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Experimental Study of the Geotechnical Behavior of Calcareous Soil Improved using Kaolinite Clay - a Comparative Study

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Abstract: *The calcareous soil is commonly composed of calcium carbonates greater than ten percent. Generally, the calcareous soils are extensively found near the coastal areas of Egypt. Accordingly, the performance of calcareous soils is usually connected with different interdependent problems, such as crushability, compressibility, and chemical dissolving. Thus, the main goal of the present study is to explore the feasibility of applying a treatment approach in the improvement of calcareous soils toward mixing the calcareous soil with Kaolinite clay. Moreover, investigating the effect of different types of water (e.g. fresh and seawater) used in compacting the treated calcareous soil on its performance. The results have shown that the addition of Kaolinite up to 9% to the mixtures significantly decreased the optimum water content but increased the maximum dry density. Wherein, both of the decrease ratio in optimum water content and the increase ratio in maximum dry density became more significant in the state of seawater. The California bearing ratio "CBR" values of the Kaolinite – carbonate mixtures increased with the addition of Kaolinite up to nine percent. However, it is lowered when it soaked in fresh water for three months.*

Key Words: *Calcareous soil, CBR, Improvement, Kaolinite clay, Seawater.*

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I. Introduction

The calcareous soils are found near coastal areas in Egypt, especially in the Mediterranean coastal line between Alexandria and El Alamein cities. Generally, the calcareous soil formations are commonly composed of calcium carbonates greater than 10%, Clark and Walker, [1]. The major problems connected with the geotechnical behavior of calcareous soils are crushability, compressibility and chemical dissolving. Wherein, particle crushing are more significant in calcareous sands, Coop and Airey, [2]. Datta et al., [3] found that the tendency to crushing of calcareous soil increases with an increase in: (1) the amount of thin-walled shell fragments; (2) the amount of grains having large intraparticle voids; (3) the coarseness of grains; and (4) the uniformity of its gradation.

Dissolving of calcareous soil is a process, which the carbonate minerals separated from soil. Generally, dissolving process of calcareous soil could occur in water with a pH less than eight, Suarez and Rhoades, [4]. Accordingly, dissolving of calcareous soil, when subjected to fresh water with pH equal to seven, could increase the particle weakness and produce micro-cracks in the outer surface of the particles. Therefore, particle crushability and compressibility may also be increased and hence, resulting instability in many forms of foundation problems and slope failure, Ahmed et al., [5]. Construction without soil improvement is usually impractical due to anticipated large settlements. In this regard, the calcareous soils need stabilization for the better usage.

Over several years, the increasing cost of construction materials in Egypt has created the need for research to use locally and readily available materials with different admixtures to improve their performance. In addition to the cost benefit, these admixtures usually are conventional soil/fill materials (e.g. Kaolinite clay). Consequently, In situ grouting of these soils may improve their weakness. Various studies investigated the geotechnical behavior of the cemented carbonated sands (e.g., Saxena and Lastrico, [6]; Dupas and Pecker, [7]).

Calcareous soils are found next to coastal areas. Accordingly, seawater may represent the nearest and the most economic natural water used in compacting the soil to use in earthwork projects present. Review of the literature shows that many previous studies investigated the performance of untreated calcareous soils whereas there is paucity of data regarding the geotechnical behavior of treated calcareous soils stabilized with Kaolinite clay. Thus, the present study focused on examining a possible treatment technique to enhance the performance of calcareous soils by mixing the calcareous soil with conventional soil/fill materials (e.g. Kaolinite clay), and to account for the optimum mixing ratios. In this regard, an extensive experimental program was carried out under different loading conditions considering the effect of using seawater by compacting the mixtures. These applications of using available material can help to reach economical solution that fulfills both the structural as well as the environmental and sustainability requirements.

II. Materials

II.1 The used calcareous soil:

As a part of the framework of this study, bulk samples of calcareous soil were needed. Thus, the calcareous soil samples used in this study were collected from a natural beach deposit located at North Coast, Mediterranean Sea (specifically Badr village, Egypt). The area lies between Latitude 30° 49′ 45"N and Longitude 29° 10′ 10"E and the height from the sea is (1.0 to 1.5) m. they were collected by a disturbed sampling method at average depths of (1.0 to1.3) m. The location from which the calcareous soil samples were collected is shown in Figure (1).

Fig. 1: Location of bulk samples of tested calcareous soil in Egypt.

II.2 The used Kaolinite clay characteristics:

It is well known that a silicate, such as feldspar, may produce various clay materials during weathering such as Kaolinite. Kaolinite clay is a layered silicate mineral, with one tetrahedral sheet of silica (SiO_4) linked through oxygen atoms to one octahedral sheet of alumina (AlO_6) octahedra, forming a two-layer mineral is called diphormic clays (l : l minerals) as shown in (Fig. 1), Deer et al., [8].

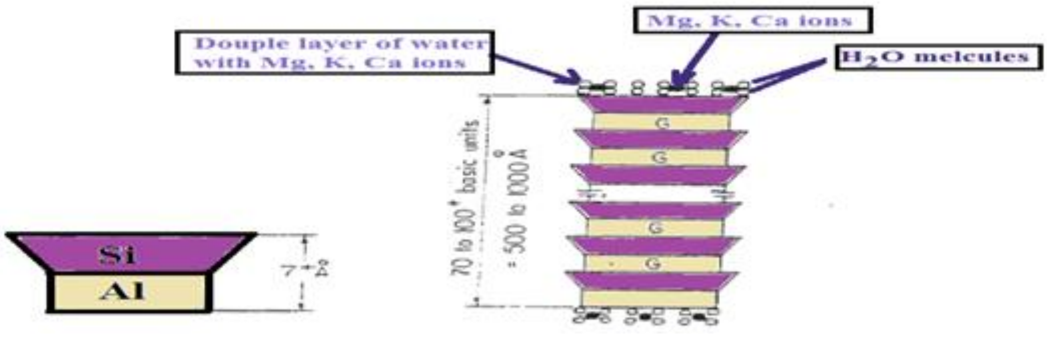

Fig. (2): Kaolinite clay mineral, Deer et al., [8].

