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The Engineering Characteristics of Silty Loess Contaminated with Natural Salts

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ABSTRACT

A considerable part of Golestan Province is covered by loess soils, most of which are of the silty loess type, which is one of the most problematic soils. The proximity of the Caspian Sea leads to salinity of the groundwater in some areas of the province. Due to high evaporation, salts reach the surface and cause salinization of the silty loess soils at the surface. The presence of soluble salts can lead to changes in the engineering properties of silty loess soils at the site of construction projects. It is therefore necessary to investigate the influence of salts on the geotechnical properties of silty loess soils. The aim of this study was to investigate the effect of sodium chloride or halite (NaCl) and calcium sulphate or gypsum ($CaSO_4.2H_2O$) salts, as the two most abundant natural salts, on the engineering properties of silty loess soils. For this purpose, silty loess soil samples were collected from Maraveh Tappeh city, Golestan province, Iran. Geotechnical tests including uniaxial compressive strength, shear strength and standard compaction tests were then carried out on soil samples in the natural state and with 3, 5, 7, and 9% NaCl and $CaSO_4.2H_2O$. Based on these tests, the variation in optimum water content (ω_{opt}), maximum dry density (ρ_{dmax}), uniaxial compressive strength (UCS), cohesion (C), internal friction angle (φ) were evaluated. The results showed that these parameters increased with increasing both natural salts concentration. Finally, the reason for the changes in the engineering properties of the soil samples due to the presence of these two natural salts was discussed.

Introduction

Loess soils cover about 10% of the land area worldwide (Li et al., 2016). Loess soils have been deposited widely within the Caspian Lowland of Northern Iran during Pleistocene (Frechen et al., 2009). Loess as the most important collapsible soil has caused damage to the buildings constructed upon it (Assallay et al., 1997). The metastable honeycomb structure of loess is too sensitive to wetting such that it collapse in response to wetting (Houston et al., 1988). Collapsible soils usually have a high void ratio and relatively low density. Therefore, soil grains readily rearrange to a denser packing state upon wetting (Bolzon, 2010). Several factors control the collapsibility of soils such as age of deposition (over consolidation), grain size distribution, clay content, pore shape, degree of cementation, , soluble salt content, physical properties, degree of saturation, environmental condition (climatic and vegetation), and so on (Rollins et al., 1994; Lin, 1995; Aziz et al., 2006; Reznik, 2007; Yuan and Wang, 2010; Momeni et al., 2012; Li et al., 2016).

Soluble salts have a major influence on the collapsibility of soils due totheir higher solubility potential which leads to structural collapse upon wetting (Rao and Revanasidsappa, 2002; 2006). Crystalline salts act as agents in dry soils. Loess soils typically have the moisture content of 8% and soluble salts are considered to dissolve in water even when the water content is

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less than 8% (Tan, 1988). According to Li et al. (2016), the collapsibility of loess soils, especially non-self-weight collapsible loess, cannot be attributed to the solution of salts alone. Non-self-weight collapsible loess soils possess natural water content of 21%–24%. The efficiency of soil improvement using salt depends on several factors including economic considerations, soil type, the environmental conditions, and the salt availability (Abbeche et al., 2010).

The effect of salinity on the geotechnical properties of different soils has been investigated in several studies (Warkentin and Yong, 1960; Barbour and Yang, 1993; Gleason et al., 1997; Sivapulliah and Savitha, 1999; Di Maio, 2004; Arasan and Yetimoglu, 2008; Yukselen- Aksoy et al., 2008; Mishra et al., 2009; Shariatmadari et al., 2011; Spagnoli and Sridharan, 2012), while these studies are still rare for loess soil as a problematic soil. Loess soils constitute a major part of the surface soils of Golestan province, and previous studies have shown that they can be classified into three subtypes: sandy loess, silty loess, and clayey loess (Feyznia et al., 2005), and these three subtypes have different grain size distributions and engineering properties. The focus of this study is on silty loess, which is the most common soil type in the study area, and many villages and urban areas are built on this soil type.

Loess soils have a honeycomb structure, which causes them to have many voids on a microscopic scale. The soil grains in this structure are cemented together by various materials such as clay minerals and natural salts. In the presence of water or under dynamic loading (caused by an earthquake), this porous structure collapses, which causing large settlements in loess soils. These large deformations may cause serious damage to civil structures and infrastructure located on loess soils. Accordingly, the present study aims to investigate the effect of two soluble salts (i.e., NaCl and $CaSO_4.2H_2O$) on the geotechnical properties of silty loess soils from Maraveh Tappeh city. Then, the effects of these salts on optimum water content (ω_{opt}), maximum dry density (ρ_{dmax}), uniaxial compressive strength (UCS), cohesion (C), and friction angle (φ) were investigated. Furthermore, investigating the effect of natural salts, especially halite, on the geotechnical properties of different types of soils, especially coastal soils, has been studied by various researchers, but the focus of this study is on the problematic loess soils of Golestan province, which are mixed with different percentages of natural salts including halite and gypsum.

Geological description of the sampling area

The sampling area is located south of the city of Maraveh Tappeh in the northern part of Iran. The Caspian lowlands of northern Iran are part of the Eurasian loess belt. This belt extends from Central Asia and China to northwestern Europe. Dust and loess deposits have accumulated in northern Iran during the Pleistocene glaciations. According to Frechen et al. (2009), the thickness of silty loss deposits exceeds 25 m in some parts of the sampling area (Fig. 1).

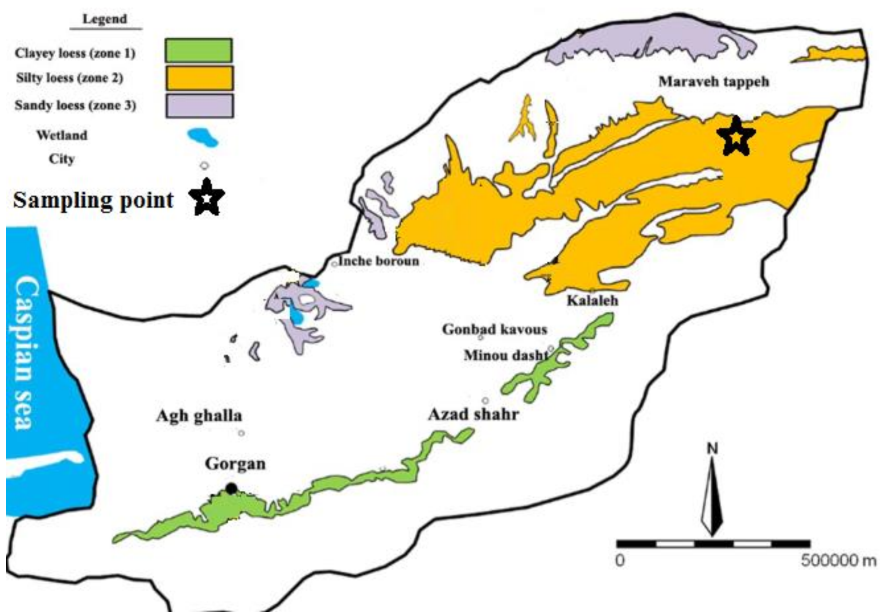


Fig. 1. Distribution of different types of loess soil on the map of Golestan province (Feyznia et al., 2005) and sampling area

The Pleistocene silty loess has been transported over short distances due to the presence of coarse dust components. The climate of the sampling area, namely the city of Maraveh Tappeh, is semi-arid with an average annual precipitation of less than 300 mm (Wang et al., 2017). Land subsidence due to the presence of collapsible silty loess soils was evident in the vicinity of the sampling area. Damage to roads and the formation of sinkholes were the most common phenomena caused by loess collapse in the study area (Fig. 2).

