Geopersia 2022, 12(2): 353-368
DOI: 10.22059/GEOPE.2022.343219.648660

RESEARCH PAPER

Effects of the Persian Gulf water and fine content on the mechanical properties and microstructure of sandy soils

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Received: 17 May 2022, Revised: 03 July 2022, Accepted: 25 July 2022

Abstract
Recently, many infrastructures, such as buildings, highways, petrochemical, and refinery facilities have been constructed on seaboards of the Persian Gulf region. In this area, for many geotechnical projects, the improvement of the engineering properties of soft and loose soils is necessary. In the area, the use of freshwater to obtain the required properties of soils for structures such as roads and highways is costly and not economically feasible. Therefore, the idea of using sea/saltwater instead of freshwater has significant benefits to the community, as it decreases the amount of freshwater being used which is of high importance. In this study, Saline water has replaced fresh water. Compaction, unconfined compression, and California bearing ratio (CBR) tests have been performed on sand samples with different fine contents. In addition to major changes in soil microstructure, the results showed that the stabilization of samples with saline water causes more bearing capacity and strength. The CBR and unconfined compressive strength (UCS) have been improved up to 11.3% and 12.2%, respectively. With increasing in salinity of water, the maximum dry density (MDD) of the soil samples increased up to 4.4% but optimum moisture content (OMC), liquid limit (LL), and plastic limit (PL) decreased up to 36.2%, 4.0%, and 6.6%, respectively. The results displayed that the lower the percentage of fine content, the higher the value of CBR and UCS.

Keywords: Sand, Sea/Saltwater, Soil strength, Soil stabilization, Soil structure.

Introduction

Modification of the earth materials or soil stabilization is a type of engineering treatment for soils, which consists of improving their mechanical and geotechnical properties, especially for base and subbase layers of roads (Bell, 1993). Depending on the initial ground conditions, soil properties, desired outcomes, availability of material and equipment, environmental concerns, and cost, the engineer may select from a wide choice of ground improvement and soil stabilization methods that will help solve the challenges of poor site conditions and inadequate soil qualities (Hausmann, 1990; Nicholson, 2015).

Recently, many infrastructures, such as buildings, highways, and petrochemical and refinery facilities have been constructed on seaboards of the Persian Gulf region. In this area, for many geotechnical projects, the improvement of the engineering properties of soft and loose soils is necessary. In the Persian Gulf district, the use of freshwater to obtain the required properties of soils for structures such as roads and highways is costly and not economically feasible. The region has been also experiencing drought in recent years. Therefore, the idea of using sea/saltwater instead of freshwater has significant benefits to the community, as it decreases the

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amount of freshwater being used which is of high importance.

It is well known that the pore water chemistry significantly affects the physiochemical, hydro-mechanical, and engineering properties of soils (Mitchell & Soga, 2005; Chai et al., 2016; Song et al., 2017; Deng et al., 2014; Di Maio, 1996; Abu Zeid and Abd El-Aal, 2017; Chen & Anadarajah, 1998; Mansouri et al., 2017; Zhang et al., 2016; Gajo & Maines, 2007; Sridharan et al., 2002; Mesri & Olson, 1971). The influence of saline water on soil can be more eminent because of the presence of clay minerals in it and the effect on the particle surface layers. Modmoltin and Voottipruex (2009) investigated the effect of salt concentration on the liquid limit of a kaolinite soil. The results showed that increasing salt concentration and valence of exchangeable ions (Na^+ to Ca^{2+}) in the soil pore spaces decreased the interparticle repulsion and increased the force of attraction which caused an increase in liquid limit. Otoko and Nwawuike (2014) studied the soil improvement potential of the Oyorokoto saltwater concerning the compaction and CBR characteristics of laterite. Higher maximum dry unit weight was observed on the laterite samples mixed with the saltwater than tap water, but the optimum moisture content decreased. CBR also showed an increment with increasing water salinity. Akbari Garakani et al. (2018) studied the effect of three different salts that are frequently involved in transportation infrastructure (namely NaCl, $CaCl_2$ and KCl) by conducting scanning electron microscopy (SEM), filter paper, uniaxial compression and oedometer tests. Test results revealed that the soil texture and hydro-mechanical responses are significantly affected by the salt type, saline degree of saturation and applied loading paths. Results also indicated that there is a critical saline degree of saturation (corresponded to each loading path and mixing salt type), at which the magnitude and modality of the osmotic and matric suctions within the soil fabric are changed. Abdullah et al. (1997) reported that high plastic Jordan clays treated with or without Ca^{2+}, K^+, and Na^+ solutions have different maximum dry densities (MDD). In all cases, drastic reductions in swelling potential have been observed. Arumairaj and Sivajothi (2011) and Mansouri et al. (2017) have pointed out that the Atterberg limits of soil decrease as water salinity increases. Chaudhari (2001) indicated that the permeability of soil decreased with increasing water salinity owing to the reduction of double-layer thickness. Shariatmadari et al. (2011) reported that the optimum moisture content (OMC) decreases and the maximum unit weight increases as the water salinity increases. Mishra et al. (2005) studied the effect of NaCl and $CaCl_2$ on compressibility and permeability of a mixture of basalt soil and bentonite. A comparison of hydraulic conductivity for different salt solutions displays that the monovalent cation has less effect than divalent cation.

The compressibility characteristics of the mixture were decreased with an increasing salt concentration of the pore fluid. Ajalloeian et al. (2013) concluded that the Atterberg limits, compression, and swelling indices decrease and the consolidation coefficient and shear strength parameter increase as pore water salinity increases. In addition, the results of dispersion tests showed that there was no dispersion in the soil in contact with saline water. Ören and Kaya (2003) observed that the compressibility of clays treated with Na^+, Ca^{2+}, and Al^{3+} solutions differs from each other, and the compression index order is Al-clay>Ca-clay>Na-clay.

To the authors' knowledge, the influence of sea/saltwater on the geotechnical properties of sandy soil with different fine contents (FC) has not been studied yet. In the present research, the effect of the Persian Gulf water (PGW) on the Atterberg limits, compaction characteristics, unconfined compressive strength (UCS), and California bearing ratio (CBR) of three types of sandy soils with different fine contents have been investigated. This research emphasizes the sustainable use of saline water in the region instead of freshwater resources in infrastructure construction, especially roads and highways.