The used Kaolinite clay is delivered from Sina in Egypt. The classification of the tested Kaolinite clay was established according to USCS. The used Kaolinite was in an uncemented as matrix of inorganic Sandy Silt and Kaolinite Clay with low plasticity "CL", which is composed of 23.2% Sand, 56.2% Silt and 20.6% Clay. Liquid limit (L.L) is about 27.1%, plastic limit (P.L) is about 13.7%, plasticity index (P.I) is about 13.4%, activity is about 0.65 and the permeability is about 5.0E-07 cm/sec. Furthermore, the Atterberg limits shows that the soil is fairly plastic and suitable for embankment construction. Moreover, X-ray diffraction is applied to determine the mineral content of the used Kaolinite. The total dissolved salts of the used Kaolinite Clay are about 285 mg/L, which is considered a low salinity material, and chloride is about 36 mg/L. Physical properties and mineralogy of the used Kaolinite are plotted in Figures (3) through (5) and summarized in Tables (1) & (2).

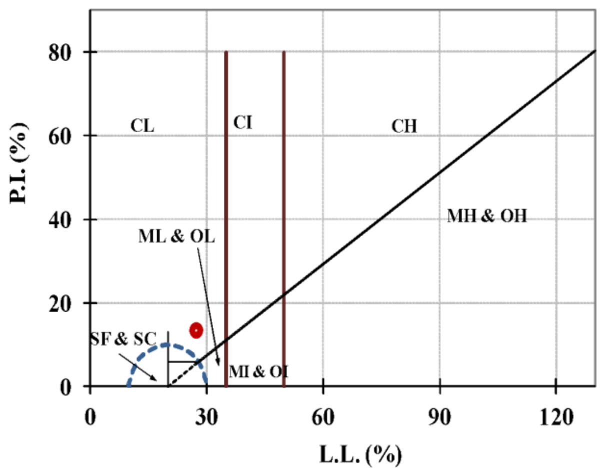

Fig. (3): Casagrand's plasticity chart for the used Kaolinite.

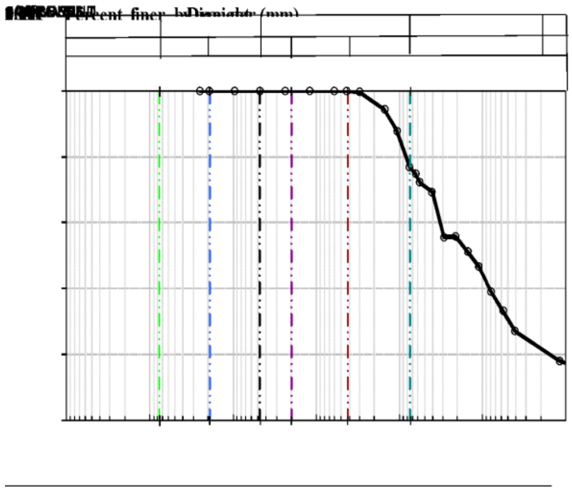

Fig. (4): Hydrometer analysis of the used Kaolinite.

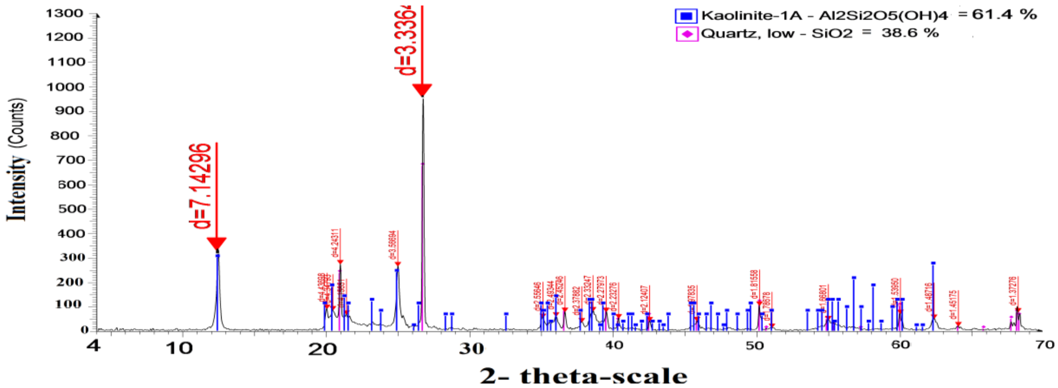

Fig. (5): X-Ray Diffraction of the used Kaolinite.

Table (1): Physical properties of used Kaolinite clay.

Atterberg limits			Texture, Soil Components (from hydrometer analysis)			Soil group	Activity	Permeability
L.L (%)	P.L (%)	P.I (%)	Fine Sand (%)	Silt (%)	Clay (%)			
27.1	13.7	13.4	23.2	56.2	20.6	CL	0.65	5.0E-07

Table (2): Chemical composition of the used Kaolinite clay.

Soil Components (from X-Ray Diffraction)		T.D.S (mg/L)	SiO_4 (mg/L)	AlO_6 (mg/L)	Cl (mg/L)	NaCl (mg/L)
Kaolinite (%)	Quartz (%)					
61.4	38.6	285	88	95	36	40

II.3 The used water samples:

Seawater samples are obtained from the Mediterranean Sea between Latitude 30° 54′ 36.52" N and Longitude 29° 24′ 54.32" E. Accordingly, The tap water from the soil mechanics lab was used as a control water sample. Investigation on the major ions of the used seawater is based on more than three samples collected from two sections distributed along the above-mentioned location on the Mediterranean Sea. The chemical analyses were carried out on the collected water samples to evaluate some predominant chemical characteristics, e.g. ionic and salt concentrations. For fresh and sea water samples ,respectively, the total dissolved salts are about 314 mg/L and 37696 mg/L, Chloride ions are about 71 mg/L and 21753 mg/L and Sodium ions are about 46 mg/L and 14060 mg/L. The ionic and salt concentrations of water samples are given in Table (3).

