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The effect of porewater salinity on the physical and mechanical properties of clayey soils

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ABSTRACT

Saline soil refers to soil with a high concentration of ions such as sodium and chloride, which destroys structures and construction materials. Thus, it's crucial to understand their nature and behavior. This study examines the effect of salinity on the compaction and shear characteristics of clayey soils by adding two types of salt, sodium chloride, and sodium sulfate, with different concentrations (0.5%, 1%, 2%, and 5%) to two clayey soils in Iran. Eighteen soil samples were prepared, and tests were carried out in three repetitions. The results showed that the samples' optimum moisture content and maximum dry density were within the range of 20-23%, and 1.56-1.63 gr/cm^{-3}, respectively. These changes were within acceptable tolerance limits, suggesting that salt concentration has a negligible effect on the compaction characteristics of clayey soils. However, salinity concentrations significantly affected the shear strength parameters. Adding 0.5% sodium sulfate decreased cohesion by 50% and 35% in the high and low plastic clayey soils, respectively. Similarly, 0.5% sodium chloride reduced cohesion by 47% in the low plastic soil and 35% in the high plastic soil. Furthermore, the internal friction angle increased by 20% in the low-plastic soil and 34% in the high-plastic soil with 0.5% sodium sulfate. It was also found that the type of anions and cations, as well as the plasticity of soils, play a crucial role in describing the relation between pore water salinity and shear parameters of soils.

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1. Introduction

Saline soils are characterized by having more than 0.3 percent soluble salts and often exhibit undesirable features such as erosion, swelling, solution, etc., in engineering construction bed material (Liu et al., 2020; Shen et al., 2022). These soils are predominantly found in arid, semi-arid, and coastal regions across the globe (Stipho, 1985). The amount and type of salt present in saline soils typically have dynamic changes due to natural environmental conditions (evaporation, precipitation, etc.) and human activities such as farming (Wang et al., 2020). Variations in salt content can lead to alterations in the structural properties of the soil and its engineering characteristics, leading to issues such as slope instability, settlement, etc. (Han et al., 2020; Liu et al., 2020). Thus, it is essential to investigate the impact of salt content on the physical and mechanical properties of saline soils to ensure the safety of engineering structures. Previous research has demonstrated that the salinity of pore water significantly influences the mechanical behavior of soft soils, such as the compressibility potential of soils and shear strength properties (Onitsuka et al., 2003; Xing et al., 2009; Horpibulsuk et al., 2012; Geng et al., 2022). For example, Geng et al. (2022) reported that compressibility decreases with increasing salinity. However, the results of studies on the effect of salinity on soil strength increases with increasing salinity (Sridharan et al., 2002; Paassen and Gareau, 2004), others have reported different results (Yan and Chang, 2015; Al-Obaidi et al., 2018). Numerous studies have been made on the effects of the chemical composition and concentration of salt in pore water on the mechanical properties of soil has been extensive. Studies have focused on compressibility (e.g., Horpibulsuk et al., 2011; Deng et al., 2018) and shear strength (e.g., Siddiqua et al., 2011; He et al., 2014; Mokni et al., 2014; Tiwari and Ajmera, 2015; Zhang et al., 2016; De Rosa et al., 2016). These studies generally have shown that pore water salinity significantly affects the mechanical properties of marine soft soils. For example, Maio and Fenelli (1994) conducted direct shear tests with montmorillonite and kaolinite saturated in sodium chloride solutions and concluded that the shear strength of montmorillonite increases with increasing pore water salinity, while the strength of kaolinite does not change significantly with salinity.

Saline soils are classified based on the type of salt present in sulfate, carbonate, and chloride saline soils. The negative impact of salinity on yield stress and other engineering properties must be considered in engineering studies. For instance, Pan et al. (2023) examined the effect of pore water salinity on the compressive behaviors of marine clay stabilized with ash and concluded that while the compression index in the pre-stress stage is not affected by changes in salinity It decreases as salinity increases during the post-stress stage. Additionally, the yield stress of the soil decreases with increasing salinity but significantly increases over seven days.

In carbonate saline soils, different contents of salts such as $NaHCO_3$ can have varying effects on soil properties. Shen et al. (2024) studied the impact of different $NaHCO_3$ contents on the Atterberg limits, shear strength, and compressibility of a carbonate saline soil and found that when the $NaHCO_3$ content is less than 1.5 percent, the plasticity index and compressibility of the soil increase, while shear strength decreases. However, beyond this threshold, soil porosity decreases, and mechanical properties improve due to the cementation effect of salt crystals.

Understanding the mechanisms behind all these changes is essential. For instance, Di Maio (1996) and Maio and Fenelli (1994) found that chloride content significantly affects the mechanical behavior of bentonite. They attributed this effect to changes in the thickness of the bound water surrounding clay particles. Kang et al. (2019) observed that clay minerals under different concentrations of sodium chloride exhibit varying microstructural characteristics that influence their mechanical properties.