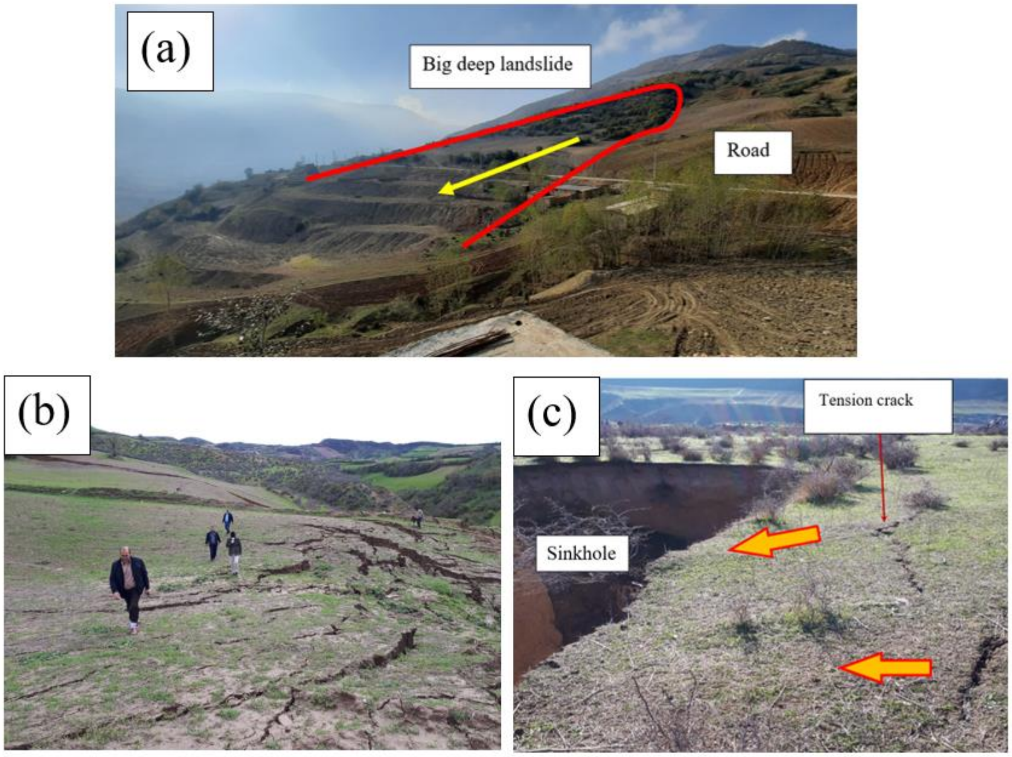


Fig. 2. Sign of land subsidence due to presence of silty loess soils in sampling area; a) old big deep landslide damage to rural road, b) recent deep landslide in loess hill cause damage to rural houses and c) generation of sinkhole in silty loess soils

Material and Methodology

For conduct the present study, silty loess soil samples were collected from the south of the city of Maraveh Tappeh. Grain size distribution, plastic limit (PL), liquid limit, plastic index (PI), ω_{opt}, ρ_{dmax}, UCS, C, and φ were obtained through various tests including Atterberg limits test, uniaxial compressive strength, compaction test, and shear test according to ASTM (2005). Five samples were used to determine each geotechnical property and then their mean values were obtained. XRF test was used to determine the mineralogical and chemical composition of selected soils. NaCl and $CaSO_4.2H_2O$ are two common salts in the Caspian Sea water (Ghadiri et al., 2006). These salts, which are carried by the wind, contaminate the soils and structures in the coastal areas (Zalooli et al., 2018). The salts used in this study were NaCl and $CaSO_4.2H_2O$. To reconstruct saline soil samples, NaCl and $CaSO_4.2H_2O$ salts at concentrations of 3, 5, 7 and 9 wt% were dissolved separately in distilled water. The soil samples were then added to the different concentrations of saline water and thoroughly mixed to saturation. In the next step, the soil samples were placed in sealed plastic containers at room temperature for 2 weeks to allow the soil and saline water to react with each other. The soil samples were then exposed to room temperature (24℃) until they were completely dry. After drying, the soil samples were crushed to prepare samples for conducting UCS, shear strength and compaction tests (ASTM, 2005). Fig. 3 shows the flow chart of the present study.