Table 3: Ionic and salt concentration of water samples.

	Salinity (g/Kg)	T.D.S (mg/L)	Cl^- (mg/L)	Na+ (mg/L)	Mg^{++} (mg/L)	Ca^{++} (mg/L)	Calcium Hardness as $CaCO_3$
Tap water	314	71	46	117	9	30	314
Seawater	37,696	21,753	14,060	35,813	1453	659	37,696

III. Experimental work

The experimental work was carried out in the lab of the construction research Institute (CRI) of the National Water Research Center, Egypt. The proposed improvement method depends on increasing the cohesion strength and decreasing the permeability by mixing the natural calcareous sand with Kaolinite. Therefore, the proposed experimental program was designed to add three mixing ratios 3%, 6% and 9% of Kaolinite to the carbonate sand. Moreover, it was designed to assess the effectiveness of the suggested method to enhance the geotechnical behavior of calcareous soils for earth works applications. Moreover, investigating the effect of different types of water (e.g. fresh and seawater) used in compacting the treated calcareous soil. Consequently, the samples were subjected to 0, 4 and 90 days of soaking period wherein, all the tested samples whether compacted with fresh or sea water are soaked in fresh water. At the end of each period, the CBR test was carried out to determine the CBR value. A number of laboratory tests were carried out to determine the soil properties before and after the suggested improvement method. The tested samples were taken from the three mixtures in addition to the natural calcareous sand. The laboratory tests included chemical, physical and mechanical tests. Accordingly, the laboratory tests included chemical analysis (to evaluate some predominant chemical characteristics, e.g. carbonate content); mechanical tests on compacted material (to reveal the geomechanical behavior, e.g. shear parameters by triaxial test and modified proctor compaction test, in addition to the California Bearing Ratio-(CBR). Physical tests are conducted to ascertain the soil physical properties, e.g. particles gradation. The following sections describe the material used in the experiments and tests results.

IV. Results and Discussion

IV.1 Identification of natural calcareous soil

The Index & Engineering properties of the natural calcareous soil and the soil treated with Kaolinite were determined following ASTM D 422 – 63, [9]. The uniformity coefficient value (Cu) of the natural soil is 2.06 and The Coefficient of curvature (Cc) is 0.87.The classification of the tested calcareous soils was established according to USCS. The North Coast carbonate sand was in an uncemented as a matrix of fine to medium carbonate sand (fairly uniform grading carbonate sand "SP"). The modified proctor compaction test was conducted according to ASTM D1557 [10], for the samples compacted with fresh water, the maximum dry density is 1.9 gm/cm³ with an optimum moisture content of 22.5%. However, for the same soil but compacted with seawater, the maximum dry density is 2.0 gm/cm³ with an optimum moisture content of 17.00%. The CBR test was conducted according to ASTM D1883 [11]. After zero, four and ninety days soaking in fresh water, the CBR values for the samples compacted with fresh water are 1.9, 3.1 and 1.4. However, for the same soil but compacted with seawater, they are 2.1, 4.8 and 4.8. The consolidated monotonic drained triaxial test (ICD) was conducted following ASTM D4767 [12], After zero, four and ninety days soaking in fresh water, the friction angle values for the samples compacted with fresh water are 41^0, 39^0 and 37^0. However, for the same soil but compacted with seawater, they are 41^0, 40^0 and 38^0. Gradation curve and the properties of the natural soil are shown in Figures (6) & (7) and Tables (4) through (6).

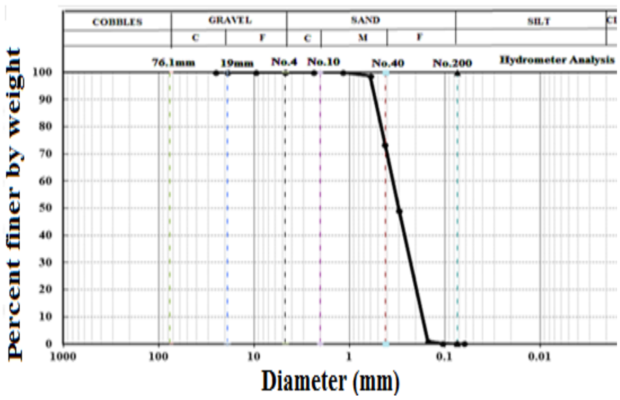

Fig. 6: Grain size distribution curve of natural tested calcareous sand).

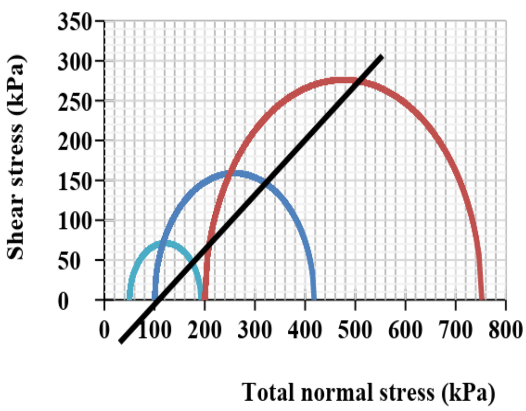

Fig. 7: Mohr circles results for natural sand.

Table 4: Chemical composition of natural calcareous soil samples

Description	Results
Carbonate Content "$CaCo_3$" (%)	97.5
Silicate Content "SiO_2" (%)	1.8
Clark and Walker [10] Classification	Carbonate sand
T.D.S (mg/L)	604

Table 5: Physical and Index properties of natural calcareous soil samples.

Description	Results
Color	light tan
Uniformity coefficient (Cu)	2.06
Coefficient of curvature (Cc)	0.87
Fine Sand Content (%)	72.3
Medium Sand Content (%)	27.7
USCS Classification	SP

Table 6: Mechanical properties of natural calcareous soil samples.

