, and unconfined compressive strength of the grouted sand decrease as the (Water: CKD) ratio increases, this can be attributed to the bleeding caused by the surplus quantity of water. It has been concluded that for each (CKD) percentage there is an optimum (Water: CKD) ratio, at which the suspension has its optimum viscosity. When the (Water: CKD) ratio exceeds the optimum ratio; the suspension becomes fluid, and the concentration of (CKD) is reduced because of bleeding, which leads to weak bonds between sand particles and a reduction in the values of the studied properties [25], [26], [27]. On the other hand, when the (Water: CKD) ratio is low, the suspension is highly concentrated and therefore has high viscosity and less penetration ability [4], [25].

Hence for each (CKD) percentage, the values of the studied properties are the best at the optimum (Water: CKD) ratio. The results indicated the important impact of the (Water: CKD) ratio, where the improvement of studied properties of the grouted sand varies depending on the (Water: CKD) ratio, and the effect of (Water: CKD) ratio is more if the (CKD) content is more. While the values of internal friction angle (Ø) increase as the (Water: CKD) ratio increases.

The results of this study are in accordance with the results of previous studies [5],[7],[8]. Where they reported that cement grouts improve the properties and bearing capacity of sandy soils, so the cementation effect of (CKD) is similar to that of Portland cement, in addition to an important advantage of (CKD) is

that (CKD) particles are smaller than Portland cement particles. Thus, the diffusion ability of (CKD) suspension into the sand is better than that of Portland cement suspension. Hence (CKD) grouts can be injected in formations with small voids as fine-grained sands where Portland cement grouts cannot penetrate.

6 CONCLUSIONS

- The grouted sand with (CKD) grouts has obtained a high unconfined compressive strength, which increases with the increase of (CKD) content and curing period.
- The values of shear strength and cohesion of grouted sand increase as (CKD) content and curing period increase. Whereas the values of internal friction angle (ϕ) increase as (CKD) content, curing period, and (Water: CKD) ratio increase.
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- The extent of improvement in the values of internal fraction angle (Ø) is low when compared to the extent of enhancement in the values of shear strength and the cohesion (C) of the grouted sand.
- The values of permeability decrease with the increase of (CKD) content and curing period.
- (Water: CKD) ratio has an essential effect, for each (CKD) percentage there is an optimum (Water: CKD) ratio, at which the suspension has its optimum viscosity, which results in the best spread and distribution of grouting suspension and leads to the best values of the studied properties. The effect of the water: CKD) ratio is greater when (CKD) content is higher.
- There is a greater effect of the curing period at higher percentages of (CKD) as compared to low percentages.
- Permeation grouting using (CKD) grouts is an easy, effective, and economical way to enhance the mechanical properties of coastal sandy soil.

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