Influence of Salinity on the Microstructure and the Shear Strength of Urmia Lake Sandy Soils

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ABSTRACT

Saline soils are widely distributed across arid, semi-arid, and coastal regions of the world. Understanding their physical and mechanical properties is essential for identifying and addressing challenges associated with civil engineering projects. This study investigates the effect of salt type and concentration on the shear strength and suction variations of saline aeolian sands from the Lake Urmia basin. After desalinating the soil, sodium chloride (NaCl) and sodium sulfate (Na_2SO_4) were added to the soil at concentrations ranging from 2% to 12%, and the prepared samples were subjected to direct shear tests at two different moisture contents. Microstructural changes under different salt and moisture conditions were also examined using optical microscopy. Finally, suction variations were measured for samples treated with 12% salt at different moisture contents. The results indicate that the effects of salts on the shear strength of aeolian sands depend on moisture content and salt crystallization–dissolution processes. At a constant moisture content, increasing the concentrations of both sodium chloride and sodium sulfate resulted in higher shear strength. However, increasing moisture content from 5% to 10% at constant salt concentration decreased the shear strength of sodium chloride-treated samples but increased that of sodium sulfate samples. Moreover, sodium chloride predominantly affected the osmotic component of total suction, whereas sodium sulfate had a greater influence on the matric component. These findings contribute to a better understanding of the mechanisms through which different salts influence the behavior of non-clayey granular soils.

KEYWORDS

Granular soils, sand, salt, microstructure, shear strength.

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1. Introduction

Saline soils are widely distributed in arid, semi-arid, and coastal regions, where repeated cycles of salt dissolution and crystallization can alter soil structure and geotechnical behavior [1, 2]. Soil shear strength is influenced by several factors, including salt type and content, moisture content, and suction, which comprises both matric and osmotic components [3, 4]. Among common salts, Na2SO_4 can increase matric suction because of its relatively high water absorption capacity, whereas NaCl primarily affects osmotic suction and may temporarily enhance soil strength through salt cementation [5, 6]. However, such cementation is often unstable and may weaken following salt re-dissolution [7, 8]. Although numerous studies have investigated the behavior of saline fine-grained soils, the response of saline aeolian sands remains insufficiently understood, particularly under different salt types and moisture conditions [9, 10]. Therefore, this study investigates the effects of NaCl and Na_2SO_4 on the shear strength, suction, and microstructure of saline aeolian sand collected from the Urmia Lake basin.

2. Methodology

Samples were taken from aeolian sand in the Jabal Kandi area on the western shore of Lake Urmia. The soil was classified as poorly graded sand (SP) and saline soil. To ensure sample uniformity, the fractions passing the No. 100 and No. 200 sieves were remixed at a ratio of 60:40. Figure 1 shows the gradation envelope of the studied soil. Desalination was carried out by repeated washing with distilled water until the electrical conductivity decreased to below 250 µS/cm [2, 5].

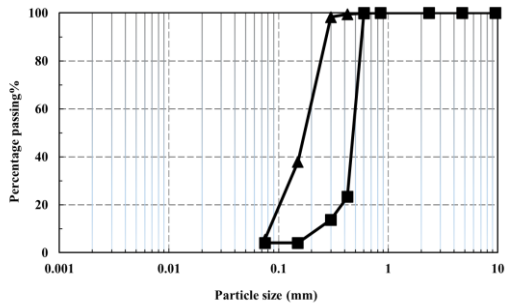

Figure 1. Gradation envelope of the studied base soil from the Jabal Kandi region, western shore of Lake Urmia.

Reconstituted saline samples were prepared by adding NaCl and Na_2SO_4 solutions corresponding to 2, 4, 6, and 12% of dry soil weight. The samples were then cured for 24 h, dried, crushed, and sieved [2, 4, 5].