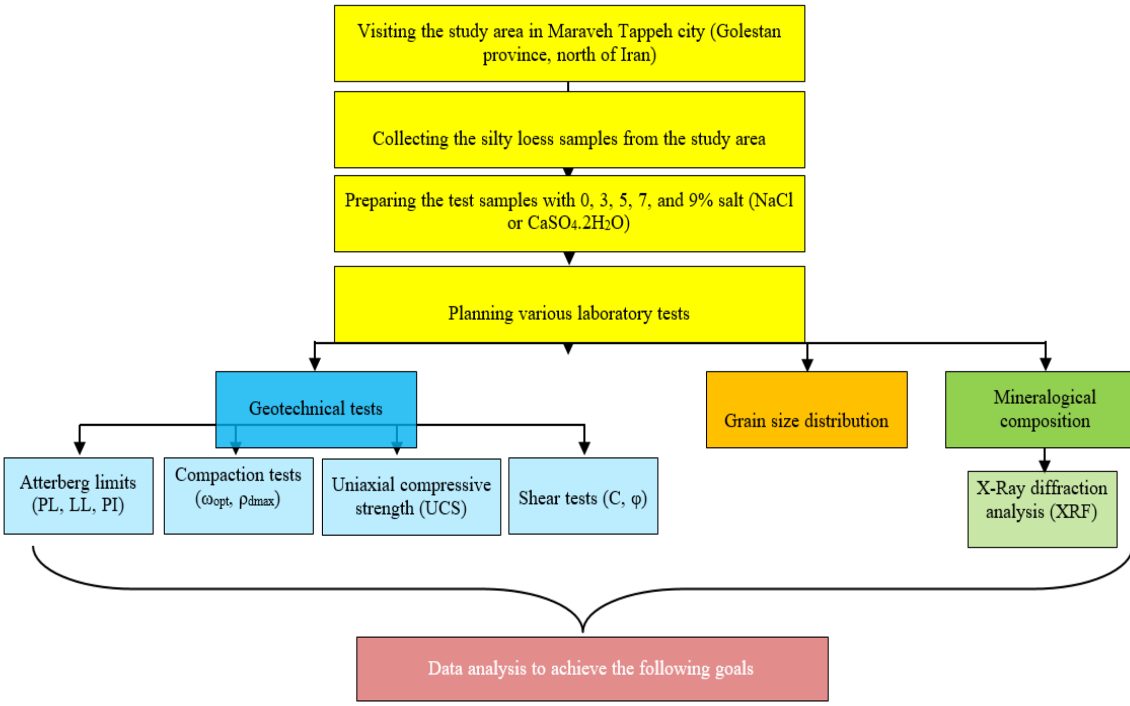


Fig. 3. The method of conducting the presenttudy.

Geotechnical test procedure

Preparation of samples

Different methods of sample preparationwere presented, and it was also noted that the method of preparing the samples will play a significant role in the results of the tests. Considering that the purpose of these experiments is to investigate the effect of two natural salts including sodium chloride (NaCl) and calcium sulfate ($CaSO_4.2H_2O$) on the geotechnical parameters of silty loess soils, the samples were mixed and prepared by manual method because the homogeneity of the mixtures was of particular importance in the present study and this method provides the possibility of preparing homogeneous samples as well (Fig. 4).

To remold the saline soil samples tested, sodium chloride and calcium sulphate salts at 3, 5, 7 and 9 percent by weight of the soil were completely dissolved in some distilled water and added to the soil gradually and by hand. Distilled water was then added to the soil until it was saturated and completely mixed with the silty loess soil. The samples were then placed in closed plastic containers at room temperature for 28 days to allow the soil and salts to react with each other in the presence of water. At the end of the specified time, the samples were placed in the open to dry completely, and after drying, the clumps were crushed to powder and ready for testing.

Fig. 4. Sampling of silty loess from study area

Atterberg limit

The standard (ASTM D4318) provides the method for determining the liquid limit, plastic limit and plastic index of soils.

This standard describes two methods (a) wet and (b) dry for sample preparation for testing. It should be noted that the dry method was used in the present study. This standard defines two methods for determining the liquid limit. These two methods are called multi-point and single-point. The single-point method is used in this research.

In order to prepare the samples for this test, the soil mixture prepared with different percentages of salts was first stirred with an electric stirrer at a slow speed for at least ten minutes until the soil lumps turned into powder. The powder obtained was then mixed with some water according to the standard of this test and the Atterberg tests were carried out using the single point method. Figure 5 shows the Casagrande test apparatus.

Fig. 5. Device and procedure of Atterberg tests

Compaction test

Compaction is the process of reducing the volume of soil by removing air through the application of force. Compaction is used to increase the shear strength and reduce the permeability of the soil. The mechanism of compaction is such that when water is added to dry soil, the soil particles absorb a thin layer of water at the surface, and as more water is added, these thin layers become thicker and allow the soil particles to rollover each other more easily. If there is shear stress between the soil particles, this layer will play a similar role to lubrication in mechanical machines in the sliding mechanism between the grains.

The compaction test is carried out according to the standard (ASTM D: 698-78). Figure 6 shows the compaction device used in this study. In this test, about 4 kg of air-dried soil is taken for the compaction test and if there is a lump in the soil, it is crushed by hand. Then we pass the soil through sieve number 4 and collect all the soil that has passed through this sieve and put it in the tray. We then add enough water to this soil and mix it so that its moisture content is close to 5%. The wet soil is placed in the test mold in three equal layers, and each layer must be compacted with 25 blows of a standard Proctor hammer before the next layer is placed in the mold.

Fig. 6. Compaction tests device used in the present study

Uniaxial compressive strength test

In this test, the confining pressure is zero. An axial load is applied rapidly to the specimen until failure. At the moment of failure, the minimum principal total stress is equal to zero and the maximum principal total stress is equal to δ1 or δc.

The unconfined uniaxial compressive strength test in the present study was carried out according to the standard (ASTM, D2166) on the sample studied under natural conditions and with different percentages of salts. For this purpose, after carrying out the compaction test and obtaining the maximum dry unit weight and the optimum percentage of water content for the soil samples, the samples were prepared for the unconfined compressive strength test. It should be added that the average diameter of the cylindrical samples was 3.5 cm and their height was approximately 7 cm. Fig. 7 shows the remolded sample and the UCS apparatus.

Fig. 7. Device of unconfined uniaxial compressive strength test in the present study

Direct shear test

The direct shear test determines the shear strength of a sample of the soil under investigation at a given failure surface. Typically, three specimens are tested at different vertical stresses to determine the effect of the vertical stress in the failure surface on the soil resistance and to determine the failure envelope (in the special case of determining the Moore-Coulomb envelope parameters).

In this test, the prepared specimen is placed inside the cutting box. The cutting box consists of two square molds or two metal rings placed on top of each other. At the end of the specimen consolidation, the two cutting box molds are moved at a constant displacement rate due to the applied vertical stress, and during the movement the force required to apply this displacement is measured.

The direct shear test in the present study is based on the ASTM D: 3080-90 standard and the strain control method. In the strain control method, the amount of displacement applied to the specimen is constant and the changes in force on the specimen are measured. The direct shear apparatus is shown in Fig. 8.

Fig. 8. Device of direct shear test used in the present study

Results and discussion

The grain size distribution of studied soil is presented in Fig. 9. Studied soil is classified as CL-ML (low plasticity clay-Low plasticity silt) according to the Unified Soil Classification System (USCS).

