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Geotechnical characteristics of saline soft soils improved by chemical agents

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Abstract. Chemical stabilization is a typical method for enhancing salinity in soils. In this regard, an effort has been made to evaluate the effect of chemical substances and stabilizers of Portland cement on the geotechnical characteristics of salt soils. Due to their geologic makeup, textural characteristics, and climatic factors, the majority of the soils in the southern part of Iraq are notable for having a wide variety of formations. Because the soil particles in the saline regions of Thi-Qar governorate are encircled by molecules of chlorides, sulfates, or other salt species that function as link agents to fill in the gaps in the dry state, these soils may generally be categorized as saline soils. The sort of salt in such soil determines how it should be disposed of. The objective of this study is to investigate the effect of adding different types of salt compounds including NaCl, $MgCl_2$, Na_2SiO_3, and $CaCl_2$ with various percentages 2, 4, 8, and 10 % and Portland cement for improving the consistency limits and shear strength of saline soft soils. It was found that adding cement materials and a group of chlorides NaCl, $MgCl_2$, Na_2SiO_3, and $CaCl_2$ increased the unconfined compressive strength of the soil from 290 to 814, 506, 404, 574, and 422 kPa, respectively, and decrease the consistency limits.

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1. Introduction

The sides of the Euphrates River bank are formed by fine sediments of silt or silty clay, and mud accumulating on the bank and at the top portion of the natural flood zone level, which work to obstruct the flow of the river and seem like a steep barrier. River water is diverted from the neighboring plains and utilized to build car parks and many engineering structural compounds like dams, bridges, liquefaction-pumping stations, etc. When the sides of rivers are safe and stable, the procedure of exploiting them becomes easier. If they are unstable and on the verge of collapsing, the process of exploitation is delayed. The soils along the Euphrates River bank in the southern region of Iraq were classified as saline soft soils. When the subgrade is fine soil, a tricky issue arises in civil engineering applications [1].

Many studies were conducted on the topic of soil stabilization utilizing different additives. The usual process for clayey soil stabilization is stabilization by adding lime and cement. Nevertheless, there is justification for studying inexpensive additives, which can be utilized to modify the features of soils. Any mechanical, hydrological, physicochemical, biological, or any combination of these approaches used to modify specific features of natural soil deposits is referred to as ground improvement or ground modification. The goal of ground improvement is to enhance the strength and minimize the settlement of existing soils, or to modify their permeability [2]. Saline soils are created from hydrated gypsum natural resources $CaSO_4.2H_2O$, SiO_2, calcite $CaCO_3$, or NaCl salt, which covers ground surface. When the moisture content is raised up because of capillary action and evaporation of the water from the ground, and the salinity of water increase for these soils to the limits of sedimenting of salts because of water evaporation. So, the water table acts an essential way to the presence of salty soil [3, 4]. With a chloride salt level greater than 3%, salty soil is a highly conductive system [5]. Saline ions penetrate electric porous media with water migration and subsequently react with soil atoms [6]. The hydration range of chloride ions is likewise greater, and they can absorb water [7]. Without treatment, such filling would not fulfill the required strength and anti-deformation standards for use in construction due to physical and chemical issues, such as salt expansion, dissolution, and moisture absorption [8]. The microstructures of treated soil are affected by chloride ions, as are the strength properties [9]. In the short and long term, chloride ions have a significant impact on the strength of improved soil [10, 11].

Because the presence of significant amounts of saline indicates that the geotechnical properties of clayey soils may change in the presence of infiltrating water, engineering properties of clayey soils mixed with sodium chloride revealed that the plasticity index and unconfined compressive strength (UCS) decrease as salt content is increased [12]. The addition of chloride salt improved the structure of the lime-soil combination significantly. It increased the amount of coarse soil particles while decreasing the soil's overall surface area. The degree of homogeneity was lowered by increasing the salt level, whereas the salt amount had a linear connection with the microstructure's characteristics, such as the bone area, appearance ratio, and roundness [13]. Addition of up to 8 % calcium chloride improved lateritic soil. Calcium chloride is not convenient as an independent stabilizer but can be passable as a modifier or as an admixture in the cement stability of lateritic soil [14]. In Shatt Al-Arab Southern Iraq, the influence of salinity on the geotechnical properties of fine grain soil was investigated. Atterberg limits, standard compaction, consolidation, and soil shear strength are examples of laboratory testing. The presence of detectable amounts of dissolved salts in water can cause changes in the engineering characteristics of the soil [15].