Material and Methods

Soils

Soil samples used in this study were collected from Asaluyeh port, the southeast part of Boushehr province, in the south of Iran. Figure 1, shows the particle size distribution curves of three sandy soil samples with 5, 10, and 15% of FC according to ASTM D422 (2007). According to ASTM D2487 (2011), these soil samples can be classified as poorly graded sand (SP), poorly graded sand with silt (SP-SM), and silty sand (SM), respectively. The coordinates of the sampling locations for SP, SP-SM, and SM samples are X=667345.056, Y=3035726.811; X=661619.958, Y=3032273.208; and X=669842.436, Y=3030140.061, respectively. Table 1 summarized the physical properties of the soils. Table 2 shows the results of X-ray fluorescence (XRF) analysis used to determine the chemical composition of the soil samples.

Water

To investigate the effect of saline water on the properties of soil samples, the Persian Gulf saline water and distilled water (DW) were used to perform geotechnical tests. The PGW was sampled from Asaluyeh port. The coordinates of the sampling location are X=665664.524 and Y=3034610.087. Table 3 displays the results of the chemical analysis of the PGW.

Sample preparation and testing procedure

In this study, ASTM D4318 (2017) was used to prepare samples and determine the LL, PL, and plasticity index (PI) of them.

Table 1. Physical properties of the soils

Soil	LL (%)	PL (%)	G_s	MDD (g/cm^3)	OMC (%)	Fine content (%)	D_{60} (mm)	D_{30} (mm)	D_{10} (mm)	C_U	C_C
SP	NP[a]	NP[a]	2.57	1.87	12.1	4.9	6	1.8	0.13	46.2	4.2
SP-SM	25	22	2.57	1.86	13.0	10.2	5.4	2.2	0.075	72	10.5
SM	26	22	2.55	1.83	14.1	15.4	-	-	-	-	-

[a] Non-plastic

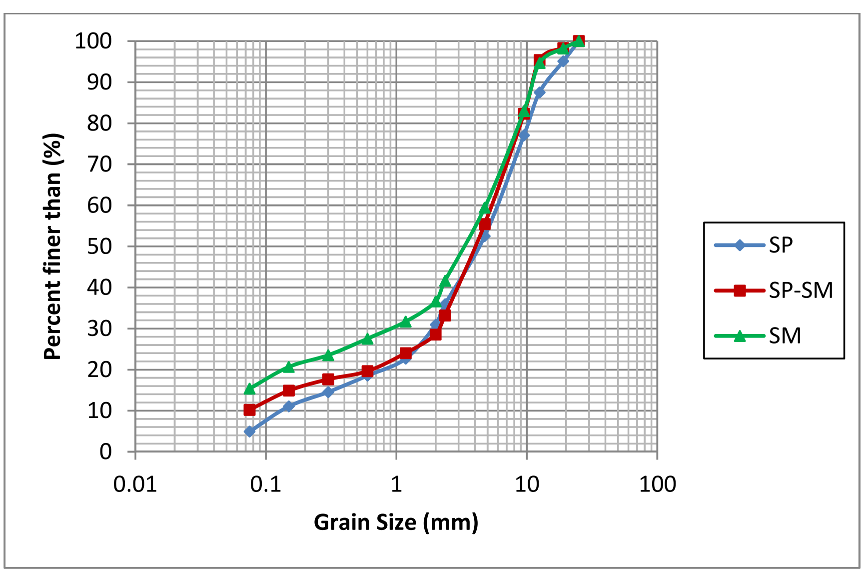

Figure 1. The particle distribution curves of the soil samples

Samples preparation and testing procedure for specific gravity (G_s), standard Proctor compaction tests, unconfined compression tests (UCT), and California bearing ratio (CBR) tests have been according to ASTM D854 (2014), ASTM D698 (2012), ASTM D2166 (2006), and ASTM D1883 (2014), respectively. For UCT, a standard Proctor compaction test was carried out to find the density and optimum moisture content of the samples. Then, the samples for the mentioned test were compacted in the mold with static compaction at determined MDD and OMC. For CBR and UCT tests, the prepared samples were put into closed containers at room temperature for 3 days to reach equilibrium.

Results and Discussion

Atterberg limits

Atterberg limits are extensively used for the identification, description, and classification of fine-grained soils and as a basis for preliminary assessment of their mechanical properties. The limits are liquid limit (LL), plastic limit (PL), and shrinkage limit (SL). LL and PL control the consistency of fine-grained soils. Figure 2 shows the influence of the PGW on the LL, PL, and PI of SP-SM and SM samples.

It can be seen that the values of LL and PL of samples were decreased with the increase in pore fluid salinity due to using the PGW, whereas the PI of samples was increased. The decrease in LL has been 4.0% and 3.8%, and the reduction in PL has been 5.4% and 6.6% for 10 and 15 percent of fine content, respectively. The increase in PI has been 6.6% and 2.5% for 10 and 15 percent of fine content, respectively. In general, the variation of Atterberg limits has not been so significant. Several researchers have been examined the effect of salt solution on the Atterberg limits of fine-grained soils. The number of studies that have been reported LL and PL reduction is significant (e.g., Mansour et al., 2008; Pandian et al., 1991; Shariatmadari et al., 2011; Messad & Moussai, 2015; Li et al., 2016; Chai et al., 2016; Di Maio, 1996; Yukselen-Aksoy et al., 2008; Ajalloeian et al., 2013; Abu Zeid and Abd El-Aal, 2017; Mishra et al., 2005). The decrease in LL and PL by using the PGW can be attributed to the presence of the high valance exchangeable cations such as Ca^{2+} and Mg^{2+} in the seawater (Table 3) that reduce the distance between particles by decreasing the repulsive forces in the soil microstructure. This causes the Van der Waals' attractive force, and Coulombic bonds to be dominant, hence increasing capillary stress that formed between particle boundaries and finally forming the aggregation (Rao et al., 1989). A comparison between the field emission scanning electron microscopy (FESEM) images of the SP-SM specimen (Fig.3 and Fig. 4) confirms this phenomenon. Clay particles show dispersed microstructure in Fig. 3 before mixing the samples with the PGW. The structure changed to the flocculation type (Fig. 4) by using the PGW. The aggregation or flocculation reduces the available surface for interaction with water which is negatively reflected in the Atterberg limits (Rao et al., 1989; Pandian et al., 1991; Mansour et al., 2008; Abu Zeid & Abd El-Aal, 2017).