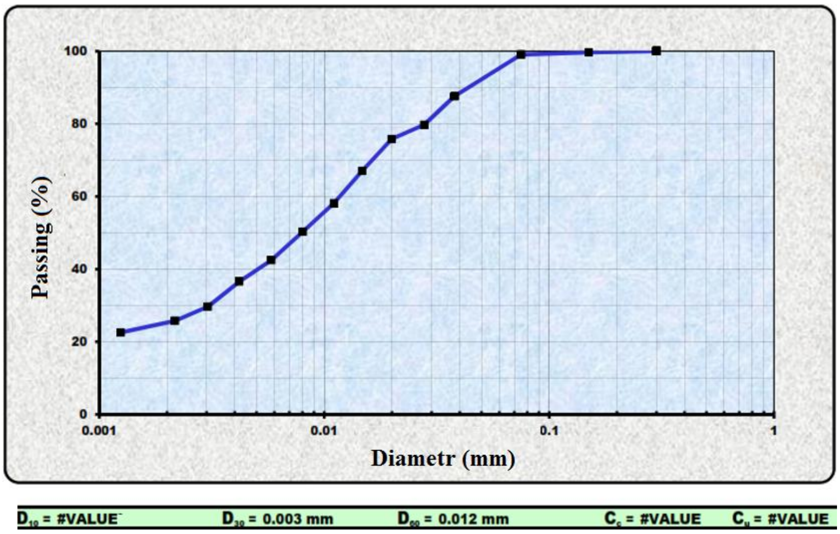


Fig. 9. Grain size distribution of soil under study

The information obtained from the XRF test is used for quantitative and qualitative chemical analysis. Fig.10 shows the XRF spectrum of the silty loess soil studied. In this spectrum, each of the peaks shown corresponds to a specific element. Peaks of greater height and thickness indicate a greater concentration of the desired element in the sample. According to the appearing peaks, the main elements of the studied soil are Fe, Al, Mg, Na, Ca, Si, O. In Table 1, the values of the constituents of the soil sample are presented. From this table, it can be seen that SiO2 and Al2O3 are the most abundant constituents of the sample, with percentages of 54.22 and 9.77% respectively.

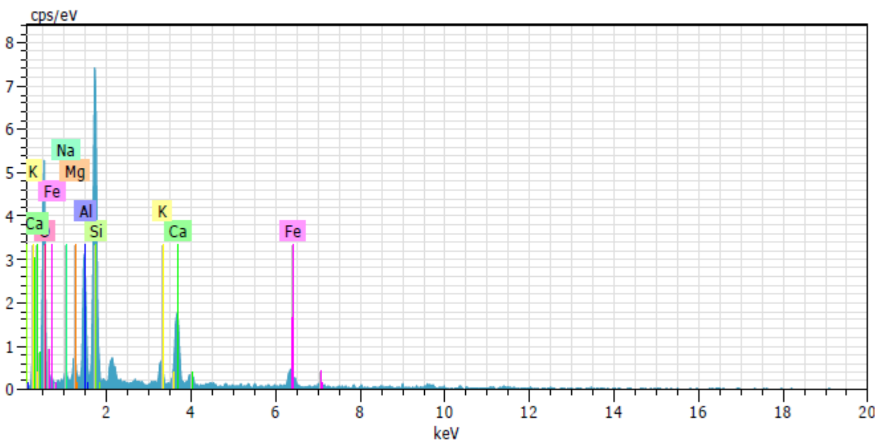


Fig. 10. The pattern of the XRF analysis for studied silty loess sample

Table 1. Results of XRF of sample

Oxides	SiO_2	Al_2O_3	Na_2O	MgO	K_2O	MnO	CaO	P_2O_5	Fe_2O_3	SO_3
Value	54.22	9.77	2.00	4.05	2.50	0.07	13.78	0.14	4.22	1.00

The values of the physical and mechanical properties of soil with 0, 3, 5, 7, and 9% NaCl and $CaSO_4.2H_2O$ salt are listed in Table 2.

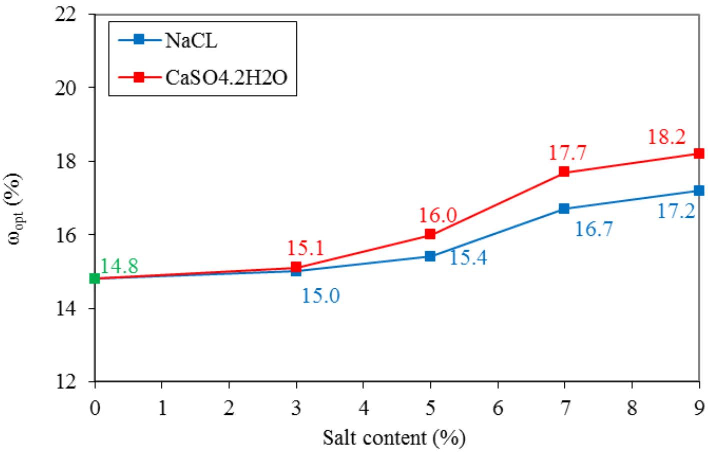
Table 2. Mean values of geotechnical properties of sample

Salt type and content (%)		PL (%)	LL (%)	PI (%)	ω_{opt} (%)	ρ_{dma} (g/cm^3)	UCS (KPa)	C (KPa)	φ (°)
Fresh soil		22.4	34.8	12.4	14.8	1.76	88	19.2	18.4
	3	-	-	-	15.0	1.80	92	22.0	20.6
NaCl	5	-	-	-	15.4	1.85	100	25.5	22.2
	7	-	-	-	16.7	1.94	111	33.2	24.3
	9	-	-	-	17.2	1.98	116	36.8	26.9
	3	-	-	-	15.1	1.77	90	21.1	19.1
$CaSO_4.2H_2O$	5	-	-	-	16.0	1.80	96	23.7	20.6
	7	-	-	-	17.7	1.84	103	27.2	22.4
	9	-	-	-	18.2	1.89	108	30.5	23.8

* Liquid limit (LL), Plastic limit (PL), Plastic index (PI), Optimum water content (ω_{opt}), Maximum dry density (ρ_{dmax}), Uniaxial compressive strength (UCS), Cohesion (C), Friction angle (φ)

The results of the soil compaction tests show that the mean values of ωopt and ρdmax increase with increasing salt content (Fig. 11). The ωopt values for soils containing $CaSO_4.2H_2O$ are higher than those containing NaCl, while ρdmax in soils containing NaCl is higher than those containing $CaSO_4.2H_2O$. The mean values of UCS increase with increasing salinity (Fig. 12). The increase in UCS was greater for samples containing NaCl than for those containing $CaSO_4.2H_2O$. The variation of the mean values of C and φ are shown in Fig. 13. Both internal φ and C show a positive relationship with salinity.

a



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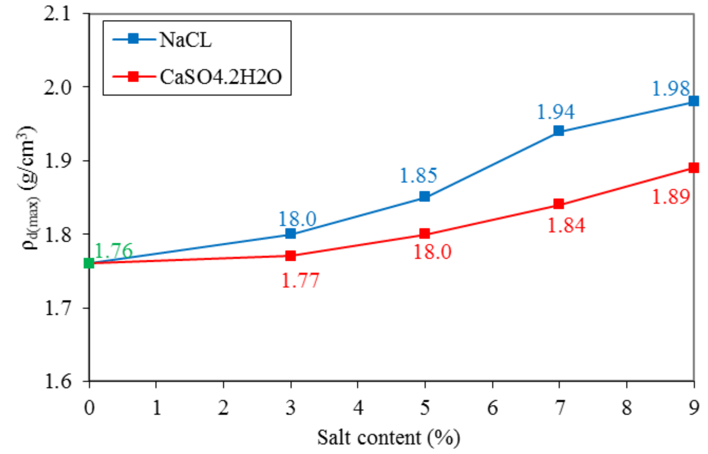


Fig. 11. The results of soil compaction test versus salt content: a) optimum water content and b) maximum dry density.