The effect of magnesium chloride ($MgCl_2$) emulsion on the geotechnical properties of clay soils was evaluated by different researches. Turkoz et al. [16] explained that the increasing the $MgCl_2$ content decreased the soil consistency (Atterberg limits). The fact that addition of NaCl, $CaCl_2$, and $MgCl_2$ filled up the voids between particles of soil as particle size of NaCl, $CaCl_2$, and $MgCl_2$ is smaller than soil particles and can be easily replaced the voids. The compression index and swelling index were decreased with increasing the chloride compound percentage [17]. Moayedi et al. [18] studied affected of sodium silicate system binders of the physicochemical characteristics of the soft soil. It was conducted a number of batch tests. According to the results, adding 3 mol/L of Na_2SiO_3 may raise the UCS of soil in group testing by up to 220 % of its baseline strength, while adding activators $CaCl_2$ and/or $Al_2(SO_4)_3$ can boost UCS values by up to 270 %. Additionally, adding $CaCl_2$ at greater concentrations (such as 1 mol/l) had no appreciable impact on the UCS findings. The objective of this study is to investigate the effect of adding different types of salt compounds including NaCl, $MgCl_2$, Na_2SiO_3, and $CaCl_2$ with various percentages 2, 4, 8, and 10 % and Portland cement for improving the consistency limits and compressive strength of saline soft soils. The methodology of this study includes: First, collecting soil from the study area and conducting a series of conventional tests to know its geotechnical properties. Second, mixing the natural soil with a variety of salts each added with different percentages as demonstrated in experimental work section to obtain saline soil samples. Third, testing the samples. Finally, analyzing the obtained results.

2. Methods

2.1. Salinity's Impact on the Physical Properties of Soils

The invading water also has a tendency to flow into the voids between the platelets due to the relatively higher concentration of ions close to the platelet, which causes the platelets to become further separated. When there is too much space between the platelets, dispersion takes place, which results in the platelets being carried away by the flowing water and perhaps getting stuck in big soil pores, further reducing the rate of absorption. The top layer of soil may expand and become saturated if water cannot get through it. Sodium has the opposite effect of salinity on soils. The primary physical processes associated with high sodium concentrations are soil dispersion and clay platelet and aggregate swelling. The forces that bind clay particles together are disrupted when too many large sodium ions come between them. When this separation occurs, the clay particles expand, causing swelling and soil dispersion. So, the hydraulic conductivity of the soil is impacted by soil dispersion in addition to reducing the quantity of water that enters the soil. Hydraulic conductivity describes how quickly water enters the subsoil. For instance, soils with well-defined will have a lot of microspores, fractures, and fissures that allow water to move through the soil very quickly. The hydraulic conductivity is also decreased when sodium-induced soil dispersion causes the degradation of soil structure. Hanson et al. [20] explained that the soil dispersion causes clay particles to plug soil pores, resulting in reduced soil permeability. Their ion layers tend to overlap as two platelets get close to one another, and electrical repulsive forces emerge as a result of positively charged clay particles having charged ions “attached” to them make an effort to repel one another.

The clay platelets are often kept apart with forces, resulting in the swelling of the soil. When soil is repeatedly wetted and dried, and clay dispersion occurs, it then reforms and solidifies into almost cement-like soil with little or no structure. The three main problems caused by sodium-induced dispersion are reduced infiltration, reduced hydraulic conductivity, and surface crusting. Salts that contribute to salinity, such as calcium and magnesium, do not have this effect because they are smaller and tend to cluster closer to clay particles as shown in Fig. 1. Calcium and magnesium will generally keep soil flocculated because they compete for the same spaces as sodium to bind to clay particles. Increased amounts of calcium and magnesium can reduce the amount of sodium-induced dispersion. Because sodium ions are less attracted to the platelets than are calcium ions, the layer of sodium ions extends further from the platelet, thus increasing the separation distance between adjacent platelets and inducing more swelling. Calcium ions are more strongly attracted to the platelets, and as a result, the ion layer does not extend as far from the platelets compared with sodium ions. This means a smaller separation distance between platelets and less swelling of the soil. Thus, replacing exchangeable sodium with calcium can reduce swelling and improve infiltration.

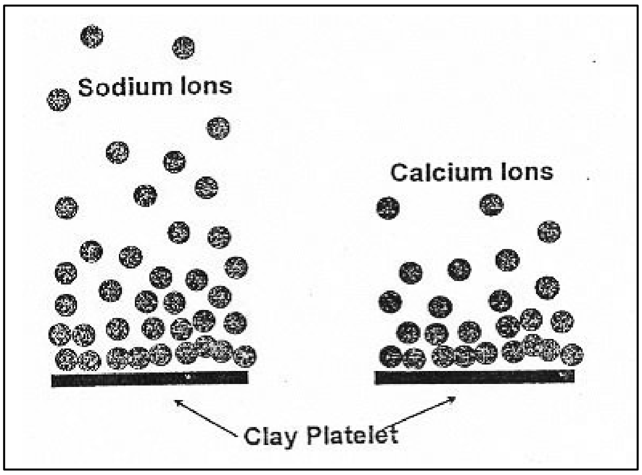


Figure 1. Behavior of sodium and calcium attached to clay particles [21].

2.2. Geotechnical Properties of the Study Area

Grayish silty clay soils were brought from south of Iraq representing a generally typical soil in the saline area at Southern Iraq. Disturbed soil samples were collected from a depth of 0.5–1 m from Al-Nasiriyah city located in the southern part of Iraq (Coordinate: Latitude = 628069, Longitude = 3427088). The study area was chosen to be between the bank of Euphrates River and the public estuary project that is considered one of the major development projects in Iraq due to its importance in transporting saline water for messages from the reclamation of agricultural lands in Central Iraq as shown by the blue mark in Fig. 2. This site has a high potential for increasing the salinization because of the drought exposed in the area. According to the standard specification ASTM D 2487-11 [21], the soil can be classified as ML (Fine grained soil). Geotechnical and chemical tests were conducted after transferring the samples to the laboratories of Civil Engineering Departments in the College of Engineering at the University of Thi-Qar. Table 1 summarizes the basic geotechnical properties of the natural soil and chemical properties.