An increment in the percent of CaO, MgO, K_2O, and Na_2O can be seen after mixing the samples with the PGW (Table 2). According to Chai et al. (2016), the value of the thickness of the diffuse double layer around clay particles is a function of the concentration and valence of cations in the pore water. The higher concentration and valence, the smaller value of the thickness of the diffuse double layer. Therefore, it is clear that the presence of divalent cations such as Ca^{2+} and Mg^{2+} in the PGW is the main reason for the reduction in LL and PL of the soils. Rao et al. (1989) and Frydman et al. (1978) reported that the presence of K^+ ions in the pore water also decreases the liquid limit, although the effect of this monovalent ion is less than that of divalent ions.

Figure 2 also shows that the LL and PL of the samples increase when the percent of fine content increases. Polidori (2007) concluded that the Atterberg limits (LL and PL) and Plasticity index (PI) are linearly proportional to fine content (FC) and only the LL-FC regression line has zero intercept value.

Table 2. Chemical composition of the soils (XRF results)

	SP		SP-SM		SM	
	Natural soil	Stabilized soil with the PGW	Natural soil	Stabilized soil with the PGW	Natural soil	Stabilized soil with the PGW
Na_2O	0.00	3.12	0.00	2.50	0.00	2.93
MgO	3.00	3.81	2.80	3.50	2.53	3.13
Al_2O_3	1.43	1.41	1.50	1.54	1.61	1.58
SiO_2	3.92	4.01	4.20	4.00	4.25	4.15
P_2O_5	0.01	0.01	0.02	0.01	0.02	0.14
SO_3	0.66	0.51	0.71	0.32	0.70	0.44
Cl	0.04	4.02	0.06	3.40	0.04	3.85
K_2O	0.23	0.37	0.21	0.34	0.25	0.32
CaO	46.90	48.90	45.30	48.60	45.80	48.35
Fe_2O_3	1.10	1.05	1.08	0.94	1.00	1.00
SrO	0.00	0.31	0.00	0.28	0.00	0.33
L.O.I	42.71	32.48	44.12	34.57	43.80	33.78

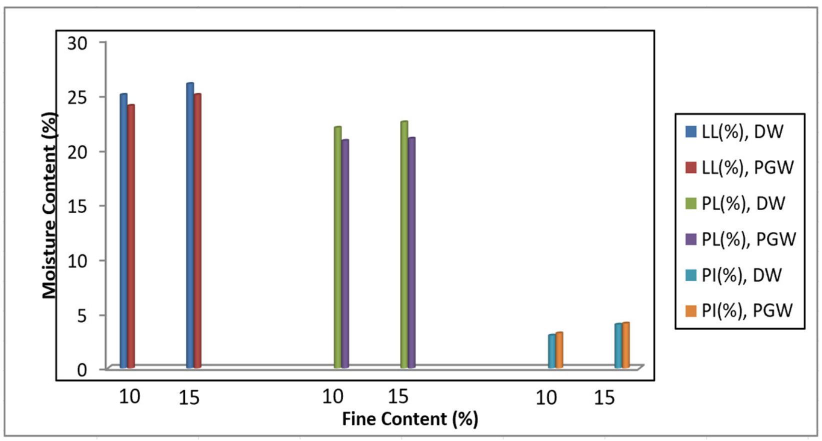

Figure 2. Variation of LL, PL, and PI with type of water and fine content percent

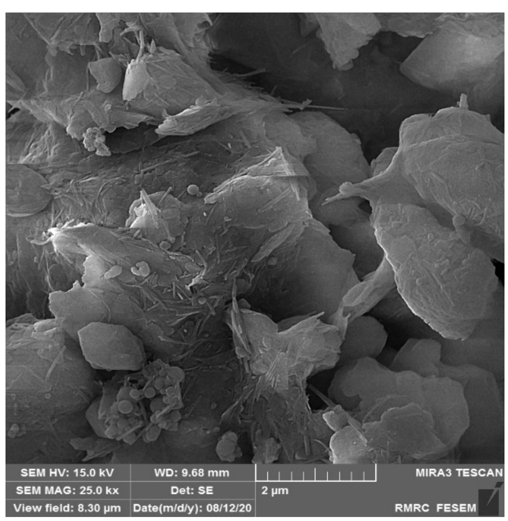

Figure 3. FESEM image of SP-SM natural soil

Table 3. Chemical analysis of the PGW in sampling location

Ions (mg/L)									pH	TDS[a] (mg/L)
Cl^-	Na^+	SO_4^{2-}	Mg^{2+}	Ca^{2+}	K^+	NO_3^-	PO_4^{3-}	NO_2^-		
26500	14000	3525	1288	1280	280	0.8	0.03	0.004	6.85	55318