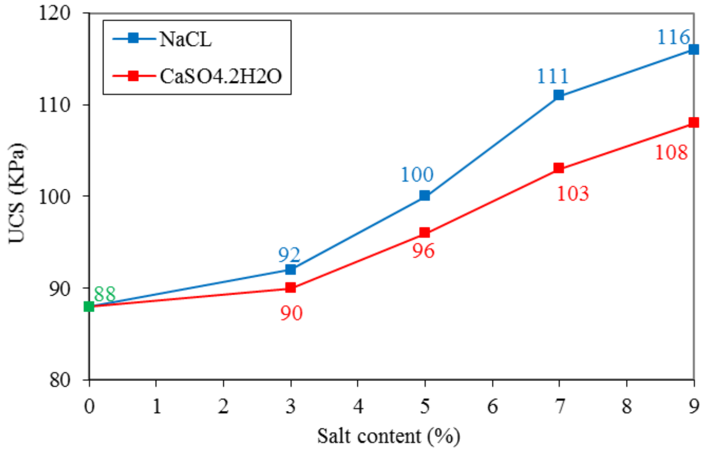
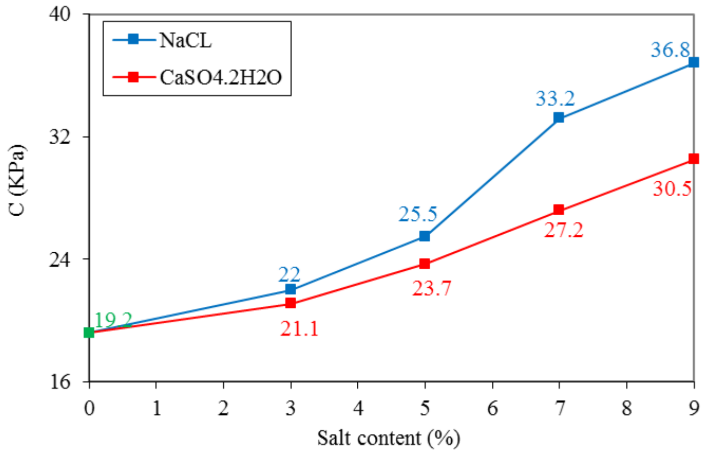


Fig. 12. Mean value of uniaxial compressive strenght versus salt content.

a



b

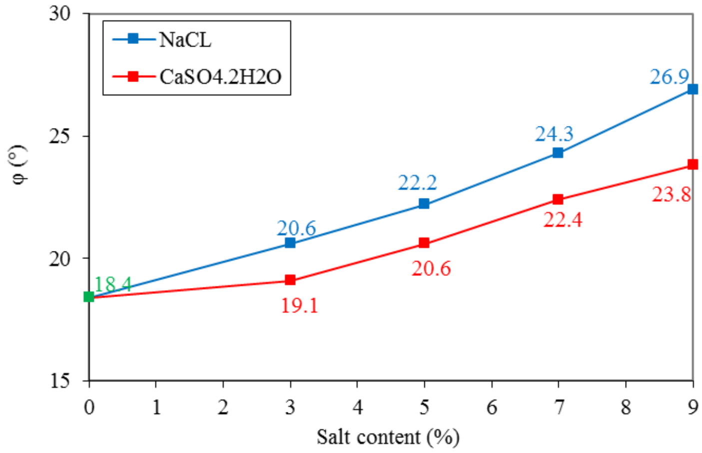


Fig .13. Variations in shear strength parameters with salt content: a) soil internal friction angle and b) soil cohesion.

The increase in ωopt and ρdmax of soils with increasing salinity is due to the water absorbing capacity of salts. Salt crystals absorb more water than sand and silt grains. Although the gradation test results showed that the soil samples contained clay-sized particles, the Atterberg limit tests showed that these particles had low plasticity (low water absorption potential). As can be seen from Figure 11, the soil mixed with $CaSO_4$-$2H_2O$ has a higher water content than the soil mixed with NaCl. The soils studied showed an exponential increase in water content as the salt content increased. Anhydrite ($CaSO_4$) is a salt with a high water uptake potential. This salt is transformed into gypsum ($CaSO_4$-$2H_2O$) when exposed to water. The ρdmax of the soil increased with increasing salinity. NaCl and $CaSO_4$-$2H_2O$ have a higher density than the soil studied. It seems that with increasing salinity, salt crystals precipitate in pore spaces and the density of the soil increases. With increasing salinity, a linear increase in ρdmax was observed in the studied soil. The results of this study were compared with those available in the literature. For example, Alainachi and Alobaidy (2010) investigated the effects of salt water from the Gulf of Basra on the Proctor compaction and CBR test results of soil samples from the city of Baniyas, Abu Dhabi, UAE. In another study, Shariatmadari et al (2011) investigated the effect of inorganic salt solutions on some geotechnical properties of soil-bentonite mixtures as barriers. They showed that the addition of salt water to the soil sample decreased and increased ωopt and ρdmax, respectively.The UCS of the studied soil increased with increasing salt concentration (Fig. 12). This result is consistent with the findings of Kumar et al. (2018). They investigated the effect of salinity on the geotechnical properties of expansive soils and found that the UCS increased with increasing salinity. The compressive strength of collapsible soils is strongly influenced by pore spaces. The concentration of salts reaches saturation and precipitates in the pores as crystals, reducing the pore space (porosity of the soil) and increasing the strength of the soil. It appears that the salt crystals fill the pore spaces and act as a cementing agent. Collapse is due to the reduction in strength associated with the loss of suction as a result of saturation (Fredlund and Gan, 1995). The suction of collapsible soils increases with increasing salinity (Rinaldi et al., 1988). It appears that the increase in suction is another reason for the increase in soil compressive strength with increasing salinity. The increase in C and φ is evidence of this phenomenon.A significant proportion of the salt content fills pores in the larger sand and silt grains and acts as a cementing agent. When the soil is wetted, only the outer layer of salt is wetted and dissolved, leaving most of the salt crystals unaffected and acting as cement. Therefore, higher salt concentrations reduce the collapsibility potential of the soil. As shown in Figure 13, C and φ show a steep increase when 5% salt is added to the soil. It appears that at lower salt contents they form a thin film around the larger silt and sand grains, but at higher concentrations they act as a cementing agent. NaCl has a more positive effect on UCS, C and φ than $CaSO_4$ salt. When $CaSO_4$ is wetted, its molar volume increases. $CaSO_4$ has a molar volume of 46 cm3/mole while $CaSO_4$-$2H_2O$ has a molar volume of 75 cm3/mole. Therefore, hydration of $CaSO_4$ results in an increase in molar volume. An increase in the volume of salt crystals can lead to the rearrangement of soil particles. The results of Naeini and Jahanfar (2017) and Maio (2018) also showed that an increase in saline solution is associated with an increase in φ and C of soil samples. These findings are in agreement with the results of the present study. The rate of change (RC) in geotechnical properties was used to compare the effect of NaCl and $CaSO_4.2H_2O$ on the geotechnical properties of the sample. The RC of geotechnical properties was calculated using Eq. (1):