Figure 2. Satellite image of the location of the test points for samples extraction.

Table 1. The geotechnical properties of the tested soil.

Soil property	Value	Specifications
D_{10} (mm)	< 0.0007	
D_{30} (mm)	0.0022	ASTM D422 [22]
D_{50} (mm)	0.0037	
D_{60} (mm)	0.0047	
Liquid limit, LL (%)	49	ASTM D4318 [22]
Plastic limit, PL (%)	38	ASTM D4318 [22]
Plasticity index, PI (%)	11	
Specific gravity, GS	2.65	ASTM D854 [22]
Maximum dry unit weight, γd max (g/cm^3)	1.61	ASTM 698 [22]
Optimum water content (%)	20	
Undrained shear strength of the natural soil, c_u (kPa)	28	ASTM D2166 [22]
Undrained shear strength after compaction (kPa)	145	
Cl (%)	1.5	BS. 1377 [23]
Organic matter, OM (%)	6.78	
Total dissolved salts, TDS (%)	9.2	
SO_3	4.1	
Gypsum content (%)	9.3	
pH	8.41	

3. *Results and Discussion*

The laboratory tests of the soil samples began immediately after receiving the samples in the laboratory. The tests were conducted in the College of Engineering, Thi-Qar University laboratory. Subsequent laboratory tests were executed to determine the physical and engineering properties of disturbed soil samples. All tests on the site have a high potential for increasing salinization because of the drought that exposed the area.

3.1. *Compaction Test*

The Proctor compaction test was carried out to determine the moisture content–dry density relationship according to ASTM (D 698) [22]. The soil was compacted into 937 cm^3 mold in 3 layers. Fig. 3 shows the dry density–moisture content relation for the soil and preparation of proctor compaction.

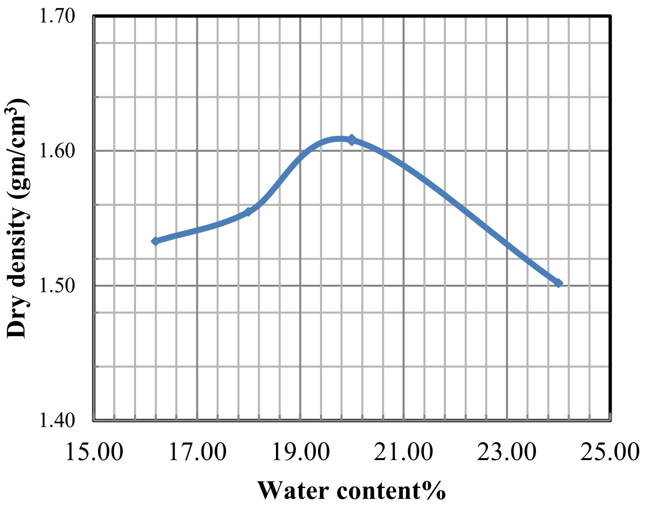


Figure 3. Results of compaction test.

3.2. *Atterberg Limits*

The liquid limit test has been accomplished using the Cassagrande apparatus according to ASTM D423-66 [21]. The plastic limit test was conducted according to the ASTM D 424-59 [21]. The chloride compounds (NaCl, $MgCl_2.6H_2O$, $CaCl_2.2H_2O$, and Na_2SiO_3) were dissolved in water and mixed with soil. These tests were carried out to investigate the effect of addition of salt on the consistency limits. Fig. 4 shows the effect of additive content on the Atterberg limits. The figure shows that the increase in additive content decreases the liquid limits for all additives. While in the case of the plastic limits, there was a fluctuation in the soil behavior and a decrease in the values of the plastic limits by adding additives, although there was a significant increase with the addition of Portland cement.

On the other hand, the all-values of plasticity index decrease with adding the additive. The dissolution of salts in water and soil leads to a change in their physicochemical properties. Changes in its physical and chemical properties as a result of the different interactions between the exchange complex and the soil solution, which lead to a change in the composition and concentration of the soil solution. The behavior of the soil with saline water depends on its physical properties at the beginning and on the adsorption capacity of ions, which in turn affect its hydrophysical properties. The initial chemical composition of the soil affects the ion exchange processes during contact of water with the soil. In addition to the accumulation of some elements, especially sodium, which leads to the deterioration of soil construction and a decrease in the movement of water and air. Finally, the amount of salt causes flocculation and agglomeration of soil particles, which results in a reduction in liquid limit. The results show that when the salinity of the pore media increases, the soil's liquid and plastic limits decrease. These results are consistent with the findings of Shariatmadari et al. [22] and Yukselen-Aksoy et al. [23].