Total and matric suction were measured at five different moisture contents using the filter paper method, [11]with the data adjusted for potential errors associated with salt precipitation [8]. All specimens were compacted to a dry density of 1.623 g/cm³. Unsaturated direct shear tests were conducted on specimens with moisture contents of 5% and 10% following 24 hours of curing to allow salt precipitation. In addition, the micro- structure of these specimens was examined at 40x magnification using an optical microscope to observe salt distribution within the pore space.

3. Results and Discussion

In the desalinated soil, matric and total suction were nearly equal. Both reached their maximum values at a moisture content of 2% and subsequently decreased with increasing moisture content [10]. In NaCl treated soil, matric suction exhibited relatively little variation, whereas total suction increased at higher moisture contents because of the contribution of osmotic suction. At low moisture contents, salt crystallization reduced the osmotic com- ponent, causing total and matric suction to become nearly equal. In Na_2SO_4-treated soil, both matric and total suctions were higher than in the desalinated soil. Matric suction was dominant at low moisture contents, whereas the contribution of osmotic suction became more pronounced as moisture content increased. Microstructural observations indicated that, at a moisture content of 5%, both salts began to precipitate at grain contacts. With increasing NaCl content, larger crystals formed and partially filled the pore spaces. However, at a moisture content of 10% crystallization decreased because of the greater extent of salt dissolution. In contrast, Na_2SO_4 continued to produce stronger interparticle bonding and thicker salt coatings even at 10% moisture, which may be attributed to its higher water absorption capacity.

NaCl increased shear strength at both 5% and 10% moisture contents, with a more pronounced effect at 5% moisture. At 5% moisture, a salt content of 4% increased cohesion by approximately 73% and the internal friction angle by 6.5%, while a salt content of 12% produced the maximum increase, with cohesion and internal friction angle increasing by approximately 173% and 22% respectively. At 10% moisture, a similar trend was observed, although the effect was less pronounced because the higher moisture content promoted greater salt dissolution. Na_2SO_4 had relatively limited effect at a salt content of 2%, however, at higher salt contents, it progressively increased shear strength, primarily through an increase in cohesion rather than the internal friction angle. Its strongest effect was observed at 12% salt and 10% moisture. This increase in strength may be

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attributed to the combined effects of increased matric suction, stronger salt-induced interparticle bonding, crystal growth, and pore filling. The detailed variations in soil cohesion and internal friction angle resulting from the addition of sodium chloride and sodium sulfate are presented in Tables 1 and 2.

Table 1. Variation of soil cohesion and internal friction angle with the addition of sodium chloride.

W=10%		W=5%			
Ø (°)	C (kg/cm^2)	Ø (°)	C (kg/cm^2)	Salt content (%)	Salt type
40.2	0.04	38.5	0.15	0	NaCl
37.5	0.16	38.5	0.15	2	
35.7	0.24	41	0.26	4	
36	0.29	41	0.3	6	
38	0.31	47	0.41	12	

Table 2. Variation of soil cohesion and internal friction angle with the addition of Sodium sulfate.

W=10%		W=5%			
Ø (°)	C (kg/cm^2)	Ø (°)	C (kg/cm^2)	Salt content (%)	Salt type
40.2	0.04	38.5	0.15	0	Na_2SO_4
38.5	0.27	36.6	0.23	2	
39	0.34	37.5	0.28	4	
40	0.4	40.5	0.3	6	
41	0.45	41.5	0.4	12	

4. Conclusions

This study examined the effects of NaCl and Na_2SO_4 on the shear strength, suction, and microstructure of aeolian sand from the Urmia Lake basin under different moisture contents. The two salts behaved differently because of differences in crystallization, dissolution, and water absorption. NaCl caused little change in matric suction but increased total suction at higher moisture because of osmotic effects. In contrast, Na_2SO_4 increased both matric and total suction. At constant moisture, salt addition generally maintained or increased shear strength through crystal formation, interparticle bonding, pore filling, and suction changes. However, increasing moisture from 5% to 10% reduced shear strength in NaCl-treated soil because of greater salt dissolution, whereas in Na_2SO_4-treated soil it enhanced shear strength by promoting crystallization and increasing matric suction.

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