Description	Results
Maximum Dry Density **"fresh; seawater"** (gm/cm^3)	1.9; 2.0
Optimum Moisture Content **"fresh; seawater"** (%)	22.5;17.0
California Bearing Ratio after zero, four and ninety days soaking in fresh water **"compacted with fresh water"** %	1.9, 3.1 and 1.4
California Bearing Ratio after zero, four and ninety days soaking in fresh water **"compacted with seawater"** %	2.1, 4.8 and 4.8
Friction angle after zero, four and ninety days soaking in fresh water **"compacted with fresh water"** %	41^0,39^0 and 37^0
Friction angle after zero, four and ninety days soaking in fresh water **"compacted with seawater"** %	41^0, 40^0 and 38^0

IV.2 Measured data of the compaction test.

The modified proctor compaction test was conducted to reveal the geomechanical behavior of the plastic mixtures. The results are plotted in Figures (8) and (9). For the mixing ratios 0%, 3%, 6% and 9% that compacted with fresh water, the maximum dry densities are 1.90 gm/cm³, 2.10 gm/cm³, 2.20 gm/cm³ and 2.17 gm/cm³ with optimum moisture contents of 22.5%, 17.1%, 11.8% and 12.1%, respectively. While for the same soils but compacted with seawater, they are 2.03 gm/cm³, 2.15 gm/cm³, 2.23 gm/cm³ and 2.23 gm/cm³ with an optimum moisture contents of 17.0%, 15.2%, 11.1% and 11.6%, respectively.

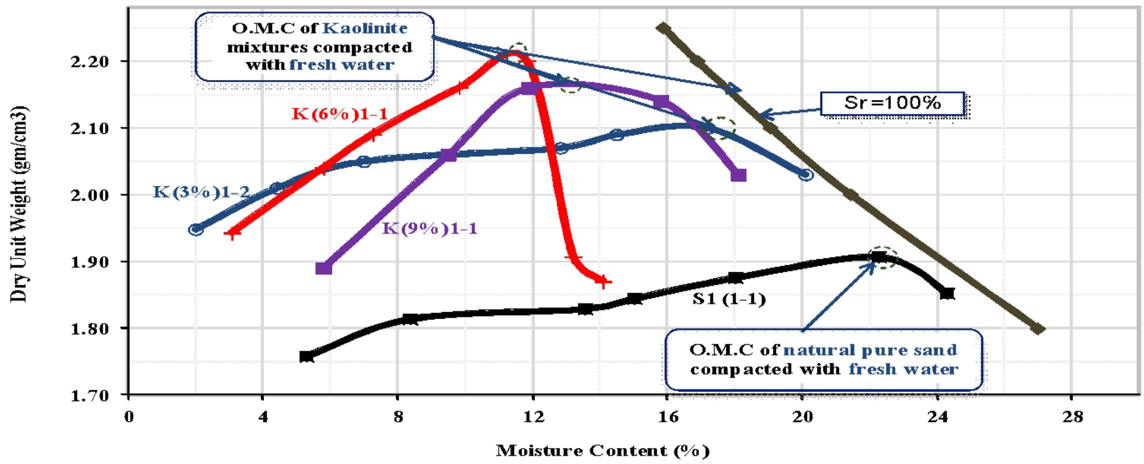

Figure 8: Modified proctor compaction curves for natural pure calcareous sand (S_1) and the three tested Kaolinite mixtures that compacted with fresh water.

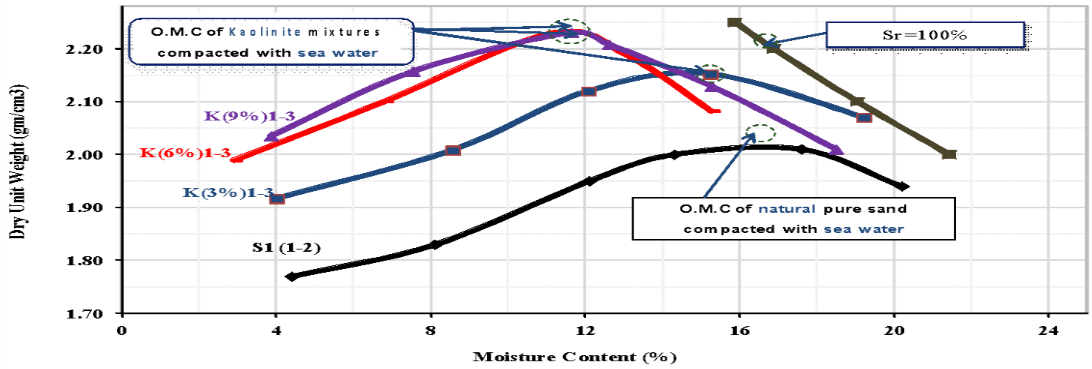

Figure 9: Modified proctor compaction curves for natural pure calcareous sand (S_1) and the three tested Kaolinite mixtures that compacted with seawater.

- <u>The effect of Kaolinite content on the compaction relationship:</u>

Lowering of the optimum water contents are due to many factors namely: (1) the significant lower water holding capacity of Kaolinite that is related to their mineralogy; (2) the lubrication wherein, the platy-shaped of Kaolinite minerals help the sand grains to slip against each other. Moreover, a gradual decrease in optimum moisture content of plastic mixtures was found due to filling the voids with Kaolinite and hence, capillary tension in the pore water may be neglected. Moreover, a gradual increase in maximum dry density is found.