[a] Total dissolved solid

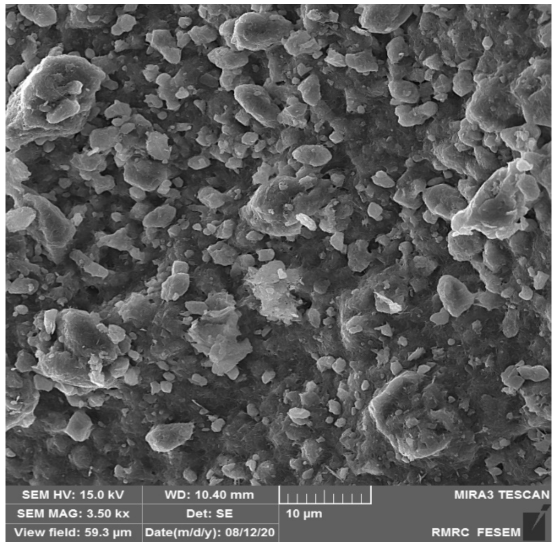

Figure 4. FESEM image of SP-SM sample after mixing with the PGW

Compaction characteristics

Standard Proctor compaction tests were carried out on the soil samples that mixed with DW and the PGW, separately. The results are plotted in Fig. 5 in the form of dry density versus moisture content. The compaction curves for the samples that were mixed with the PGW moved to the left side of the curves that belong to the samples that were mixed with DW. It means that the stabilized samples with the PGW show more maximum dry density (MDD) and less optimum moisture content (OMC). Figures 6 and 7 show the variation of MDD and OMC versus the percent of fine content, respectively. According to Figures 5 and 6, the MDD of the soil samples increased by 4.2%, 4.3%, and 4.4% for 5, 10, and 15 percent of fine content, respectively. Although the MDD of the soil samples has been increased by using the PGW, the increment was not so significant. According to Figures 5 and 7, the OMC of the soil samples decreased by 34.8%, 34.6%, and 36.2% for 5, 10, and 15 percent of fine content, respectively. This significant reduction means that the soil samples have been compacted with less moisture content if the PGW has been used. It also displays that using the PGW instead of freshwater is much more effective. Moreover, it is clear that reducing the use of the freshwater resources in some engineering projects is environmental benign and ecofriendly.

There are some reasons for this behavior. Wood et al. (1960) and Frydman et al. (1978) ascribed the behavior to the fact that at low moisture content the soil structure tends to change from edge-to-face type of flocculation to face-to-face flocculation (salt flocculation) with the increase in salinity of pore water. Consequently, during the compaction, the clay particles become more oriented, and the compacted dry density increases. Another reason for increasing MDD can be due to the increasing cation concentration or cation valence that would cause a decrease in net repulsive forces and an increase in attractive forces, hence causing clay platelets to pack in a denser configuration that increases the MDD (Sharma & Lewis. 1994).