$$\mathrm{RC}(\%) = \frac{\mathrm{GP}_{\mathrm{Initial}} - \mathrm{GP}_{\mathrm{with\ 9\%\ salt}}}{\mathrm{GP}_{\mathrm{Initial}}} \times 100 \quad (1)$$

where RC is the rate of change in geotechnical properties after increasing 9% salt; $GP_{Initial}$ and $GP_{with\ 9\%\ salt}$ are ω_{opt}, ρ_{dmax}, UCS, C, and φ of the sample with 0 and 9% salt, respectively.
The data in Table 2 are used to calculate the RC of ω_{opt}, ρ_{dmax}, UCS, C, and φ of the sample contaminated with salt. The results of RC are presented graphically in Fig. 14. In the sample with 9% NaCl, RC of the ω_{opt}, ρ_{dmax}, UCS, C, and φ were 16.2, 12.5, 31.8, 91.7 and 46.2%, respectively. In contrast, these values were 23.0, 7.4, 22.7, 58.9, and 29.3%, respectively, for sample with 9% $CaSO_4.2H_2O$. These data indicate that the NaCl effect on the geotechnical properties of the sample was greater than that of $CaSO_4.2H_2O$. According to Fig. 14, C and ρ_{dmax} of the sample are affected the most and the least after contaminated with NaCl and $CaSO_4.2H_2O$ salts, respectively.

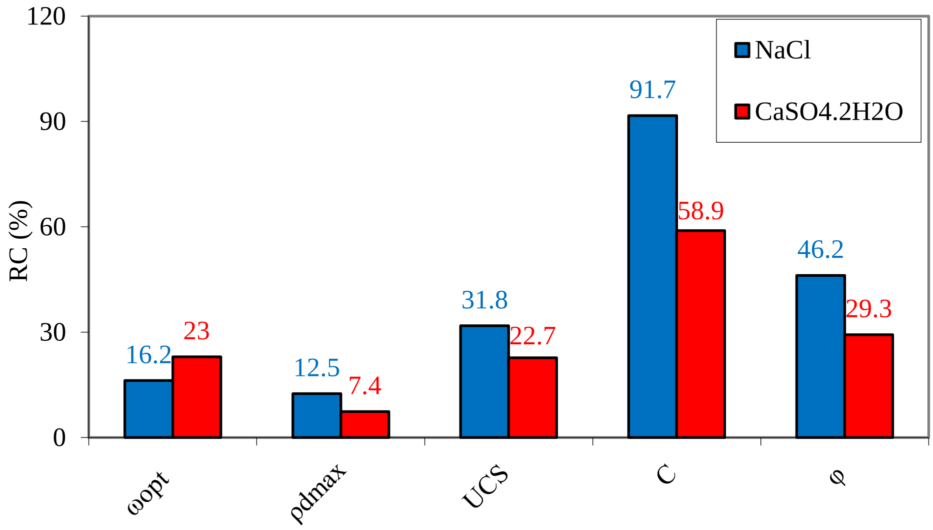


Fig .14. The RC in the geotechnical properties of the sample after 9% increasing salt

Conclusion

The effect of halite and gypsum salt concentrations on ωopt, ρdmax, UCS, C and φ of silty loess soils was investigated in the laboratory. The results showed that the engineering properties including ωopt, ρdmax, UCS, C and φ increased with increasing concentration of salts (including NaCl and $CaSO_4.2H_2O$). These data indicate that the effect of halite (NaCl) on the engineering properties of the sample was greater than that of gypsum ($CaSO_4.2H_2O$). According to Fig. 14, the cohesion (C) and the maximum dry unit weight (ρdmax) of the sample are most and least affected, respectively, after contamination with sodium chloride (NaCl) and calcium sulphate ($CaSO_4.2H_2O$) salts. The concentration of salts reaches saturation and precipitates as crystals in the pores, reducing pore space (soil porosity) and increasing soil strength. The salt crystals fill the pore spaces and act as a cementing agent. The suction of collapsible soils increases with increasing salt concentration. It appears that the increase in suction is another reason for the increase in engineering properties of the soil with increasing salt concentration. Much of the salt fills pores in the larger sand and silt grains and acts as a cementing agent. When the soil is wetted, only the outer layer of salt is wetted and dissolved, leaving most of the salt crystals unaffected and acting as cement. The physical properties of the salts control the engineering properties of the soil under investigation. The results of this article show that the engineering properties of silty loess soils improve in the presence of natural salts, including sodium chloride (NaCl) and calcium sulphate ($CaSO_4.2H_2O$). These salts act as cementing agents by crystallising in the soil texture. As these salts are readily soluble in water, it is expected that silty loess soils will be dispersive and their structure will collapse when saturated. This finding was confirmed in the soils studied, with numerous signs in the field such as collapsibility, subsidence, gully erosion, sinkholes, etc.

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ویژگی‌های مهندسی لس سیلتی آلوده به نمک‌های طبیعی

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کلیدواژه‌ها:
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چکیده

بخش قابل توجهی از استان گلستان را خاک‌های لس پوشانده است که بیشتر آن‌ها از نوع لس سیلتی بوده، که یکی از مشکل‌سازترین خاک‌ها است. هم‌جواری با دریای خزر منجر به شوری آب‌های زیرزمینی در برخی از مناطق استان می‌شود. به دلیل تبخیر زیاد، نمک‌ها به سطح زمین می‌رسند و باعث شور شدن خاک‌های لس سیلتی می‌شوند. وجود نمک‌های محلول می‌تواند منجر به تغییراتی در خواص مهندسی خاک‌های لس سیلتی در محل پروژه‌های عمرانی شود. بنابراین بررسی تأثیر نمک‌ها بر خواص ژئوتکنیکی خاک‌های لس سیلتی ضروری است. هدف از این مطالعه بررسی اثر نمک‌های کلرید سدیم یا هالیت ($NaCl$) و سولفات کلسیم یا نمک گچ ($CaSO_4.2H_2O$) به عنوان دو نمک طبیعی فراوان، بر خواص مهندسی خاک‌های لس سیلتی می‌باشد. برای این منظور نمونه‌های خاک لس سیلتی از شهرستان مراوه تپه استان گلستان جمع‌آوری شد. سپس آزمایش‌های ژئوتکنیکی شامل مقاومت فشاری تک محوری، مقاومت برشی و آزمون‌های تراکم استاندارد بر روی نمونه‌های خاک در حالت طبیعی و با ۳، ۵، ۷ و ۹ درصد $NaCl$ و $CaSO_4.2H_2O$ انجام شد. بر اساس این آزمایش‌ها، تغییرات رطوبت بهینه، حداکثر چگالی خشک، مقاومت فشاری تک محوری، چسبندگی و زاویه اصطکاک داخلی مورد ارزیابی قرار گرفت. نتایج نشان داد که این پارامترها با افزایش غلظت هر دو نمک مورد مطالعه افزایش یافت. در نهایت در این مقاله علت تغییرات خواص مهندسی نمونه‌های خاک به دلیل وجود این دو نمک طبیعی مورد بحث قرار گرفته است.