Despite existing research, the mechanisms by which pore water salinity affects the macroscopic engineering behaviors of soils are not yet fully understood. Abbasi and Nazifi (2013) reported that chloride anion promotes the formation of a flocculated structure in the soil, reducing its potential for dispersion, whereas other anions tend to induce soil dispersion to varying degrees. They explain the impact of various anions or cations on clay dispersion using the diffuse double-layer theory. According to this theory, the thickness of the double layer is influenced by the balance of repulsive and attractive forces that particles experience as they approach each other. Flocculation happens when the thickness of the double layer is sufficiently reduced, making short-range attractive forces predominant. In contrast, dispersion occurs when the double layer's thickness increases. Flocculation occurs at high electrolyte concentrations when the repulsive forces diminish and attractive forces become dominant. Conversely, as the Sodium Adsorption Ratio (SAR) increases, the thickness of the double layer grows, leading to dispersion (Sparks, 2000; Panayiotopoulos et al., 2004). As mentioned earlier, most of the studies reported in the literature were focused on the effect of salts as a general term of salinity on the physical and mechanical properties of soils, whereas the effect of different salts is different on the engineering characteristics of different soils. Therefore, the present research aims to fill this gap as much as possible. To this end, the impact of two types of salts with sodium cations and chloride and sulfate anions—the most prevalent cation and anions found in Iranian soils—on two types of clay soils was studied.

2. Material and methods

2.1. Preparation of soil samples and specimens

This research was conducted in the soil mechanic laboratory of the Iranian Agricultural

Engineering Research Institute (AERI). To this end, two clay soil samples representing the typical characteristics of predominant clay soils in Iran were collected from Kamal Abad in Alborz province and Moghan Plain in Ardabil province. According to the Unified Soil Classification System (USCS), these soils were classified as CL (a clayey soil with low plasticity having a liquid limit of less than 50 percent) and CH (a clayey soil with high plasticity having a liquid limit of less than 50 percent), respectively. Then, different synthetic soil samples were prepared by adding various percentages of sodium chloride and sodium sulfate to these soils. To achieve samples with the desired chemical properties, different amounts of these salts, including 0.5, 1, 2, and 5 percent by weight were added to the soils. Thus, considering two types of soil, two types of salt, four concentration levels of each salt, and two control samples (natural soils), a total of 18 synthetic soil samples were prepared. Each sample was identified by a unique code as shown in Table 1, where CL and CH represent the soil type, C and S indicate the salt type for chloride and sulfate respectively, and the numbers show the salt concentration.

Table 1. The specification of the synthetic samples.

Ref.	Sample Code	Soil type	Salt type	Salt percentage
1	CL-00	CL	-	0
2	CL-C0.5	CL	Sodium chloride	0.5
3	CL-C1	CL	Sodium chloride	1
4	CL-C2	CL	Sodium chloride	2
5	CL-C5	CL	Sodium chloride	5
6	CL-S0.5	CL	Sodium sulfate	0.5
7	CL-S1	CL	Sodium sulfate	1
8	CL-S2	CL	Sodium sulfate	2
9	CL-S5	CL	Sodium sulfate	5
10	CH-00	CH	-	0
11	CH-C0.5	CH	Sodium chloride	0.5
12	CH-C1	CH	Sodium chloride	1
13	CH-C2	CH	Sodium chloride	2
14	CH-C5	CH	Sodium chloride	5
15	CH-S0.5	CH	Sodium sulfate	0.5
16	CH-S1	CH	Sodium sulfate	1
17	CH-S2	CH	Sodium sulfate	2
18	CH-S5	CH	Sodium sulfate	5

To prepare the synthetic samples, the required amount of salt based on the desired weight percentage was first determined and dissolved in water. Then, the soil was added to the solution and left to dry in the laboratory environment. After one week, the samples were spread out on the ground to dry completely. Once fully dried, they were crushed with a plastic hammer and passed through a No. 10 sieve (Fig.1).