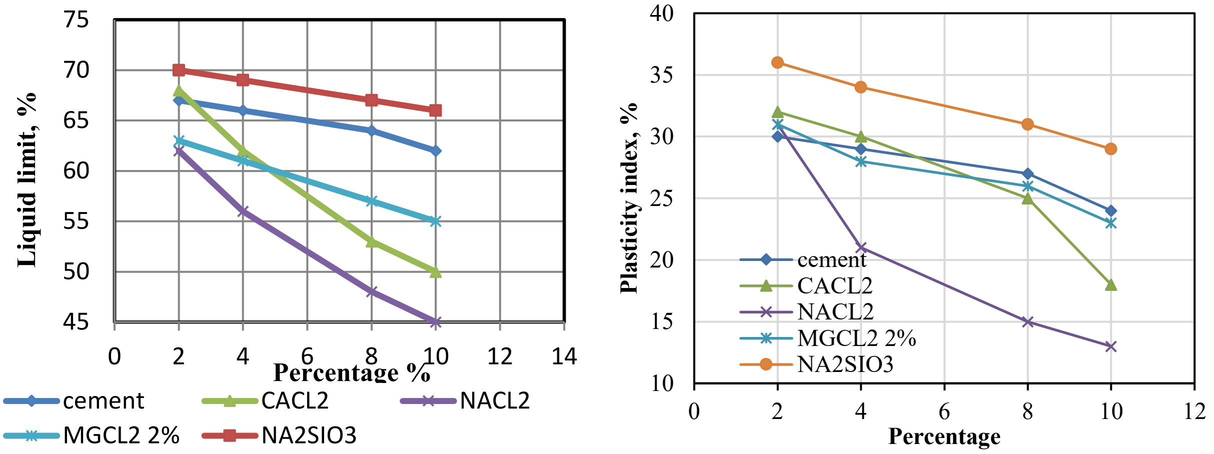


Figure 4. Consistency limits of salinity soil under different percentage of additives.

3.3. Shear Strength Results

The shear strength of soils treated with additives was investigated using UCS testing. To obtain the highest dry unit weight and optimum water content, the sample was compacted into three layers using the Harvard miniature compaction device. The compacted specimen's diameter was 33 mm and 70 mm in length. The results of the undrained shear strength were treated by adding (Portland cement, NaCl, $MgCl_2.6H_2O$, $CaCl_2.2H_2O$, and sodium silicate) under different percentages of additives (0, 2, 4, 8, and 10) % are shown in Table 2.

Table 2. The undrained shear strength results for different chemical agents.

Additive, %	Unconfined compressive strength, UCS (kPa)					
	Natural compacted soil	NaCl	$MgCl_2.6H_2O$	$CaCl_2.2H_2O$	Portland cement	Na_2SiO_3
0	290			290		
2		282	404	422	682	574
4		506	316	352	814	518
8		484	206	304	582	422
10		200	208	250	506	326

Portland cement was added at 0, 2, 4, 8, and 10 %, respectively, to the natural clay soil and obtained UCS as shown in Fig. 5. According to the UCS test, the UCS increased as the percent of common cement increased. However, it was discovered that when ordinary cement was mixed with 8 and 10 % of cement mixing, the results were unsatisfactory due to the absence of bonding between the cement and the soil.

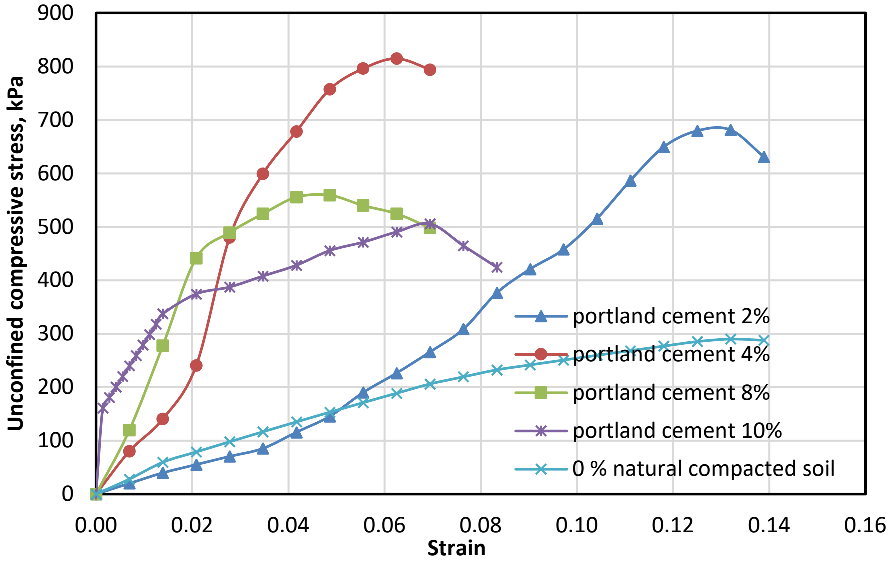


Figure 5. Unconfined shear strength of soil treated with several percentage of Portland cement.