- <u>The effect of water type used in compacting the soil on the compaction relationship:</u>

Generally, it is found that all of the tested samples that compacted with sea water exhibit lower optimum water content (O.M.C) and higher maximum dry density (ɤ dry max) than the same soils but compacted with fresh water. This behavior is due three main factors: firstly, the absolute viscosity of the used water, whereas the absolute viscosity of seawater is greater than it in the fresh water and hence, the optimum water content (O.M.C) is reduced. Secondly, the density of the water used, the density of seawater is higher than it in the fresh water that increases the maximum dry density ($ɤ_{dry\ max}$) of the matrix. Finally, the ionic exchange that rapidly occurs in fine soils after adding water. Whereas, Sodium ions that found in the sea water increases the ionic exchange, and increases the calcium ions around Kaolinite particles that occur due to hydration process. The existing low electro-negative ions that found in Kaolinite particles are replaced by both of calcium and sodium ions and furthermore the thickness of double layer is lowered (Puppala et al., [12].

IV.3 Measured data of California bearing ratio test

California bearing ratio (CBR) soil samples were compacted at the optimum moisture content at various soaking period of zero, four and ninety days which they were soaked in fresh water. The results are plotted in Figure (10).

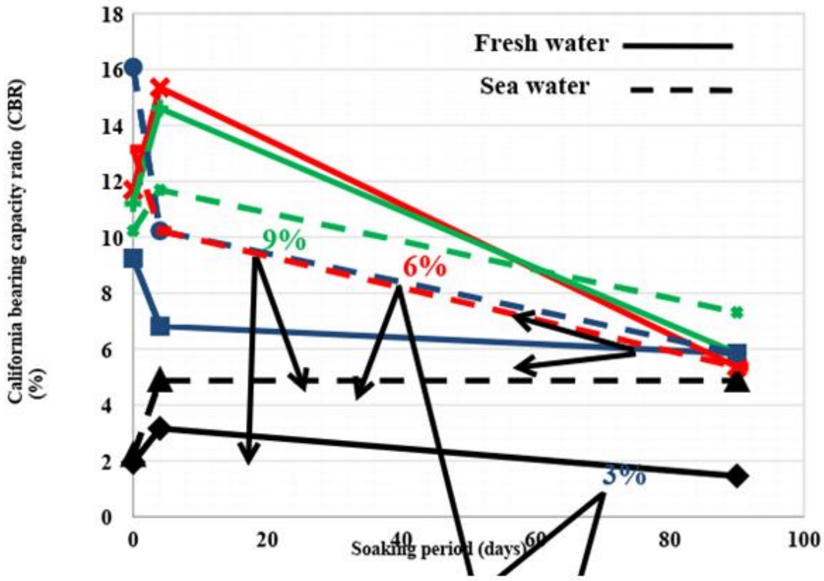

Figure 10: Effect of soaking period on California bearing ratio (CBR) for the tested mixtures.

- **<u>Firstly, at the unsoaked state,</u>** for the mixing ratios 0%, 3%, 6% and 9% that compacted with fresh water, the California bearing ratio (CBR) values are 1.9%, 9.2%, 11.6% and 11.2%, respectively. However, they are 2.2%, 16.1%, 13.1% and 10.2% for the same mixtures but compacted with seawater.
- **<u>Secondly, after four days soaked in fresh water,</u>** for the mixing ratios 0%, 3%, 6% and 9% that compacted with fresh water, the California bearing ratio (CBR) values are 3.1%, 6.8%, 15.3% and 14.6%, respectively. However, they are 4.8%, 10.2%, 10.2% and 11.6% for the same mixtures but compacted with seawater.
- **<u>Finally, after ninety days soaked in fresh water,</u>** for the mixing ratios 0%, 3%, 6% and 9% that compacted with fresh water, the California bearing ratio (CBR) values are 1.4%, 5.8%, 5.3% and 5.8%, respectively. However, they are 4.8%, 5.8%, 5.3% and 7.3% for the same mixtures but compacted with seawater. Thus, it is found these high increase ratios in (CBR) values comparing the Kaolinite mixtures to pure carbonate sand, when they compacted with fresh water is due to the pozzolanic reaction that increases the gel action with time.

Figure (10) showed that for all samples compacted with fresh water, the California bearing ratio (CBR) was increased after four days soaking except K(3%-F) then it decreased. Initially, the soil is partially saturated having negative pore water pressure or suction. This suction causes water to enter the soil from its top and bottom until it becomes fully saturated. For all samples compacted with sea water, it is obvious from this figure that the California bearing ratio (CBR) are decreased as the soaking period increased for both of mixture K(3%-S) and K(6%-S). On the other hand, that the California bearing ratio (CBR) was increased after four days soaking for both of mixtures K(0%-S) and K(9%-S) then it decreased. It is quite obvious from these figures that the soaking period has a significant effect on the California bearing ratio (CBR) indicating that the four days soaking period for the carbonate soil can lead to a serious false estimation of the soil strength. Wherein, the drop in California bearing ratio CBR is very sharp after about four days.

IV.4 Modulus of subgrade reaction "K"

It is the ratio of applied pressure divided by the corresponding soil movement. Stiffness is the most effective mechanical characteristic of soils in pavements. Furthermore, it is important to evaluate modulus of subgrade reaction "K_s". The modulus of subgrade reaction (Ks) was determined using the CBR soil samples before and after each soaking period. The results of the tested sands are reported in Tables (7) and are plotted in Figure (11).

Table 7: Calculating modulus of subgrade reaction "K" from "CBR" for the tested Kaolinite mixtures.

		Modulus of subgrade reaction "K" (kg/cm^3)			
		S_1 (0%)	**K(3%)**	**K(6%)**	**K(9%)**
Compacted with fresh water	**Unsoaked state**	**4.7**	**26.5**	**24.1**	**29.9**
	Soaked in fresh water for <u>four days</u>	**8.8**	**15.2**	**30.7**	**33.9**
	Soaked in fresh water for <u>three months</u>	**3.8**	**14.5**	**9.8**	**10.4**
Compacted with sea water	**Unsoaked state**	**5.6**	**34.2**	**26.7**	**21.3**
	Soaked in fresh water for <u>four days</u>	**12.5**	**25.7**	**27.0**	**22.5**
	Soaked in fresh water for <u>three months</u>	**13.1**	**13.4**	**10.4**	**13.0**

The following observations were found: firstly, soaking in fresh water results in a progressive increase in the modulus of subgrade reaction (Ks) with increasing soaking period up to four days. Secondly, after ninety days soaking in fresh water, the modulus of subgrade reaction (Ks) decreased. Consequently, it is recommended to use the soaked CBR test values for ninety days.