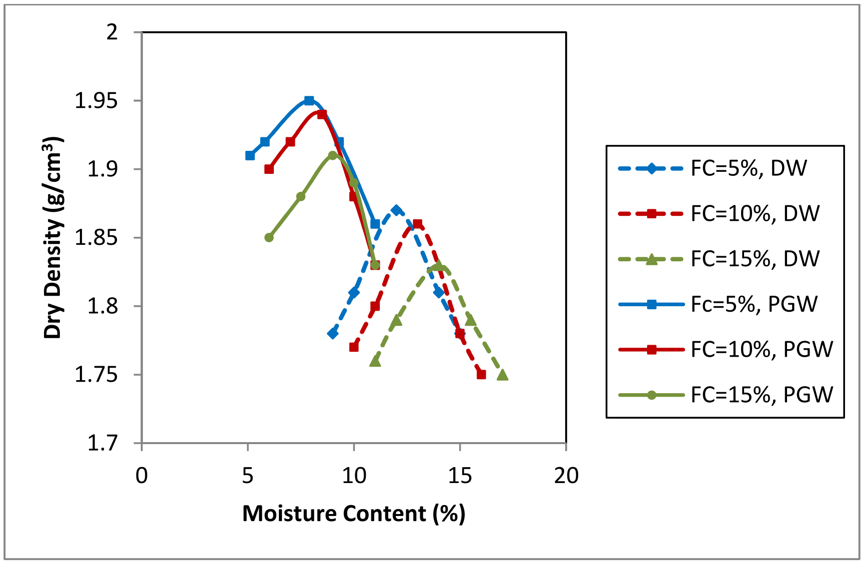

Figure 5. Variation of dry density with moisture content

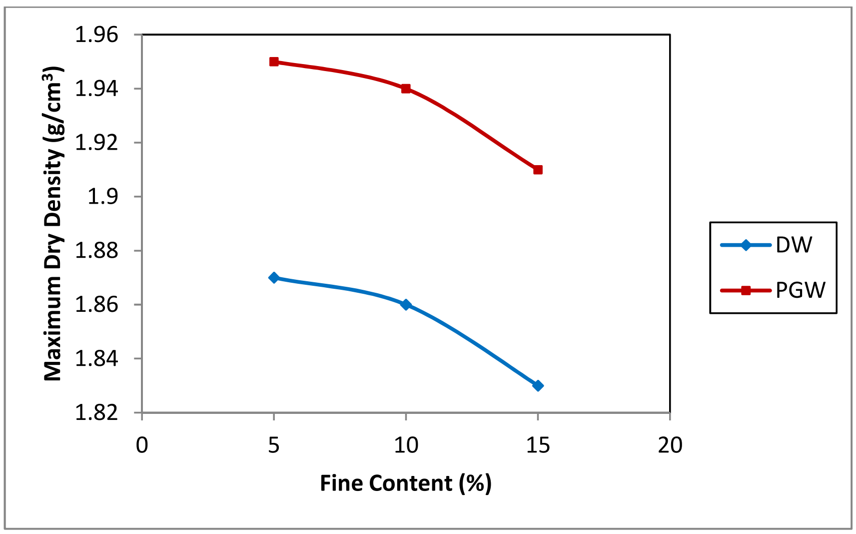

Figure 6. Variation of MDD with fine content percent

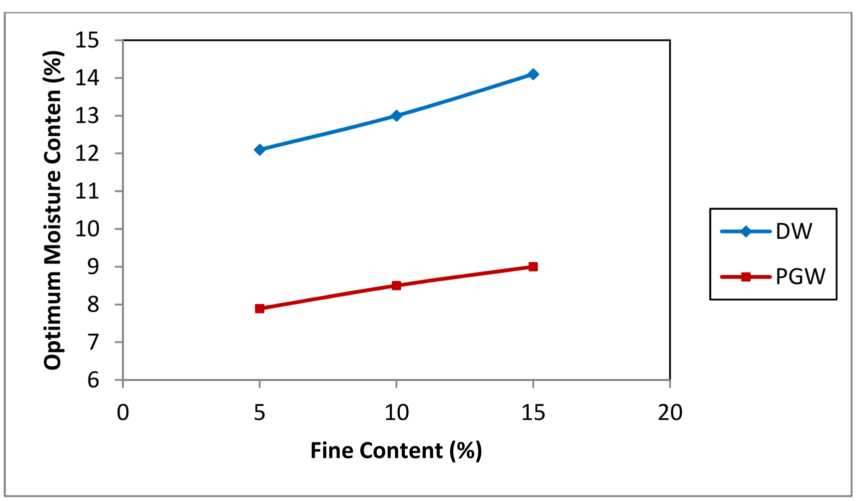

Figure 7. Variation of OMC with fine content percent

Shariatmadari et al. (2011) reported that with increase in salinity of the pore fluid, the thickness of the diffuse double layer reduces; therefore, using the same amount of compaction energy, the particles pack better together and the MDD increases. Slowinski and Masterton (1990) explained that the increase in the dry density could be because of a chemical reaction between the salt molecules and soil particles, which partially contains lime. Magnesium, potassium, and sodium chlorides from salt react with calcium oxides and hydroxides from the soil to form calcium chloride, which hardens the soil and increases the dry density.

The reduction in the OMC as the salinity increased may be attributed to the higher the face-to-face flocculation the lower amount of water required for lubrication. Spangler and Handy (1982) pointed out that NaCl and $CaCl_2$, which are very common in seawater can lubricate the soil particles and improve compaction.

According to Figure 6, the MDD of samples decreases when the percent of fine content increases. This behavior was seen in both samples, whether mixed with DW or the PGW. As the percentage of fine content in the samples increases, the percentage of water requires for soil compaction increases, which causes a decrease in soil density. Kim et al. (2018) reported that at greater fine content, sand grains would be surrounded by fine particles rather than a void filled with fines. Thus, the dry density appeared to decrease with the further addition of fines. According to Figure 7, the OMC increases with the increase of fine content in the samples. The increment in the water content can be attributed to the presence of fine particles that increase the amount of water required for soil compaction. The higher percent of fines, the more water for densification.

California bearing ratio (CBR) and unconfined compressive strength (UCS)

The California bearing ratio (CBR) test is a penetration test used to assess the subgrade strength of roads and pavements. The results of the test are applied to determine the thickness of pavements. Bowles (1992) believed that the CBR value demonstrates an indirect measure of the strength of the subgrade soil (while the UCS value is a direct measure of strength), and it is also used to assess soil stiffness modulus and shear strength. That is why there should be a correlation between the CBR values and the strength values of soils. Nagaraj and Suresh (2018) presented a direct linear relationship between the CBR and UCS as follows:

$$CBR=0.03\ UCS \quad (1)$$

Therefore, it can be concluded that the factors affecting the CBR and UCS are the same.

Figures 8a and 8b show the applied load versus penetration in the CBR test for the samples that were mixed with DW and the PGW, respectively. The results indicate an increase in the applied load for 2.5 and 5 mm penetrations in the CBR test after using the PGW. When the penetration is equal to 2.5 mm, the increase in applied load has been 11.1%, 10.8, and 10.0% for 5, 10, and 15 percent of fine content, respectively. When the penetration is equal to 5 mm, the increment in applied load has been 10.4%, 11.4%, and 10.8% for 5, 10, and 15 percent of fine content, respectively. Results show that the increase in the applied load has been significant to some extent.

Figure 9 shows the unconfined compressive stress-strain curve for both mentioned specimens. The UCS value increased after using the PGW. The increase in the UCS has been 12.2%, 6.1%, and 9.6% for 5, 10, and 15 percent of fine content, respectively, which is slightly significant. Several factors can enhance the CBR and UCS values. One of the most important factors is related to the microstructure changes of the specimens while mixed with the PGW.

Figure 3 shows the FESEM image of the natural SP-SM soil. The dispersed fabric between clay platelets can be seen. There are also some micropores between particles. After adding the Persian Gulf saline water to the sample, various changes in the microstructure happened. One of them is the crystallization of salts in the pore spaces (Figure 10) which causes a reduction in the void ratio and plays an important role in cement fabrication that can improve the CBR and UCS values.

The increase in the UCS and CBR values can also be interpreted by the flocculation mechanism of clays (Figure 4) and the diffuse double layer theory suggested by Stipho (1985), Gleason et al. (1997), and Schmitz et al. (2004). The saline water decreases the thickness of the diffuse double layer, causing the soil structure to shrink and increase attraction forces, so boosting the flocculation of clay particles and subsequently increasing the packing of particles and leading to higher strength.