Soil can also be stabilized by chemical stabilization. Sodium chloride is the ionic compound of sodium and chloride. The results show that sodium chloride can be effectively dissolved in water quickly and provide enough sodium ions for exchange ionic reactions with clayey soil. The function of this chemical (sodium chloride) is to form a cluster of fine particles and bind them together. The sodium chloride dosage is added in 2, 4, 8, and 10 % by weight of soil. The UCS increases from 290 to 506 kN/m^2 upon the addition of 4 % sodium chloride. However, it was discovered that when sodium chloride was mixed with 8 and 10 % of salt mix, the results showed a decrease in the undrained shear strength as shown in Fig. 6.

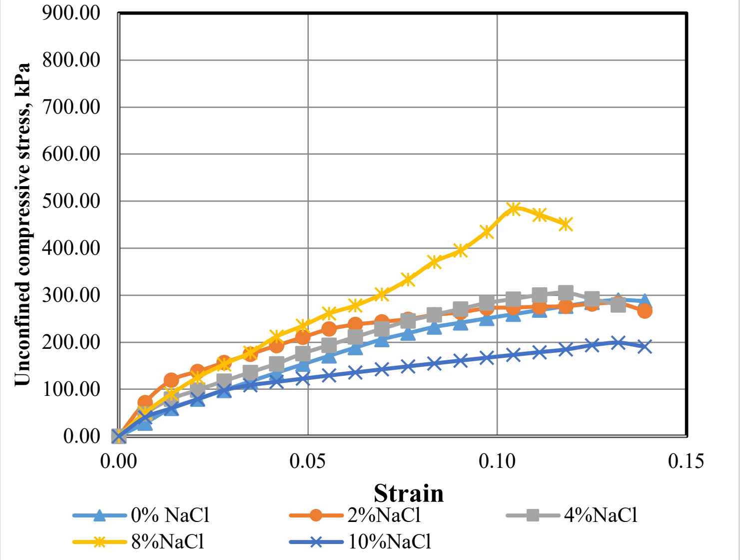


Figure 6. Strength test results for soil under different percentage of sodium chloride.

An inorganic salt called calcium chloride is created as a by-product of making sodium carbonates. The property of calcium chloride is hygroscopicity. This is how calcium chloride attracts and absorbs water. Both temperature and relative humidity influence this. When exposed to its own moisture, it could liquefy very fast. Conversely, calcium chloride has a lower freezing point than water and a higher surface tension. Saylak et al. [25], demonstrated that the significant water-absorbing capacity of solid calcium chloride. Solid $CaCl_2$ can absorb 16.6 times its water weight at a relative humidity of 95 %. Even at a 30 % humidity condition, it can absorb approximately all of its own weight of water. Because it may change the strength, compressibility, and permeability of materials, calcium chloride has been utilized as a stabilizer. Essentially, the purpose of this chemical is to bind and aggregate small particles. So that the soil's UCS increases to 422 kN/m^2 when 2 % calcium chloride is added. Nevertheless, it was noted that the results showed a reduction in UCS when calcium chloride was mixed with 4, 8, and 10 % of the salt mix as shown in Fig. 7.

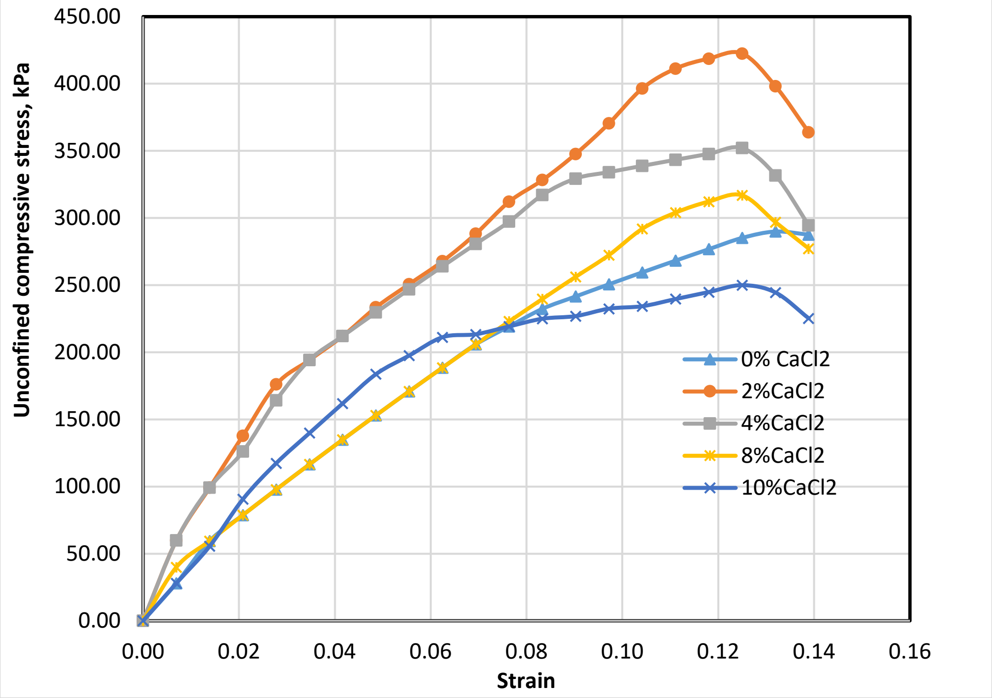


Figure 7. Strength test results for soil under different percentage of calcium chloride.