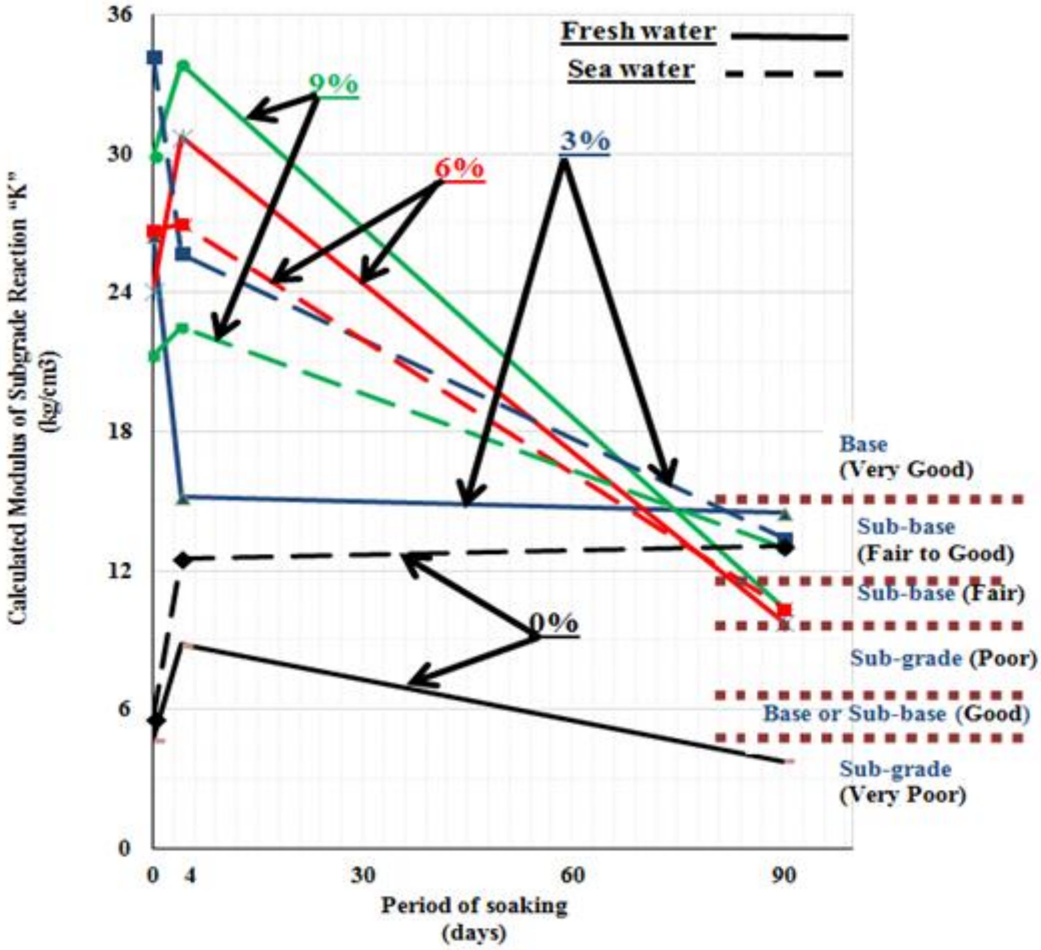

Figure 11: Effect of soaking period on the calculated modulus of subgrade reaction "K" for the tested Kaolinite mixtures whether compacted with fresh or seawater.

IV.5 Investigating the Influence of Compaction on Grading of the Kaolinite mixtures

The influence of compaction on grading of the Kaolinite mixtures is shown in Figures (12) through (19). The difference between the post and pre-testing grading curves is related to the particle crushing of the soil grains. It is found that, for a pure natural calcareous sand as shown in Figures (12) & (13), the medium sand is significantly crushed resulting an increase in the fine sand content with about 10%. Therefore, the whole virgin grain size distribution curve of the tested pure calcareous sand is shifted to fines side.

As demonstrated in Figures (14) through (19), these figures reveal that particle breakage is reduced by increasing the Kaolinite content to the calcareous sand. This occured because of the Kaolinite grains filled the voids between the grains of calcareous sand.

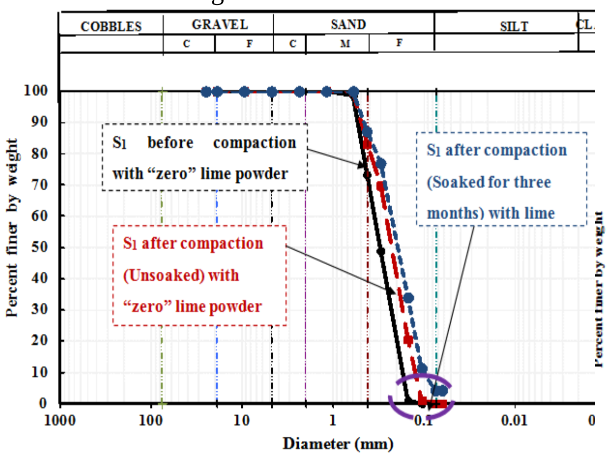

Fig. 12: Grain size distribution curves of S_1(0%)

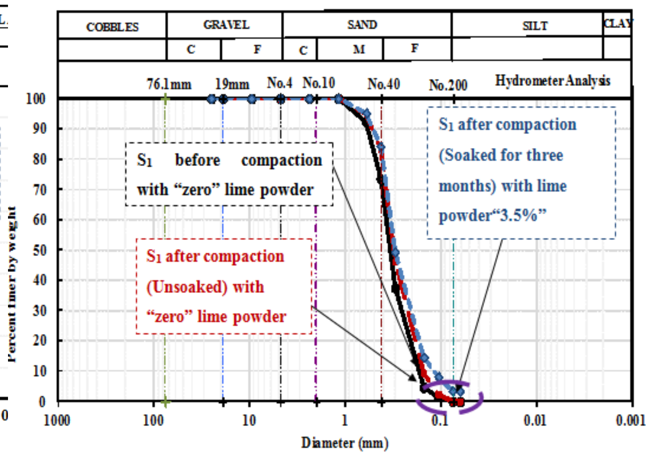

Fig. 13: Grain size distribution curves of S_1(0%)

compacted with fresh water.

compacted with seawater.