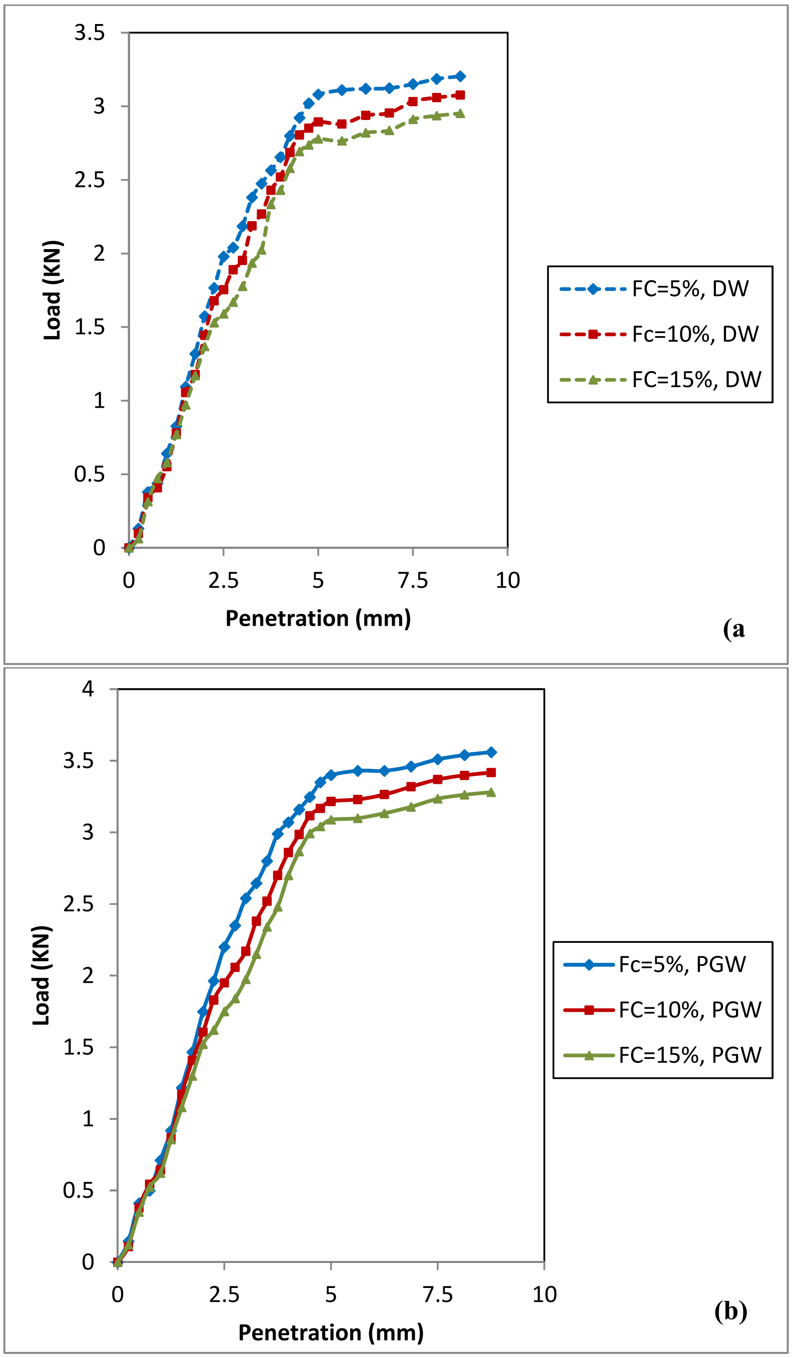

Figure 8. a) Variation of the applied load versus penetration value for the samples mixed with DW **b)** Variation of the applied load versus penetration value for the samples mixed with the PGW

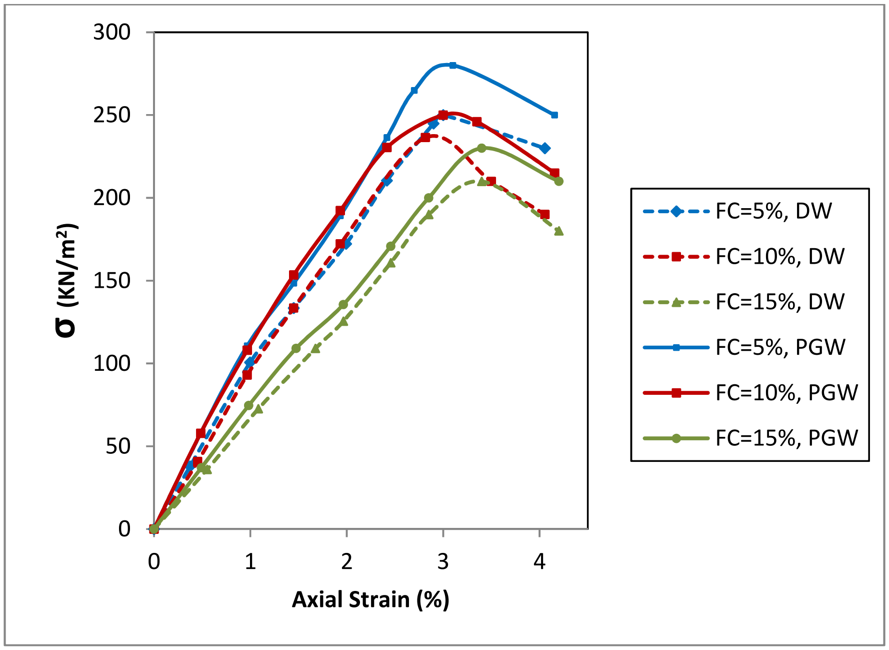

Figure 9. The unconfined compressive stress-strain curves

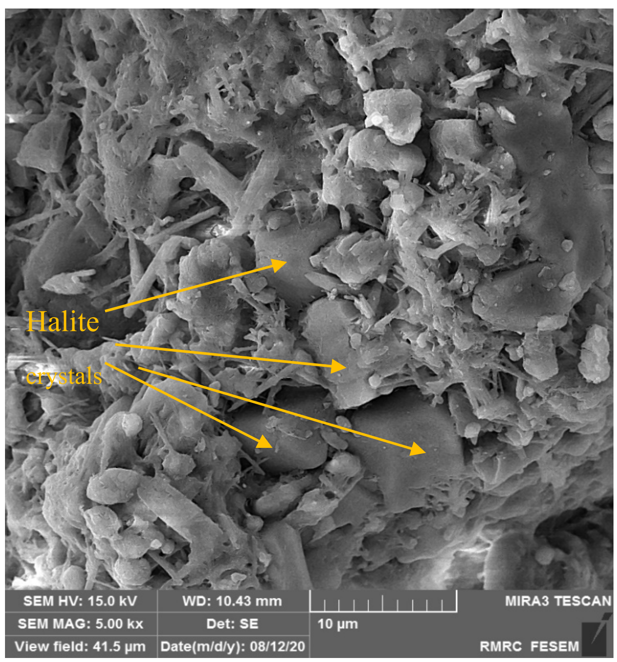

Figure 10. FESEM image of Halite crystallization in pore spaces after stabilization with the PGW

Agglomeration and flocculation of soil particles after mixing the specimens with the PGW cause an increase in the size of the particles. Moreover, the deposition of salt layers on the particle surfaces can act as a cementitious agent and also connect fine grains and form coarse grains (Figure 11). Therefore, clay particles behave more like silt. It is another reason for improving the CBR and UCS values.

As shown in Fig. 12, using brine instead of DW increases the surface roughness of the particles which can enhance the interaction between them, and increases the strength. According to Fig. 5, the reduction in the OMC of samples after mixing them with the PGW can be another reason for improving the CBR and UCS values. The decreasing moisture content causes an increase in the shear strength parameters and enhances the UCS and CBR values.