Bischofite, also known as “magnesium chloride hexahydrate” ($MgCl_2.6H_2O$), is a non-traditional stabilizer that has lately attracted the attention of researchers. Magnesium chloride is a sea salt that is used as a green stabilizer since it does not hurt plants or animals and does not corrode asphalt, concrete, pavements, or cars. On the other hand, magnesium holds an atomic number of 12, and its electronic configuration is 2, 8, 2. Thus, it has two more electrons than the closest stable electronic configuration of a noble gas, neon. As a result, magnesium tends to lose two electrons from its outermost shell and obtains a stable electronic configuration, resulting in magnesium cation (Mg^{+2}) as shown in Fig. 8. When a magnesium atom joins two chlorine atoms, two electrons are transferred from the magnesium to the chlorine, resulting in a magnesium chloride molecule. Thus, both atoms have a stable octet electronic configuration.

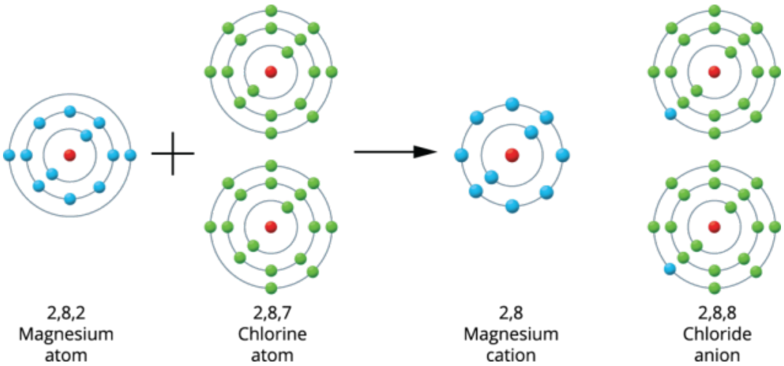


Figure 8. Ionic bond formation in magnesium chloride.

When 2 % magnesium chloride is added to soil, the UCS increases to 404 kN/m^2. However, it was discovered that when magnesium chloride was mixed with 4, 8, and 10 % of salt mix, the results showed a decrease in UCS as shown in Fig. 9.

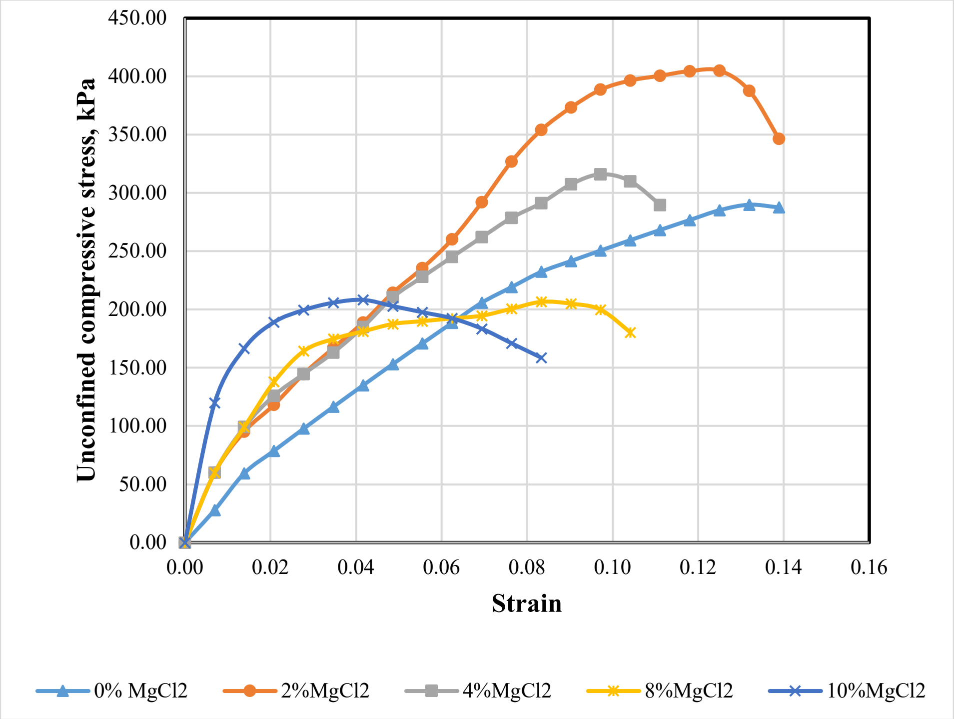


Figure 9. Strength test results for soil under different percentage of magnesium chloride.

Sodium silicates are inorganic, polymeric, alkaline silica-based materials. All silicates are made of three basic components: silica (SiO_2) for which sand is the raw material, alkali (Na_2O or K_2O) for which soda ash or potash is the raw material and water. The researcher discovered that when 2 % of sodium silicates was added to soil, the UCS increases to 574 kN/m^2. However, it was discovered that when magnesium chloride was mixed with 4, 8, and 10 % of salt mix, the results showed a decrease in UCS as shown in Fig. 10.