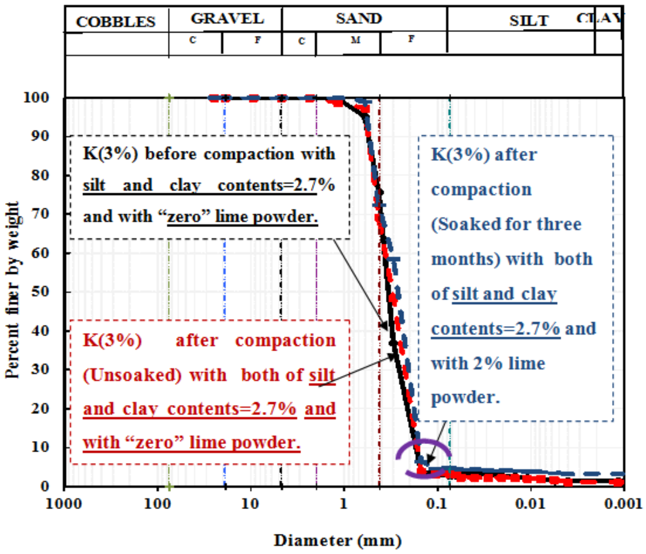

Fig. 14: Grain size distribution curves of K(3%) compacted with fresh water.

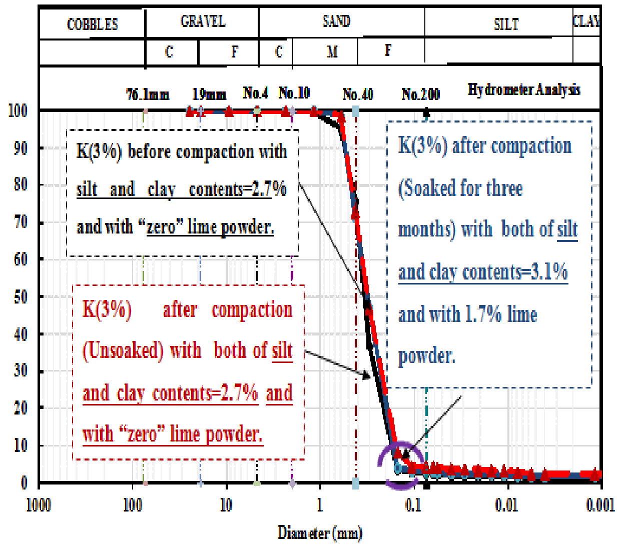

Fig. 15: Grain size distribution curves of K(3%) compacted with seawater.

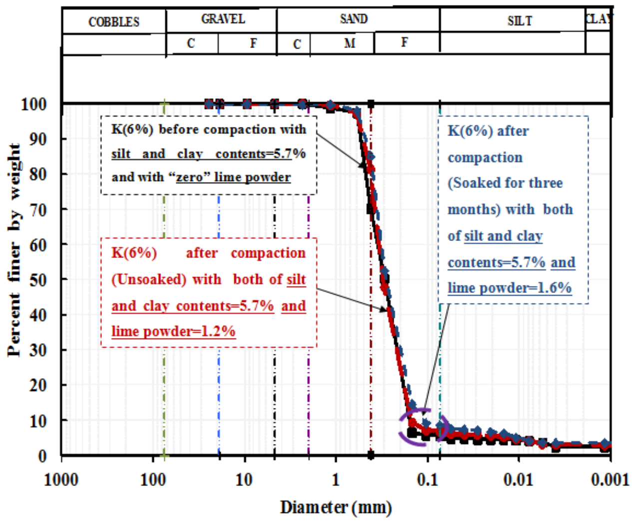

Fig. 16: Grain size distribution curves of K(6%) compacted with fresh water.

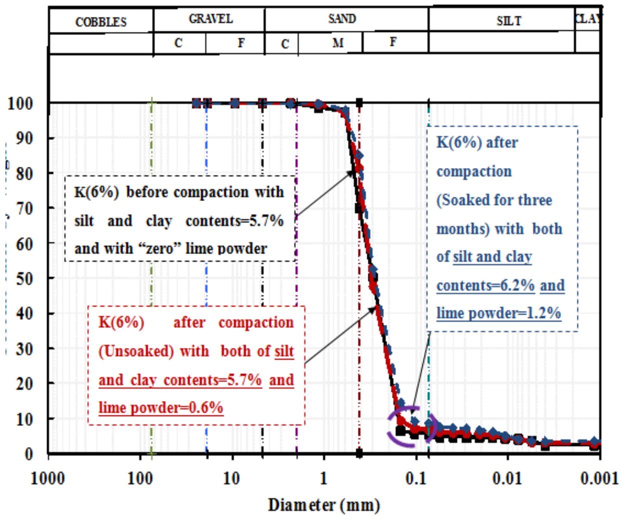

Fig. 17: Grain size distribution curves of K(6%) compacted with seawater.