Ismeik et al. (2013), Wright and Dixon (2004) believed that the brine forms a film around each particle, which enhances the strength of the particles in two ways. First, the surface tension of brine water is stronger than ordinary moisture, so it increases the cohesion of the particles. Secondly, the brine film acts as a lubricant and lets the particles to be accumulated closer together under compaction than they would be with ordinary moisture. This increases the unit weight which causes an increment in the strength.

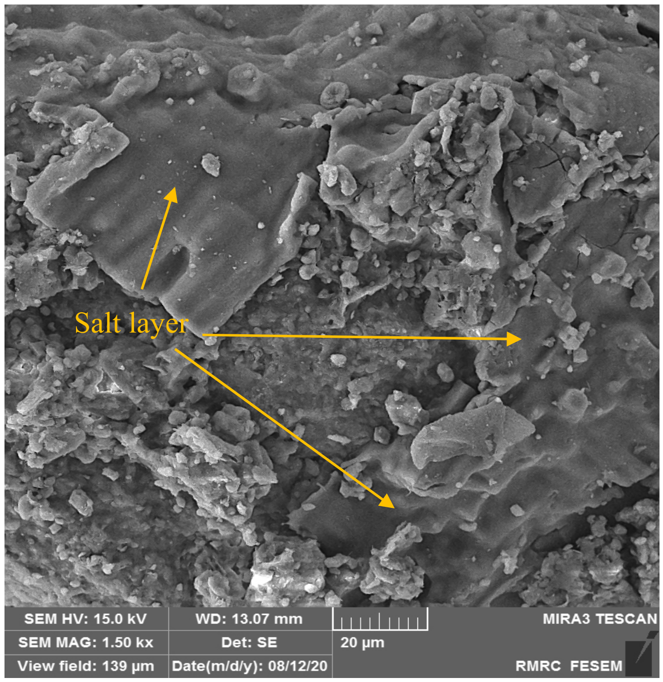

Figure 11. FESEM image of the deposition of salt layer on the particle surfaces after stabilization with the PGW

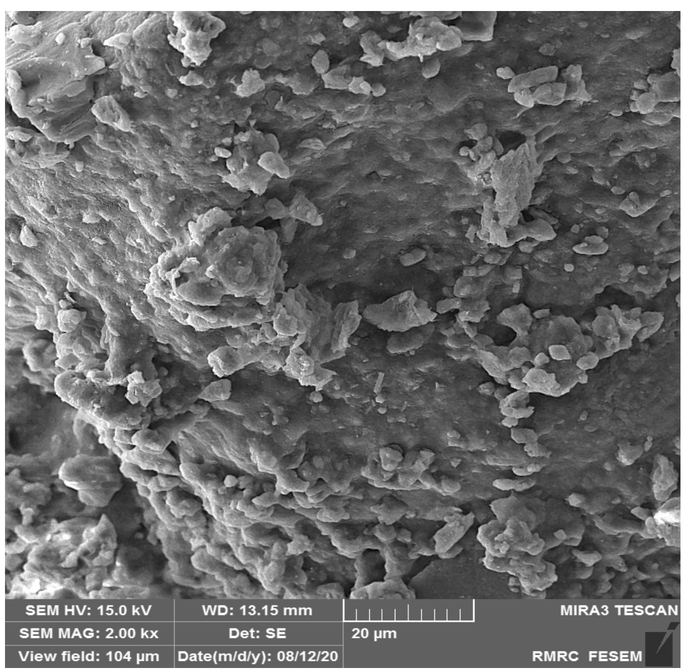

Figure 12. FESEM image of surface roughness of soil particles after stabilization with the PGW

Forming calcium chloride due to the chemical reaction between the salt molecules and soil particles or adding $CaCl_2$ solution to soils causes hardening, more dry density, and strength (Abood et al., 2007; Slowinski & Masterton, 1990).

Fig. 13 shows the CBR values versus fine content percent. On one hand, the CBR values of the PGW-stabilized samples are higher than that of samples mixed with DW. On the other hand, an increment in fine content percent causes a decrease in the CBR values of the samples that are separately mixed with DW and the PGW. According to Fig. 14, the same scenario happened for the UCS values. The strength of sand soil with a low percentage of fine content is mainly made up of internal friction, while that of the one with a high percentage of fine content is composed of both internal friction and cohesion.