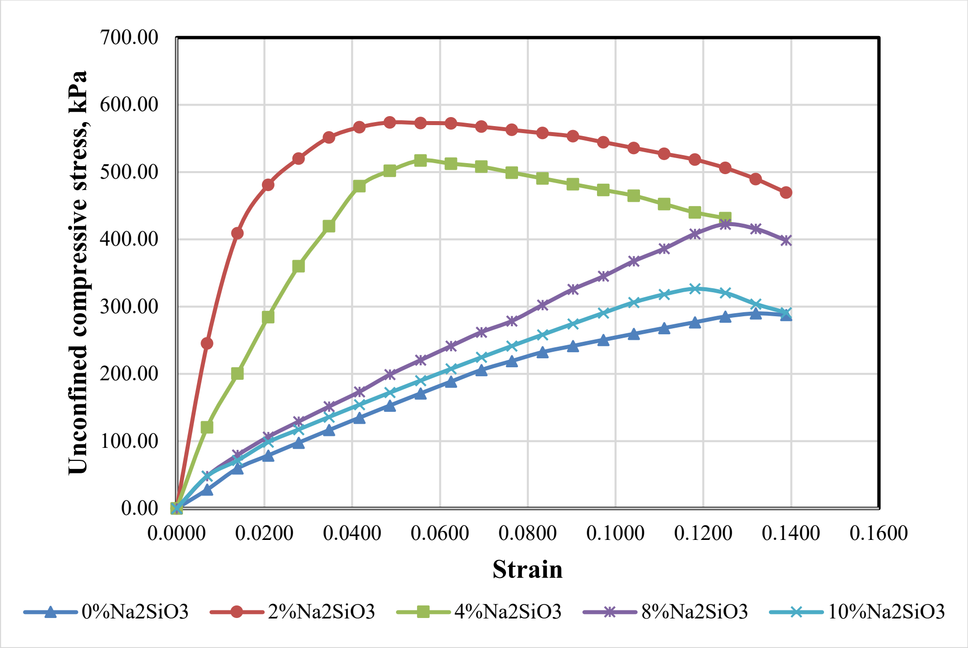


Figure 10. Strength test results for soil under different percentage of sodium silicates.

Fattah et al. [26] stated that soils located above the groundwater table are generally unsaturated and possess negative pore-water pressures. Soil suction is one of the most important parameters describing the moisture condition of unsaturated soils. They concluded that the suction increases with the decrease of the degree of saturation. The sodium silicate contains the groups called “silanol”, which may be found not only on the surface of colloidal but also within the structure of colloidal particles. The silicate attraction with water increases the hydroxide ions on the surface and within the silanol as shown in Fig. 11. The remaining (OH) experiences very weak hydrogen bonding, while if the proportion of water is low then the result will be more proportion of sodium hydroxide on silanol surface and an increase in the negative charge on the silica so high strength develops due to adhesion with soil particles.

The sodium silicate concentration effect on bonding because there are three conditions and the typical forms of the strength curve of silica concentration as illustrated in Fig. 12. The first case, if the concentration of silica is too high and drying the silica gel is by hydration of water, then the bridges crack and become weak as in Fig. 12a. The second case, when the colloidal silicate is too small in concentration, the refractory particles come together and approximate close packing, but there is no enough colloidal silica to fully reinforce all the contact positions as in Fig. 12b. The third case is when the colloidal silicate is in optimized concentration, the refractory particles attain close packing and colloidal reaches its gel concentration simultaneously as in Fig. 12c. Therefore, if water quantity is small or dehydrated from silica or evaporated, two things will happen:

- The colloidal silica concentration will increase.
- The volume of the system will decrease.

So, when we use sodium silicate ratio more than 10 %, the soil sample becomes softer and cannot be molded, so we thank that this ratio of silicate is adequate for this purpose.

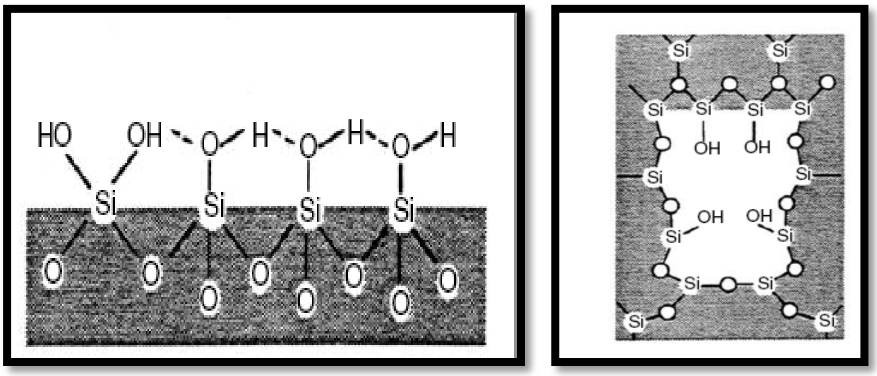
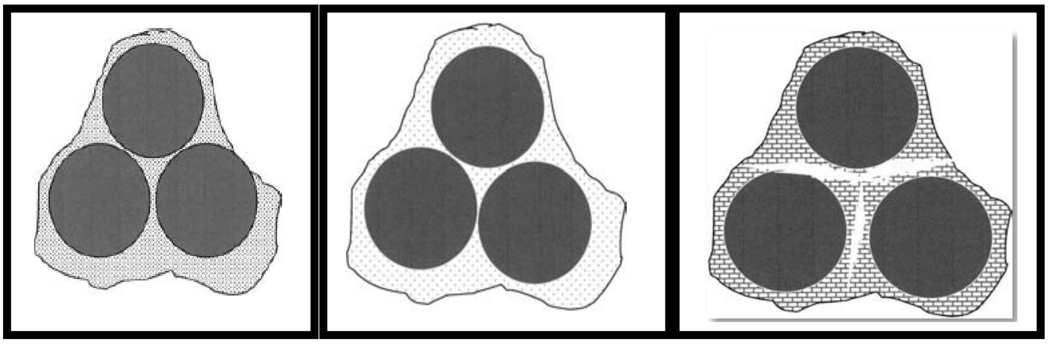


