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Impact of cooling on shear strength of high salinity soils

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ABSTRACT

Engineering activities have increased in northwestern China where high salinity soils exist extensively. This paper investigates the volumetric behavior and shear strength parameters of high salinity soils during cooling. Fine-grained saline soils with salt content varying from 36% to 2.6% were collected along a highway on the Qinghai-Tibet plateau to conduct laboratory cooling and direct shear tests. Cooling curves of soil specimens were obtained to assess the freezing point depression caused by salinity. Volumetric change data during cooling was presented. Direct shear tests were conducted at temperatures ranging from 20 °C to − 20 °C at an interval of 10 °C to obtain the shear stress-strain behavior and evaluate shear strength parameters including the cohesion and friction angle. Additional tests were carried out to investigate the effect of increased moisture content on shear strength parameters. Results showed that saline soils with > 0.5% sulfate salt will exhibit large volumetric expansion due to salt crystallization and formation of mirabilite. It was found that, as the temperature was lowered from 20 °C to − 20 °C, the shear stress-strain curves of high salinity soils demonstrated stronger dilative and strain-softening behavior, the friction angle remained constant or showed small but consistent gain, and the cohesion increased. It was interesting to find that the freezing of pore water in high salinity soils did not have nearly as large impact on soil strength as it would have for non-saline soils. In addition, a 3% increase in moisture content decreased the cohesion by 60–90% due to reduced matric suction resulted from increased degree of saturation and decreased tension at the water-soil interface. The results are of significance for highway engineering in cold regions with extensive saline soil distribution.

1. Introduction

Northwestern China, where part of the Qinghai-Tibet Plateau is located, has wide-spread saline soils and salt lakes (Wang et al., 1993; Yang, 2008). This region, with great elevation variation, has a climate varying from subtropical to cold temperate with temperature ranging from − 33 °C to 35 °C. Under very low temperatures, both salt and ice may crystallize in saline soils resulting in frost heave and salt expansion (Fang et al., 2011). The complex physical and chemical processes in saline soils under a large temperature variation cause freezing point depression, expansion or contraction, and structural alteration, which have great impact on soil engineering properties including volumetric behavior and shear strength parameters.

Salts are known to cause freezing point depression and impact the unfrozen water content at subfreezing temperature. Banin and Anderson (1974) proposed equations for predicting freezing point depression due to soluble salt content in porous media. Watanabe and Mizoguchi (2002) studied the impact of different solutes (NaCl, KCl and $MgCl_2$) on the unfrozen water content in frozen soils of different type including monosized glass powder, silty soil and clay, and found that the unfrozen water content increased with increasing salt content, with NaCl and KCl causing approximately the same increase and $MgCl_2$ causing the largest increase. Chen et al. (2006) proposed an equation for estimating the freezing temperature based on moisture content, chloride ion and sulfate ion contents in soils. Bing and Ma (2011) carried out a series of freezing temperature tests on saline clay, loess and sand, and found that the freezing temperature generally decreased with increasing salinity, increased with increasing moisture content, and the impact of common salt anions and cations on the freezing temperature followed this order: $Cl^- > CO_3^{2-} > SO_4^{2-}$ and $K^+ > Na^+ > Ca^{2+}$. Wan and Lai (2013) investigated the impact of sodium sulfate on the soil freezing temperature and found that the freezing temperature decreased from about − 0.5 °C to − 2.8 °C with sodium sulfate content increased from 0.2% to 4%. These studies showed that chloride-salt content has the greatest impact, and sulfate-salt content has much less of an influence on the soil freezing

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Fig. 1. View of a high salinity soil sampling site along the Golmud-Qarhan highway. Left: visible salt crystals (white); Right: salt precipitation in the roadside ditch along the highway.

temperature depression.