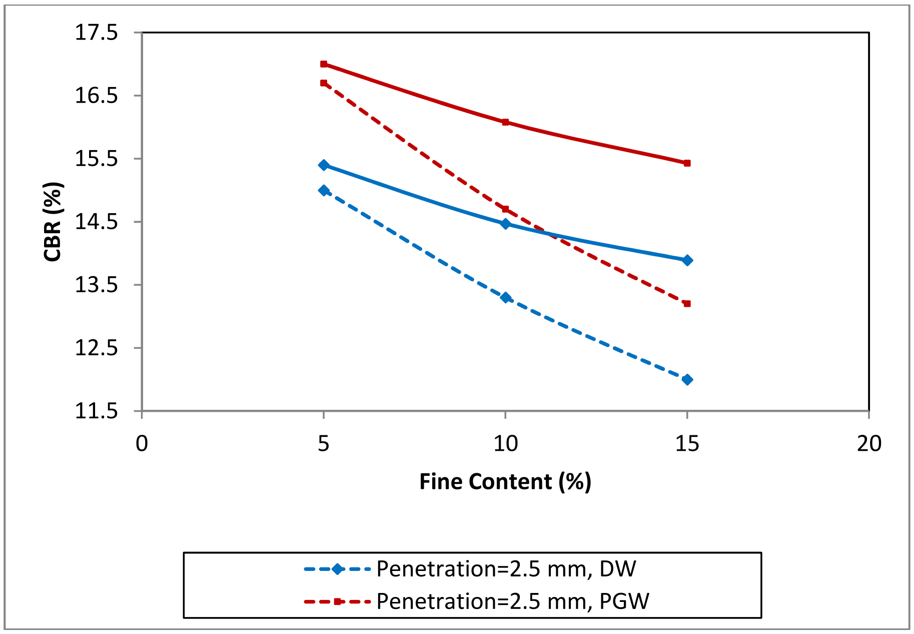

Figure 13. Variation of the CBR values versus fine content percent

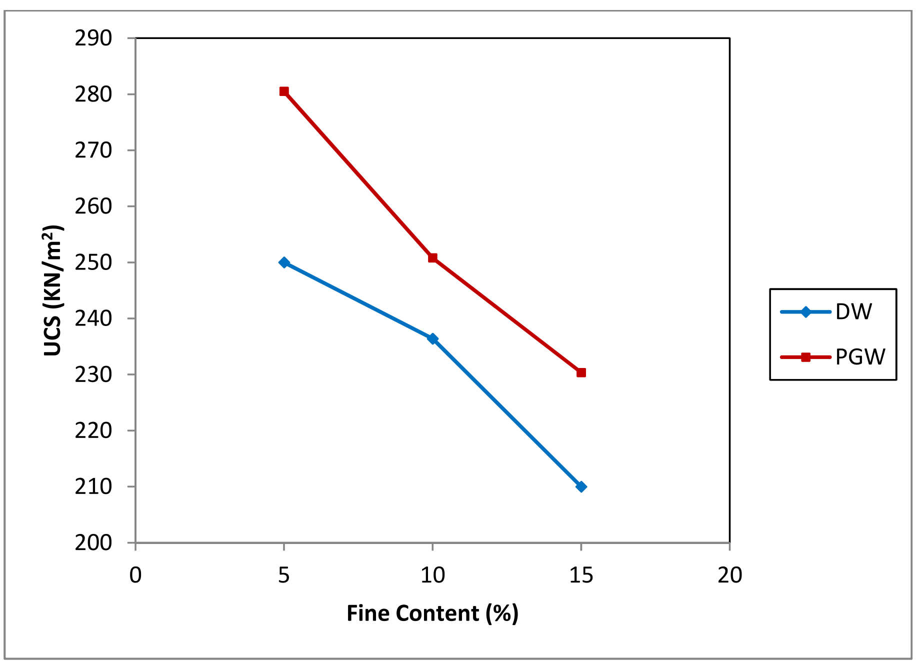

Figure 14. Variation of the UCS values versus fine content percent

The sand particles are relatively coarse and have a rough surface, so the strength of sand soil with a low percent of fine content is larger than that of with a high percentage of fine content and fine-grained soils. The strength performance of fine-grained soil can be improved by adding relative coarse sand particles, and its strength will increase with the enhanced sand content. Therefore, one of the reasons for the reduction of the UCS and CBR values is the decrease in the sand content with an increase in the fine content. Ueda et al. (2011) assessed the theoretical contribution of large and small particles on the mechanical characteristics of the mixtures of the two-sized particles. The two-dimensional discrete element methods and experiments have been adopted. The influence of the large particle on shear strength varied from one at small clay content to zero at large clay content. The shear strength of clay-sand mixture with low fine content depended on the characteristics of large size particles, and the void of such mixture seemed to be partially filled with fines. As the fine content increased, the void was completely filled and fines would surround the large size particles. Subsequently, the shear zone was likely to occur within the zone of small particles, and the behavior of the clay-sand mixture started being governed by the property of small particles. At greater fine content, sand grains would be surrounded by fine particles rather than a void filled with fines. Thus, the dry unit weight appeared to decrease with the further addition of clays. Consequently, the influence of the clay between particles increased, and the strength of the clay-sand blends become closer to that of the clay. Hence, the internal friction angle decreased as clay content increased after certain clay content. The result is a reduction in strength and CBR values.

The CBR values also decrease with an increase in water content, which is obvious because the strength of soils has a nonlinear decreasing relation with an increase in water content as well reported in the literature (Sridharan & Prakash 1999, Nagaraj et al. 2012, Ghosh 2013). Fine particles have stronger moisture holding capacity than coarse particles. The capacity will enhance when the percent of fine content increases. An increment in moisture content with an increase in fine content will reduce shear strength parameters of the samples and causes a decrease in the strength and CBR values (Figures 8 and 9).

Conclusions

In this research, an experimental study was performed to determine the effects of fine content percent and salinity of seawater on the geotechnical characteristics of sandy soils. The program included Atterberg limits (LL and PL), compaction, California bearing ratio, and unconfined compression tests. The results indicated that the stabilization of samples with saline water causes more bearing capacity and strength. The CBR and unconfined compressive strength (UCS) have been improved up to 11.3% and 12.2%, respectively. With increasing salinity of water, optimum moisture content, liquid, and plastic limits decreased up to 36.2%, 4.0%, and 6.6%, respectively, but the maximum dry density of the soil samples increased up to 4.4%. The results also displayed that the lower the percentage of fine content, the higher the value of CBR and UCS. The decrease in LL, PL, and increase in maximum dry density by using the PGW can be attributed to the presence of the high valance exchangeable cations such as Ca^{2+} and Mg^{2+} in the seawater that reduce the distance between particles by reducing the repulsive forces in the soil microstructure. The reduction in the OMC as the salinity increased may be attributed to the higher the face-to-face flocculation the lower amount of water required for lubrication. The results indicate an increase in the applied load for 2.5 and 5 mm penetrations in the CBR test and an increment in the UCS value after using the PGW. Agglomeration and flocculation of soil particles after mixing the specimens with the PGW cause an increase in the size of the particles. Moreover, the deposition of salt layers on the particle surfaces can act as a cementitious agent and also connect fine grains and form coarse grains. Therefore, clay particles behave more like silt. It is the reason for improving the CBR and UCS values. Increment in fine content percent causes a decrease in the CBR and UCS values of the samples that are separately mixed with DW and the PGW. The maximum reduction in CBR with the increase in fine content has been 20.0% and 20.9% for 2.5 mm penetration if DW and PGW are used, respectively. It was 9.8% and 9.2% for 5 mm penetration if DW and the PGW are used, respectively. The maximum decrease in UCS with the increase in fine content has been 16% and 17.8% if DW and PGW are used, respectively. The decrease in sand content and reduction in the contribution of large particles in the soil strength, decrease in maximum dry density, and increase in water content are the most significant reasons for the reduction in the CBR and UCS values with an increase in fine content percent.

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