Figure 11. Silanol groups and siloxane bridges on the surface and within of colloidal silicate [28].



-a- -b- -c-

a. Colloidal silica concentration too high
b. Colloidal silica concentration too small
c. Colloidal silica at optimum concentration
Figure 12. Bond strength of colloidal silica in solution [28].

For comparison of UCS of salinity soils after treated and natural soil were expressed in percent ratio of (qu(improved)/qu(natural)), the results are illustrated in histograms as shown in Fig. 13 for various percentages 2, 4, 8, and 10 %.

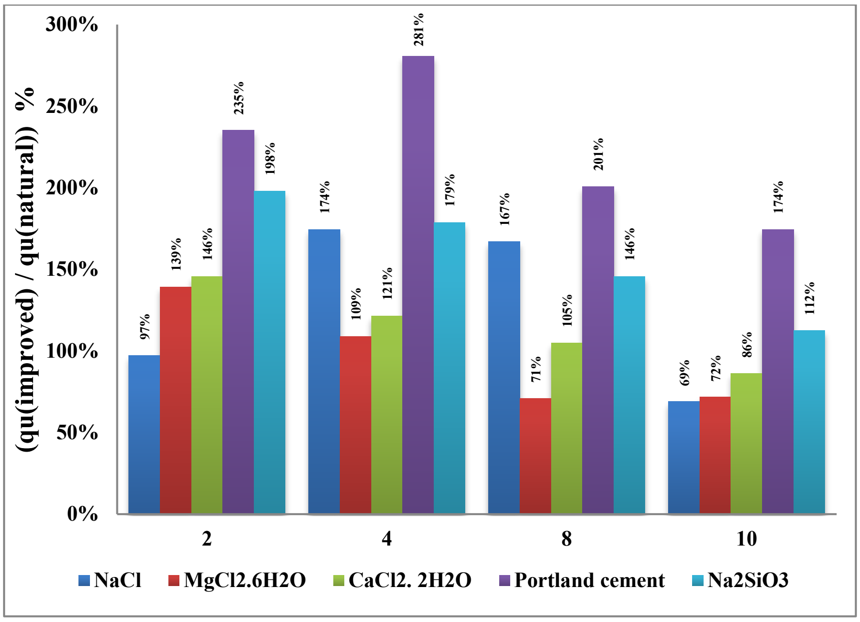


Figure 13. Strength improvement percent in saline clayey soil.

When comprising the results obtained unconfined compressive strength of salinity soils after treated and natural soil were expressed in percent ratio of (qu(improved)/qu(natural)) as illustrated above, it is possible to state that:

- NaCl – varied considerably to 174 % for adding 4 % and the decreasing to 69 % at 10 %.
- $MgCl_2.6H_2O$ – varied considerably to 139 % for adding 2 % and the decreasing to 69 % at 8 %.
- $CaCl_2.2H_2O$ – varied considerably to 146 % for adding 2 % and the decreasing to 86 % at 10 %.
- Na_2SiO_3 – varied considerably to 198 % for adding 2 % and the decreasing to 112 % at 10 %.

Portland cement – varied considerably to 281 % for adding 4 % and the decreasing to 174 % at 10 %.

4. Conclusions

To investigate the effect of different types of salts on geotechnical characteristics, different concentrations of salts (0, 2, 4, 8, and 10 %) were added to the soil. The most important conclusions were as follows:

- As salinity has risen, shear strength parameters increased. The growth of salt crystals in soil pores, as well as the location of the cement, have all been ascribed to an increase in attractive forces between soil particles, the establishment of adhering between them, and the development of attractive forces between soil particles. In the case of the low proportion of clay in the soil, a tiny portion of these changes is due to a reduction in the thickness of the double layer.
- Increasing the salt content of the soil by more than 10% has a negative impact on the shear strength of the soil.
- Generally, sodium silicate and Portland cement mostly act as active stabilizers because of their ability to alter material properties, such as strength. Essentially, the act of this chemical is to lump fine particles together and join them together.
- Adding any of the chemicals (NaCl, $MgCl_2.6H_2O$, $CaCl_2.2H_2O$, Na_2SiO_3, and Portland cement) decreased the liquid limit, plastic limit, and plasticity index of the salinity soil.

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