مقدمه

خاک‌های لس حدود ۱۰ درصد از مساحت زمین را در سراسر جهان پوشش می‌دهند (Li et al., 2016). خاک‌های لس به طور گسترده در دشت خزر در شمال ایران در طی پلیستوسن رسوب کرده‌اند (Frechen et al., 2009). لس به عنوان مهم‌ترین خاک مسئله‌دار، باعث آسیب به ساختمان‌های ساخته شده بر روی آن شده است (Assallay et al., 1997). ساختار لانه زنبوری ناپایدار لس به تغییرات رطوبت بسیار حساس بوده به طوری که در پاسخ به مرطوب شدن، فرو می‌ریزد (Houston et al., 1988). نمک‌های محلول به دلیل پتانسیل انحلال‌پذیری بالاتری که منجر به فروپاشی ساختار در هنگام مرطوب شدن می‌شوند، تأثیر زیادی بر قابلیت رمبندگی خاک دارند (Rao and Revanasidsappa 2002, 2006). نمک‌های کریستالی به عنوان عامل سیمان کنندگی در اغلب خاک‌ها عمل می‌کنند. خاک‌های لس معمولاً دارای رطوبت طبیعی ۸ درصد هستند و نمک‌های محلول در آب حل شده، حتی زمانی که درصد رطوبت کمتر از ۸ درصد باشد (Tan, 1988).

خاک لسی بخش عمده‌ای از خاک‌های سطحی استان گلستان را در بر می‌گیرد که مطالعات قبلی نشان داده است که می‌توان آن‌ها را به سه زیر گروه لس ماسه‌ای، لس سیلتی و لس رسی طبقه‌بندی کرد (Feyznia et al., 2005) و این

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سه زیر گروه انواع دانه‌بندی و خواص مهندسی متفاوتی دارند. تمرکز پژوهش حاضر بر روی لس سیلتی است که بیشترین پراکندگی را در منطقه مورد مطالعه داشته به‌طوری که روستاها و مناطق شهری زیادی بر روی این نوع خاک ساخته شده است. بر این اساس، پژوهش حاضر با هدف بررسی اثر دو نمک محلول (NaCl و $CaSO_4.2H_2O$) بر خصوصیات ژئوتکنیکی خاک لس سیلتی شهرستان مراوه تپه انجام شد. در مرحله بعد، اثرات این نمک‌ها بر رطوبت بهینه (ωopt)، حداکثر چگالی خشک (ρdmax)، مقاومت فشاری تک محوری (UCS)، چسبندگی (C) و زاویه اصطکاک (φ) مورد بررسی قرار گرفت.

مواد و روش‌ها

برای انجام این پژوهش، نمونه‌برداری از خاک لس سیلتی از جنوب شهرستان مراوه تپه انجام شد. توزیع اندازه دانه یا همان دانه‌بندی، حد پلاستیک (PL)، حد مایع، شاخص پلاستیک (PI)، رطوبت بهینه (ωopt)، حداکثر چگالی خشک (ρdmax)، مقاومت فشاری تک محوری (UCS)، چسبندگی (C) و زاویه اصطکاک (φ) از طریق آزمایش‌های مختلفی از جمله آزمون حدود آتربرگ، مقاومت فشاری تک محوری، آزمون تراکم استاندارد و آزمون برش مستقیم برپایه استاندارد ASTM (۲۰۰۵) تعیین شد. برای تعیین هر ویژگی ژئوتکنیکی از پنج نمونه استفاده شد و سپس مقادیر میانگین آن‌ها در مقاله گزارش گردید. آزمایش XRF برای تعیین ترکیب کانی‌شناسی و شیمیایی خاک لس انتخابی صورت گرفت.

NaCl و $CaSO_4.2H_2O$ دو نمک رایج در آب دریای خزر هستند (Ghadiri et al., 2006). این نمک‌ها که توسط باد حمل می‌شوند، خاک‌ها و سازه‌های نواحی ساحلی را آلوده می‌کنند (Zalooli et al., 2018). در این مطالعه از نمک‌های NaCl و CaSO4.2H2O استفاده شد. برای بازسازی نمونه‌های خاک شور در آزمایشگاه، نمک‌های NaCl و $CaSO_4.2H_2O$ در غلظت‌های ۳، ۵، ۷ و ۹ درصد وزنی به طور جداگانه در آب مقطر حل شد. سپس نمونه‌های خاک در غلظت‌های مختلف به آب‌های شور اضافه و کاملاً مخلوط شدند تا اشباع شوند. در مرحله بعد، نمونه‌های خاک در ظروف پلاستیکی مهر و موم شده در دمای اتاق به مدت ۲۸ روز قرار داده شد تا خاک و آب شور با هم واکنش نشان دهند. در ادامه، نمونه‌های خاک تا زمانی که کاملاً خشک شوند، در دمای اتاق (۲۴ درجه سانتی‌گراد) قرار گرفتند. پس از خشک شدن، نمونه‌های خاک خرد شدند تا نمونه‌هایی برای انجام آزمایش‌های UCS، مقاومت برشی و تراکم آماده شوند.

روش‌های مختلفی برای بازسازی مجدد نمونه‌ها معرفی شده و همچنین خاطرنشان شد که روش تهیه نمونه‌ها نقش بسزایی در نتایج آزمایش‌ها خواهد داشت. با توجه به اینکه هدف از انجام این آزمایش‌ها بررسی اثر دو نمک طبیعی شامل کلرید سدیم (NaCl) و سولفات کلسیم ($CaSO_4.2H_2O$) بر پارامترهای ژئوتکنیکی خاک لس سیلتی است، نمونه‌ها به روش دستی مخلوط و تهیه شدند. همگن بودن مخلوط‌ها در مطالعه حاضر از اهمیت ویژه‌ای برخوردار بوده و این روش امکان تهیه نمونه‌های همگن را نیز فراهم می‌کند. (شکل ۴).