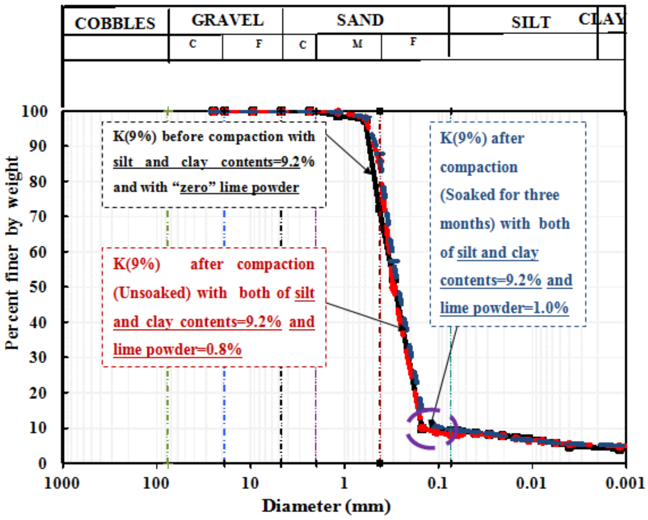

Fig. 18: Grain size distribution curves of K(9%) compacted with fresh water.

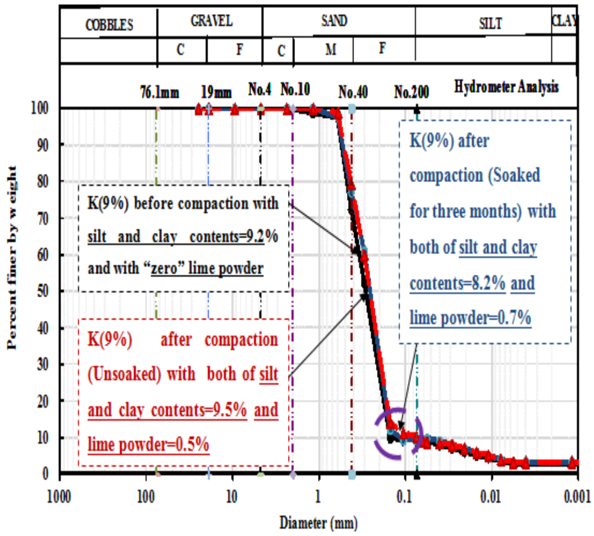

Fig. 19: Grain size distribution curves of K(9%) compacted with seawater.

IV.6 Crushability Analyses

Crushing susceptibility is considered a significant factor that influences the behavior of the treated calcareous sands to use it as a soil replacement. Furthermore, a series of the experimental program in this study was planned to assess the crushability potential of the tested Kaolinite mixtures. Accordingly, Hardin, [13] defined "Breakage potential (B_P)", as the area above the virgin grain size distribution curve. Hence, "total breakage (B_t)" after the test is defined as the difference between the areas above the curve before and after testing. "Relative breakage factor (B_r)" is defined as the ratio between the total breakage and the breakage potential. The amounts of particle crushing measured for the tested Kaolinite mixtures after testing are summarized in Table (8).

		Relative breakage factor $B_r=B_t/B_P$,				Decrease ratio in breakage factor		
		Pure sand	Kaolinite mixtures					
Sample		0%	3%	6%	9%	3%	6%	9%
compacted with **fresh water**	after compaction only	0.220	0.062	0.056	0.049	71.9	74.7	77.7
	after compaction and soaked for ninety days in fresh water	0.327	0.096	0.091	0.087	70.6	72.2	73.4
compacted with **sea water**	after compaction only	0.143	0.041	0.038	0.034	71.3	73.4	76.2
	after compaction and soaked for ninety days in fresh water	0.294	0.082	0.051	0.065	72.1	82.7	77.9

Table 8: Crushability analyses for the tested Kaolinite mixtures.

It is obvious that a significant decrease was shown in crushing susceptibility by increasing the mixing ratio of Kaolinite up to a certain limit 3%. These decrease ratios in crushing susceptibility are found due to the filling of voids in the natural sand by the fine cohesive admixture up to a certain limit 3% (when Kaolinite content equal to the void ratio of the natural sand). Whereas, any excess of the Kaolinite content after this limit up to 9% leads to a slightly decrease in crushing susceptibility. Moreover, the decrease ratios in crushability comparing the improved mixtures compacted with fresh water to natural soil range between (70.6% to 71.9%), (72.2% to 74.7%) and (73.4% to 77.7%) for K(3%), K(6%), K(9%), respectively.

V. Conclusions

The present study deals with the geotechnical performance of poorly graded carbonate sand mixed with Kaolinite. The following conclusions can be offered based on the tests results:

1. A gradual increase in maximum dry density ($\gamma_{dry\ max}$) but a gradual decrease in optimum moisture content (O.M.C) of plastic mixtures was shown by increasing the mixing ratio of Kaolinite between 3-9% to the calcareous soils.

2. Under the similar conditions (the same Kaolinite type, Kaolinite content) the CBR values (after soaking in fresh water) of the three used mixtures are decreased comparing with the unsoaked samples for the same three used mixtures.
3. Soaking in fresh water results in a progressive increase in the modulus of subgrade reaction (Ks) with increasing soaking period up to four days. However, after ninety days soaking in fresh water, the modulus of subgrade reaction (Ks) decreased. Consequently, it is recommended to use the soaked CBR test values for ninety days.
4. The CBR values of the all three treated mixtures, whether in unsoaked state or after soaking in fresh water for four or ninety days, are higher than it is in a pure calcareous soil.
5. The Atterberg's limits of the tested Kaolinite shows that the soil is fairly plastic with low permeability. Furthermore, it is suitable for embankment construction, wherein a good slope stability and low seepage losses can be achieved.
6. For best compaction, the mixing ratio of Kaolinite should be close to six percent as possible to be used as a base for roads construction or as a soil replacement. This does not affect the geotechnical behavior of sand under the effect of wetting and drying.
7. For best water channel linning, the mixing ratio of Kaolinite should be close to nine percent as possible to construct impermeable layer that exhibits low seepage losses and hence, good slope stability can be developed.
8. A gradual decrease in crushing susceptibility of plastic mixtures was shown by increasing the mixing ratio of Kaolinite between 3-9% to the calcareous soils.

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