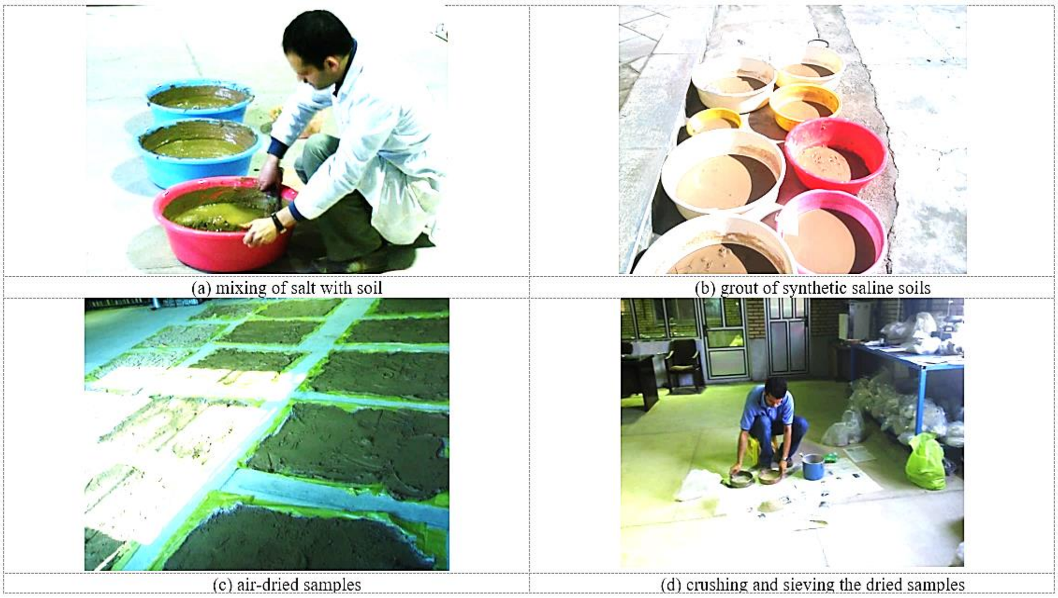


Fig. 1. Different procedures of preparation of the synthetic samples.

2.2. Determination of index properties of the samples

To identify, classify, and determine the physical properties of natural samples different tests including; grain size analysis, specific gravity (G_s), Atterberg limits (liquid limit, plastic limit, and shrinkage limit), and compaction were conducted based on ASTM test procedures and then classified according to the Unified Soil Classification System (USCS). To determine the compaction characteristics of various samples (optimum water content and maximum dry density), compaction tests were performed on the samples by Harvard miniature test. The physical and index properties of the soils are shown in Table 2.

Table 2. Physical properties of the samples.

Sample	Specific Gravity	Classification	Compaction Characteristics				Atterberg limits (%)		
	G_s	USCS	Harvard		Proctor		Shrinkage limit	Plastic limit	Liquid limit
			γ_d (gr/cm³)	ω_{opt} (%)	γ_d (gr/cm³)	ω_{opt} (%)			
Karaj	2.7	CL	1.68	22.5	1.7	21.8	16.5	23.5	47.5
Moghan	2.65	CH	1.51	27	1.5	27.5	18	27.5	67.5

2.3. Chemical analysis of treated samples

Chemical characterization of the treated samples including EC, pH, SAR, CEC, levels of anions (CO_3^{2-}, Cl^-, and SO_4^{2-}), and cations (Na^+, Ca^{2+}, and Mg^{2+}) were determined using standard test methods. To achieve this, saturated soil paste was first prepared. Subsequently, calcium and magnesium cations, and carbonate, bicarbonate, and chloride anions were measured via titration using a burette. Sodium and sulfate were measured using flame photometry and a spectrophotometer, respectively. Chloride was determined by titration with 0.01 N silver nitrate. Calcium and magnesium were measured using ethylenediaminetetraacetic acid (EDTA) titration. Carbonate and bicarbonate levels were measured through titration with sulfuric acid, in the presence of phenolphthalein and methyl orange. Sulfate concentration was determined using barium chloride precipitation and a spectrophotometer. Table 3 presents the chemical characteristics of the synthetically treated samples.

Table 3. Chemical properties of the samples.

Ref.	Sample code	EC (dS/m)	pH	Anions (meq/lit)				Sum	Cations (meq/lit)				Sum
				SO_4^{-2}	Cl^-	HCO_3^{-2}	CO_3^{-2}		K^+	Na^+	Ca^{2+}	Mg^{2+}	
1	CL-00	1.47	7.8	55.8	30	20	10	115.8	–	90.5	20	22	132.5
2	CL-C0.5	13.6	7.48	4.33	128	.4	0.6	141.33	–	89.36	29	20	138.36
3	CL-C1	25.7	7.48	4.38	250	8.2	0.6	263.18	–	186.36	37	27	250.36
4	CL-C2	30.9	7.49	2.16	310	4.6	3.4	320.16	–	239.7	55	18	312.7
5	CL-C5	97.3	7.49	4.61	1000	5.8	1.8	1012.21	–	840.1	52	58	950.1
6	CL-S0.5	9.4	7.88	70.2	30	20	10	130.1	–	100.2	20	25	145.2
7	CL-S1	12.7	7.86	100	30	20	10	160.9	–	145.07	20	25	190.0
8	CL-S2	17.1	7.88	196.7	30	20	10	256.7	–	250.6	18	22	290.6
9	CL-S5	47.3	7.88	640.5	30	20	10	700.5	–	848.4	20	22	890.4
10	CH-00	11.94	8.40	55.83	30	20	10	115.83	-	90.5	20	22	132.5
11	CH-C0.5	12.63	8.30	70.17	30	20	10	130.17	-	100.2	20	25	145.2
12	CH-C1	16.19	8.47	100.98	30	20	10	160.98	-	145.07	20	25	190.07
13	CH-C2	27.09	8.79	196.78	30	20	10	256.78	-	250.60	18	22	290.60
14	CH-C5	76.7	8.95	640.50	30	20	10	700.50	-	848.40	20	22	890.40
15	CH-S0.5	20.84	8.10	53.38	120	22	10	205.85	-	188.88	20	25	233.88
16	CH-S1	29.9	8.08	50.38	207	23	12	292.38	-	270.22	22	25	317.22
17	CH-S2	58.90	7.94	30.20	555	20	12	617.2	-	590.80	20	20	630.80
18	CH-S5	167.9	7.60	20.30	2130	25	5	2180.3	-	2265.6	22	20	2207.6