برای بازسازی مجدد نمونه‌های خاک شور آزمایش شده، نمک‌های کلرید سدیم و سولفات کلسیم به نسبت‌های ۳، ۵، ۷ و ۹ درصد وزنی خاک، به طور کامل در مقداری آب مقطر حل شده و به تدریج و به صورت دستی به خاک اضافه شدند. پس از آن آب مقطر به خاک اضافه شد تا زمانی که خاک اشباع شود و کاملاً با خاک لس سیلتی مخلوط شود. سپس نمونه‌ها به مدت ۲۸ روز در ظروف پلاستیکی دربسته در دمای اتاق قرار داده شدند تا خاک و نمک‌ها با هم در حضور آب واکنش نشان دهند. پس از گذشت زمان تعیین شده،

نمونه‌ها در فضای باز قرار داده شدند تا کاملاً خشک شوند و پس از خشک شدن، کلوخه‌ها خرد شدند تا پودر شوند و آماده آزمایش گردند.

بحث و نتایج

اطلاعات به دست آمده از آزمایش XRF برای تجزیه و تحلیل شیمیایی کمی و کیفی استفاده می‌شود. شکل ۱۰ طیف XRF خاک لس سیلتی مورد مطالعه را نشان می‌دهد. در این طیف، هر یک از پیک‌های نشان داده شده به یک عنصر خاص اختصاص داده می‌شود. قله‌های با ارتفاع و ضخامت بیشتر به معنای غلظت بیشتر عنصر مورد نظر در نمونه است. با توجه به قله‌های ظاهر شده عناصر اصلی خاک مورد مطالعه عبارتند از Fe, Al, Mg, Na, Ca, Si, O.

نتایج آزمایش‌های تراکم خاک نشان داد که میانگین مقدار ωopt و ρdmax با افزایش درصد نمک‌ها افزایش می‌یابد (شکل ۱۱). مقادیر ωopt برای خاک حاوی $CaSO_4.2H_2O$ بیشتر از خاک حاوی NaCl است در حالی که ρdmax در خاک حاوی NaCl بیشتر از خاک حاوی $CaSO_4.2H_2O$ است. مقادیر میانگین UCS با افزایش مقدار نمک‌ها افزایش می‌یابد (شکل ۱۲). افزایش UCS برای نمونه‌های حاوی NaCl بیشتر از نمونه‌های حاوی $CaSO_4.2H_2O$ بود. بعلاوه تغییرات مقادیر میانگین C و φ در شکل ۱۳ نشان داده شده است. افزایش ωopt و ρdmax خاک با افزایش مقدار نمک به ظرفیت جذب آب نمک‌ها نسبت داده می‌شود. کریستال‌های نمک نسبت به دانه‌های ماسه و سیلت، آب بیشتری جذب می‌کنند. اگرچه نتایج آزمایش دانه‌بندی نشان داد که نمونه‌های خاک دارای ذرات به اندازه رس هستند، اما آزمایش‌های حدود آتربرگ نشان داد که این ذرات دارای پلاستیسیته پایین (پتانسیل جذب آب کم) هستند. همانطور که از شکل ۱۱ مشاهده می‌شود، خاک مخلوط شده با $CaSO_4.2H2O$ دارای رطوبت بیشتری نسبت به خاک مخلوط با NaCl است. خاک مورد مطالعه با افزایش مقدار نمک افزایش نمایی در درصد رطوبت نشان داد. انیدریت ($CaSO4$) نمکی با پتانسیل جذب آب بالا است. این نمک هنگام قرار گرفتن در معرض آب به گچ ($CaSO_4.2H_2O$) تبدیل می‌شود. چگالی خشک حداکثر خاک با افزایش مقدار درصد نمک افزایش یافت. NaCl و $CaSO4.2H_2O$ دارای چگالی بالاتری نسبت به خاک مورد مطالعه هستند. UCS خاک مورد مطالعه با افزایش غلظت نمک افزایش یافت (شکل ۱۲). این نتیجه با یافته‌های کومار و همکاران مطابقت دارد (Kumar et al., 2018). با مطالعه اثر شوری بر ویژگی‌های ژئوتکنیکی خاک‌های رمبنده، مشخص شد که با افزایش شوری، UCS افزایش یافته است. مقاومت فشاری خاک رمبنده به شدت تحت تأثیر فضاهای منافذ در بافت خاک است. غلظت نمک‌ها به حد اشباع می‌رسد و در داخل منافذ به صورت کریستال رسوب می‌کنند و در نتیجه فضای منافذ (تخلخل خاک) کاهش می‌یابد و استحکام خاک را افزایش می‌دهد. به نظر می‌رسد که کریستال‌های نمک فضاهای منافذ را پر کرده و به عنوان عامل سیمانی عمل می‌کنند.

نتیجه‌گیری

نتایج این مقاله نشان داد که زمانی که غلظت نمک‌ها به حد اشباع برسد در داخل منافذ به صورت کریستال رسوب کرده و در نتیجه فضای منافذ (تخلخل خاک) کاهش یافته و متعاقباً استحکام خاک افزایش می‌یابد. کریستال‌های نمک فضاهای منافذ را پر می‌کنند و به عنوان عامل سیمانی عمل می‌کنند. با افزایش غلظت نمک، مکش خاک‌های رمبنده افزایش می‌یابد. به نظر می‌رسد افزایش مکش یکی دیگر از دلایل بهبود خواص مهندسی خاک با افزایش غلظت املاح می‌باشد. بخش بزرگی از نمک‌ها، منافذ را در میان دانه‌های بزرگ‌تر ماسه و سیلت پر می‌کنند و به عنوان عوامل سیمانی عمل می‌کنند. هنگامی که خاک مرطوب می‌شود، تنها لایه

بیرونی نمک خیس و حل می‌شود، در حالی که بیشتر کریستال‌های نمک بدون تأثیر باقی می‌مانند و به عنوان سیمان عمل می‌کنند. در نتیجه می‌توان گفت ویژگی‌های فیزیکی نمک‌ها، خواص مهندسی خاک مورد مطالعه را کنترل می‌کند.

نتایج این مقاله نشان می‌دهد که خواص مهندسی خاک لس سیلتی در حضور نمک‌های طبیعی از جمله کلرید سدیم ($NaCl$) و سولفات کلسیم ($CaSO_4.2H_2O$) بهبود می‌یابد. این نمک‌ها با متبلور شدن در بافت خاک به عنوان عامل سیمان سازی عمل می‌کنند. از آنجایی که این نمک‌ها به راحتی در آب حل می‌شوند، می‌توان انتظار داشت که خاک‌های لس سیلتی رمبنده بوده و ساختار آن‌ها در صورت اشباع شدن فرو می‌ریزد. این یافته در خاک‌های مورد مطالعه با نشانه‌های متعدد در روی زمین مانند رمبندگی، فرونشست زمین، فرسایش خندقی، فروچاله ها و غیره تائید شده است.