2.4. Compaction and triaxial tests

To determine the compaction characteristics (optimum water content and maximum dry density), of various treatments, standard Harvard Miniature compaction tests were performed .Harvard Miniature compaction (Fig. 2) was developed by Wilson (1950). In this test, the soil is compacted using a cylindrical tamping foot with a diameter of 0.5

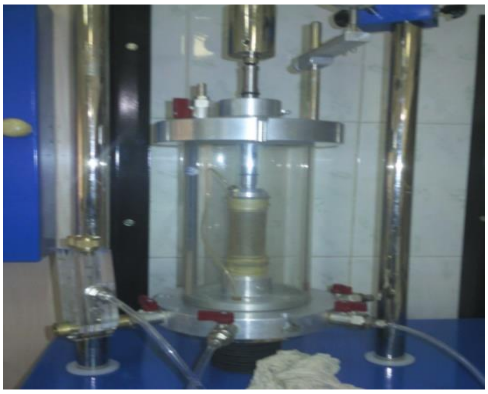
inches. The apparatus includes a mold that is 1 5/16 inches in diameter and 2.816 inches long, with a volume of 1/454 cubic feet. The tamping foot is operated through a pre-set compression spring to ensure that the tamping force does not significantly exceed a predetermined value. Typically, the test involves compacting the soil into three layers, each with 25 tamps. The primary advantages of this test are that it requires only small amounts of soil (which must pass through a No. 4 sieve) and it produces samples of dimensions suitable for unconfined or triaxial compression testing (Krystal et al., 2007). Harvard compaction Apparatus and a compacted sample are shown in Fig. 2. Each of these treatments was tested in three replicates for various physical and mechanical properties.

Fig. 2. The Harvard miniature compaction apparatus and a compacted sample.

2.5. Unconsolidated-Undrained triaxial compression tests

Also, to determine soil shear parameters, a triaxial compression test Apparatus was used (Fig. 3). In this research for evaluation of shear strength parameters of treated soils the Unconsolidated-Undrained, UU, Triaxial tests were conducted by ASTM standard test procedures. This test method involves determining the strength and stress-strain relationships of a cylindrical specimen of cohesive soil, which can be intact, compacted, or remolded. The specimens are placed in a triaxial chamber and subjected to a confining fluid pressure. During both the application of the confining fluid pressure and the compression phase, no drainage of the specimen is allowed. The specimen is then axially loaded at a constant rate of axial deformation (strain-controlled). In this test method, the compressive strength of the soil is measured in terms of total stress. As a result, the observed strength depends on the pressure generated in the pore fluid during the loading process. Also, fluid flow into or out of the soil specimen is not allowed while the load is applied. Consequently, the resulting pore pressure and, therefore, the strength, will differ from what is observed when drainage is permitted. Test detailed procedures are given by ASTM D2850.

(a) assembling of the specimen on the cell base



(b) the triaxial test apparatus

Fig. 3. The triaxial test apparatus and assembling of the specimen.

3. Results and discussion

3.1. The effect of salinity on compaction characteristic of soils

By conducting the Harvard miniature compaction test on the various treatments, the compaction curves for each of the test samples were plotted. Using these curves, the compaction characteristics, namely the maximum dry unit weight and the optimum moisture content for all the test samples were determined. Figs. 4 and 5 show the compaction curves of the samples examined for the two salts. Also, the optimum moisture content and maximum dry density values of the synthetic samples are presented in Table 4.

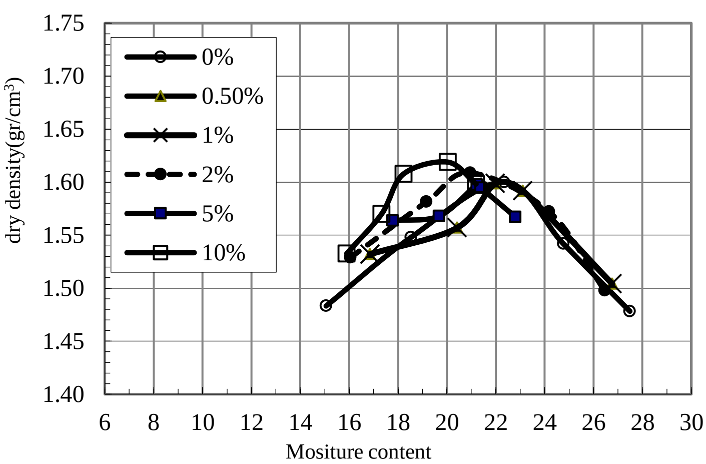


Fig. 4. The compaction curves for the samples containing sodium chloride.

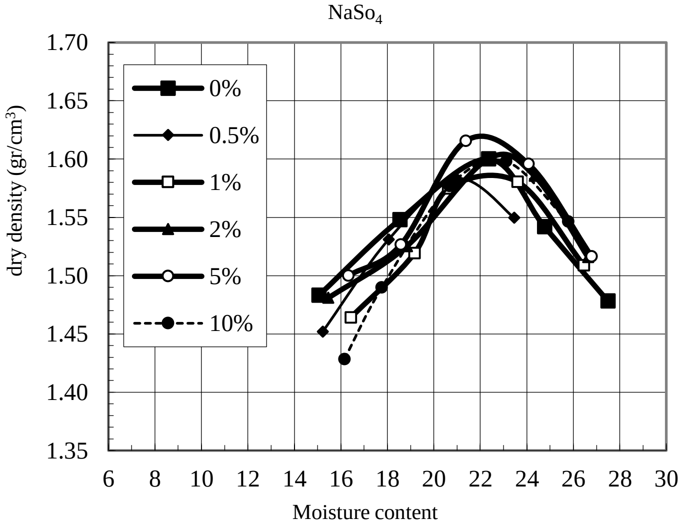


Fig. 5. The compaction curves for the samples containing sodium sulfate.

According to these Figs and Table 4, it is observed that for all the concentration levels, the optimum moisture content varied between 20 to 23 percent. In practical projects, a tolerance of 2 percent is considered acceptable for the optimum moisture content. In this study, for the natural soil sample, with an optimum moisture content of 22 percent, the range of 20 to 24 percent is considered acceptable. Therefore, it can be concluded that the effect of different types and amounts of salts on the optimum moisture content is insignificant and can be ignored. Additionally, the range of maximum dry density obtained for the various samples was between 1.56 and 1.63 g/cm^3, with the difference between the highest and lowest values being less than 5 percent. This amount is also less than the acceptable tolerance for the maximum dry density.

Table 4. The results of compaction tests.

Salt percentage	Optimum water content	Maximum dry density
CL-00	21.8	1.57
CL-C0.5	21.6	1.58
CL-C1	21.5	1.58
CL-C2	21.4	1.58
CL-C5	20.5	1.64
CL-S0.5	21	1.58
CL-S1	20.8	1.59
CL-S2	20.8	1.60
CL-S5	20.5	1.64
CH-00	27.4	1.52
CH-C0.5	27.2	1.49
CH-C1	27.1	1.50
CH-C2	26.8	1.53
CH-C5	26.5	1.55
CH-S0.5	27.2	1.48
CH-S1	27.2	1.50
CH-S2	27	1.51
CH-S5	26.8	1.52

3.2. The effect of salts on the shear characteristic of the soils

The UU triaxial tests were conducted on samples containing both sodium chloride and sodium carbonate salts with different concentrations to determine the cohesion (C) and internal friction angle (Ø) in three replicates. To evaluate the effect of salt concentration and type on soil cohesion and internal friction angle, graphs depicting the changes in cohesion and internal friction angle concerning sodium sulfate and chloride concentrations were plotted (Figs. 6 and 7).

As shown in Figs. 6 and 7, with the increase in sodium sulfate concentration up to 0.5 percent, the cohesion of the soil decreases. For both soil samples, the minimum cohesion was observed with the addition of 0.5 percent sodium sulfate where the cohesion of the soils reduces to about 60 kPa in the CH sample and 100 kPa in the CL sample indicating 50 and 35 percent reduction in comparison to natural soils, respectively. As the salt concentration increases from this value onward, cohesion rises slowly. When the sodium chloride concentration reaches up to 0.5 percent, cohesion decreases in both samples in the same way as for sodium sulfate, dropping to about 83 kPa in the CL sample and 97 kPa in the CH sample, which represents reductions of approximately 47 and 35 percent compared to natural soils. When the sodium chloride concentration increases from 0.5 to 2 percent, cohesion increases, reaching its maximum value at 2 percent sodium chloride. Further increases in sodium chloride concentration led to a continuous decrease in cohesion, reaching a minimum value of 55 kPa in both soil samples at 10 percent sodium chloride.

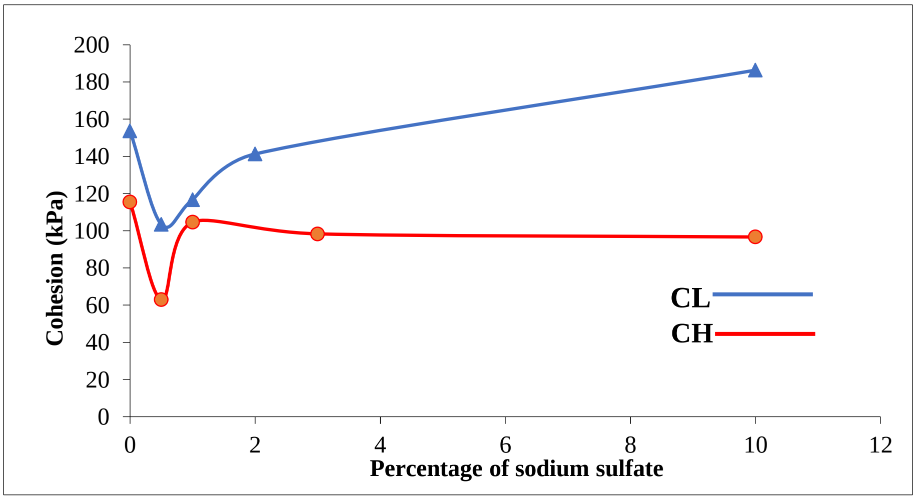


Fig. 6. The changes in cohesion concerning sodium sulfate concentration.

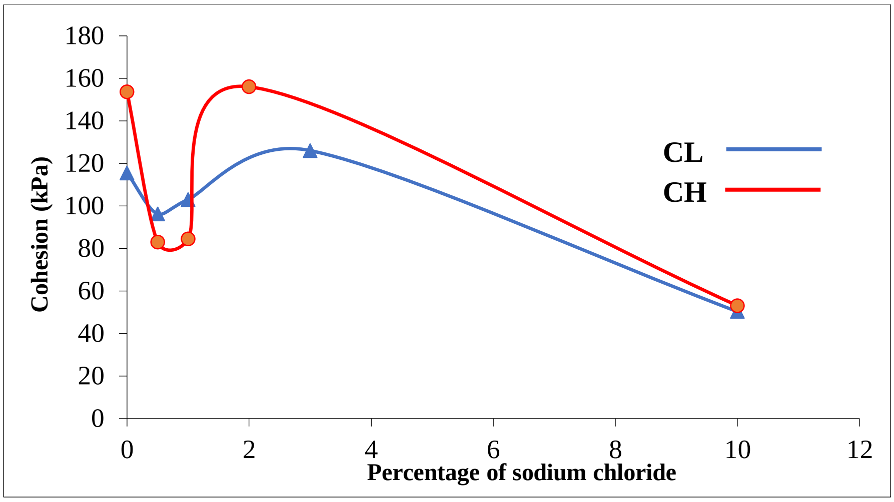


Fig. 7. The changes in cohesion concerning sodium chloride concentration.

Figs. 8 and 9 illustrate how the internal friction angle changes with different amounts of sodium sulfate and sodium chloride salts for the soils under study. According to Fig. 8, unlike the cohesion, the internal friction angle increases as the sodium sulfate concentration increases up to 0.5 percent in the CL sample and 1 percent in the CH sample, which indicates about 20 and 34 percent increase in the internal friction angle, respectively. Also, when the salt concentration increases from these values onwards, the internal friction angle decreases up to about 2.5 percent of salt. After that, the increasing trend continues as the salt concentration increases. Thus, salt concentration does not have a constant effect on the internal friction angle. In fact, up to a certain concentration (about 1%), sodium sulfate increases the internal friction angle, but after that, it decreases the internal friction angle back to its initial value. Subsequently, for concentrations above approximately 2.5%, the internal friction angle increases with further increases in the salt concentration. These variations indicate a similar trend for sodium chloride. However, as can be seen in Fig. 9, the effect of sodium chloride on the CH soil is much more than on the CL soil, implying that sodium chloride has a greater effect on soils with high plasticity compared to those with low plasticity.

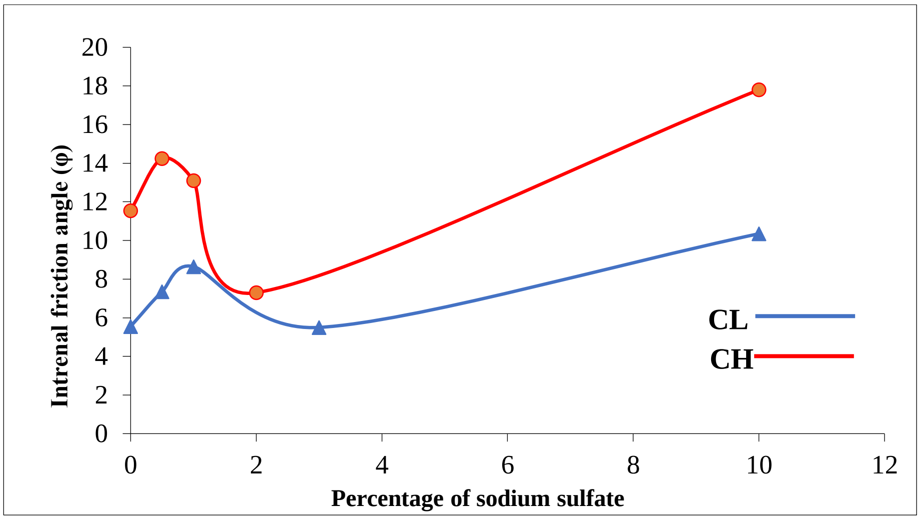


Fig. 8. The changes in the internal friction angle concerning sodium sulfate concentration.

Figs. 10 and 11 show the variation of the angle of internal friction and cohesion of the soils with the total amount of salinity in terms of electrical conductivity, EC, regardless of the type of salt.

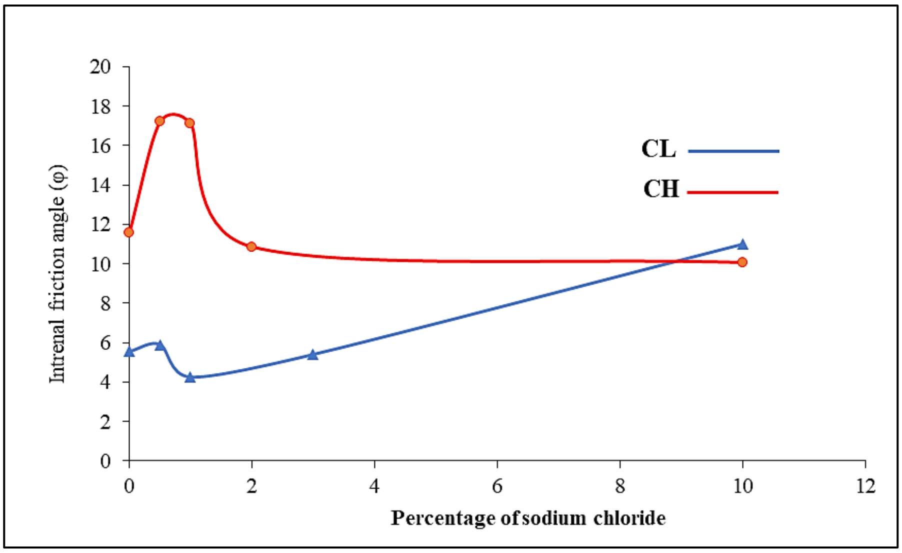


Fig. 9. The changes in the internal friction angle concerning sodium chloride concentration.

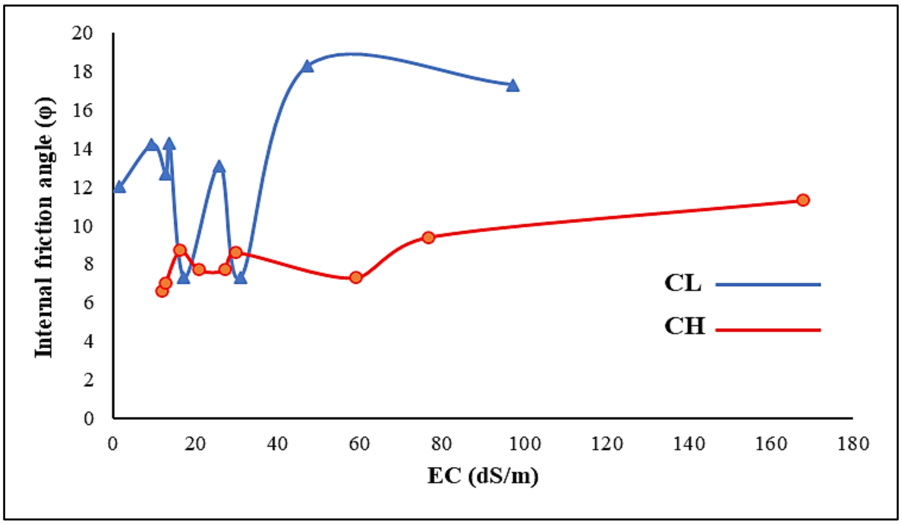


Fig. 10. The changes in the internal friction angle for the EC.

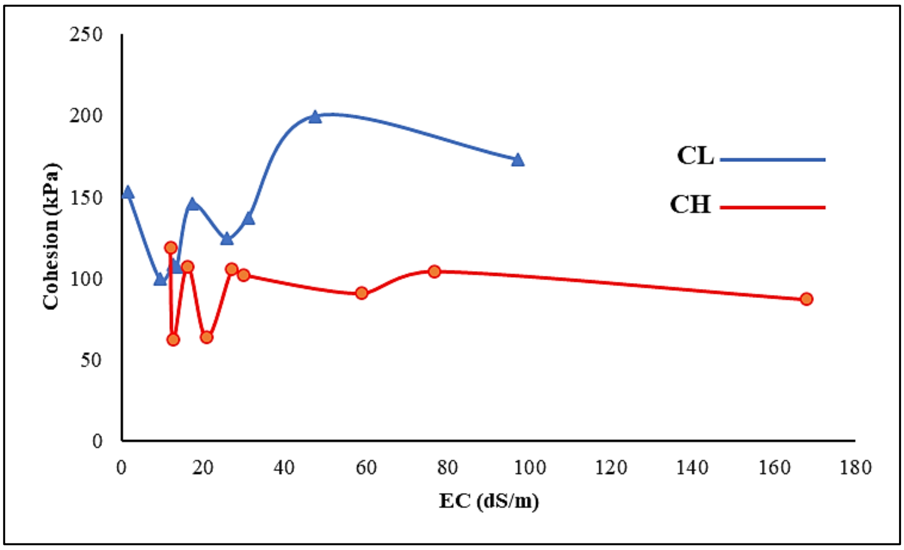


Fig. 11. The changes in the cohesion for the EC.

As can be seen from Figs., there is no clear relationship between electrical conductivity and shear parameters. That means the effect of salinity on soil shear properties cannot be expressed only by the amount of salinity in terms of electrical conductivity, EC, instead in addition to salt concentration, the type of anions and cations as well as the plasticity of soils play a crucial and decisive role in explaining the relationship between pore water salinity and shear parameters of soils. Based on the overall results obtained from this research, it is obvious that the effect of the salts on the maximum dry unit weight of the soil is also negligible. In which, the amount and type of soil salinity do not significantly impact the compaction characteristics of the soils. These findings agree with findings reported by other researchers (Nasr, 2015).

Also, it was found that in cases where the increase of salt in the soil reduces its cohesion, it increases the internal friction angle of the soil and vice versa. This issue is in complete agreement with the concept of these two parameters. Also, it is found that the effect of salts depends on the quantity and type of anions and cations existing in the pore water of soil and the index properties of the soils. Furthermore, it was also found that there is no clear relationship between electrical conductivity and shear parameters, and then, the effect of salinity on soil shear properties cannot be expressed only by the amount of salinity in terms of electrical conductivity, EC.

These findings Also, generally the fiction angle and shear strength of soil. The overall findings of this study are consistent with the results presented by Deng et al.(2021), in which the friction angle and shear strength of clayey soils increase with an increase in pore water salinity.

4. Conclusion

The study found that soil salinity does not significantly impact compaction characteristics such as optimum water content and maximum dry density. However, an increase in sodium sulfate concentration up to 0.5% decreased cohesion by about 50% in CL soils and 35% in CH soils, with a slight increase beyond this concentration. Similarly, sodium chloride reduced cohesion by about 50% in CL soils and 35% in CH soils, with a continuous decrease reaching a minimum of 55 kPa at 10% sodium chloride. Unlike cohesion, the internal friction angle increased with sodium sulfate concentration up to 0.5% in CL soils and 1% in CH soils, indicating a 20% and 34% increase, respectively. Beyond certain concentrations, the internal friction angle decreased before increasing again at higher salt concentrations, showing a similar trend for sodium chloride. The effect of sodium chloride was more pronounced in CH soils than CL soils, suggesting a greater impact on high-plasticity soils. The study also highlighted that the effect of salts depends on the type and number of anions and cations in the pore water and soil index properties. There is no clear relationship between electrical conductivity and shear parameters, indicating that salinity's effect on soil shear properties cannot be solely expressed by electrical conductivity.

The type of anions and cations, along with soil plasticity, plays a crucial role in describing the relationship between pore water salinity and shear parameters. However, the present study has certain limitations, including its focus on specific clayey soils in Iran, which may limit the generalizability of the results to other soil types or regions. The controlled laboratory settings and specific salt concentrations examined might not fully reflect real-world conditions with varying environmental factors. Future research should expand to include a broader range of soil types and regions, considering adequate replication for each test to statistical analysis, investigating long-term effects of salinity on soil properties, exploring the impact of various salts and combinations, and developing effective soil treatment methods to mitigate the adverse effects of salinity.

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