At temperatures below 0 °C, salt crystallization started to occur as chloride salt combined with unfrozen water to produce $NaCl·2H_2O$ (Swenne, 1983). In contrast, sulfate salt starts to crystallize and form mirabilite ($Na_2SO4·10H_2O$) at a temperature as high as 32 °C, and its volume can increase by as much as 200%, compared with about 20% for chloride salt crystallization (Liang, 1985; Archer, 1992). Nassar and Horton (1997) deduced an equation for describing water and salt transfer and suggested that the main driving forces of salt transfer are the temperature gradient, moisture content and solute concentration. Bao et al. (2006) studied the salt expansion of undisturbed saline soils subject to freeze-thaw cycles. Niu et al. (2008) investigated the mechanism and characteristics of salt expansion in saline soils. Steiger and Asmussen (2008) studied the crystallization process of sodium sulfate in porous materials. Espinosa et al. (2008) elaborated the process of salt crystallization, hydration and deliquescence in porous media.

The physical and mechanical properties of saline soils have been the subject of many studies. Chen et al. (1989) tested the unconfined compressive strength of high salinity soils subject to repeated freeze-thaw cycles at room temperature. Biggar et al. (1993) carried out pile loading tests in saline permafrost and concluded that the salt content is a key factor affecting the stress-strain behavior. Fatani and Khan (1993) reported foundation issues related to saline soils including low bearing capacity and tilting of low-rise building due to dissolution of salt rock underneath the footing. Brouchkov (2003) tested the bearing capacity of fine-grained saline soils with different salt contents at different temperatures, and found that chloride saline soils formed by deposition in the sea have the lowest bearing capacity. Chen et al. (2007) investigated the influence of freeze–thaw cycles on the cohesion of saline soils at room temperature. Bing and He (2009) conducted uniaxial compression tests of soil samples with different content of sodium sulfate and moisture content subject to varying number of freeze-thaw cycles at room temperature and found that saline soils, in general, showed a brittle fracture. Carteret et al. (2013) conducted shear strength testing on compacted specimens of granular road pavement with different combinations of salt concentrations and moisture contents, and found that the presence of natural salts can have a positive effect on the shear strength of granular road pavements, whereas it would cause debonding of the bituminous surfacing from the pavement. Recent studies (Xu et al., 2016a; Xu et al., 2016b; Liao et al., 2016) investigated the mechanical behavior and strength criteria of frozen saline soils by triaxial tests.

In summary, most of the existing studies were examining the freezing point depression, volume change of salt crystals, and stress-strain and shear behavior of saline soils at room temperature. Few studies have addressed the impact of salt crystallization on the overall volumetric behavior, and possible influence of cooling on the shear strength parameters of high salinity soils. This paper investigates the volumetric, stress-strain and shear strength parameters of high salinity soils during cooling by using saline soil samples with chloride- and sulfate-salt contents collected from a highway site on the Qinghai-Tibet plateau. Freezing point depression was confirmed by cooling curves and experimental data on volumetric and mechanical behavior of saline soils were presented. The impact of cooling and increased moisture content on the shear strength parameters of saline soils were described, and the mechanisms were discussed. The implication of the findings to and insight for engineering with high salinity soils was presented.

2. Testing program

2.1. Description of soil sample properties

Four representative saline fine-grained soils with high chloride- or sulfate-salt content were collected along the Golmud-Qarhan highway. This highway is located on the Qinghai-Tibet Plateau with a cold and arid continental climate. Rainfall mainly concentrates from May to September with an average monthly precipitation of < 7 mm which accounts for > 80% of annual precipitation. Fig. 1 shows views of the selected site for high salinity soil sampling. Salt crystals are often visible in the soil or in the ground water. The basic index properties and ion contents of soil samples were tested according to Chinese Highway Engineering standard (JTG E40, 2007). Fig. 2 contains the grain size distributions, and Tables 1 and 2 show the index properties and the ion contents of the samples, respectively. According to the Unified Soil Classification System, soils in HC-1, HC-2 and CS-1 groups were classified as lean clay (CL), while soils in CS-2 group were classified as silt (ML). The total salt content of the four groups ranges from 36% to 2%. HC-1 and HC-2 denote two groups of saline soil with high chloride salt content (≥ 15%) and low sulfate salt content (≤ 0.5%), whereas CS-1 and CS-2 denote two groups of saline soil with low chloride-salt (≤ 5%)

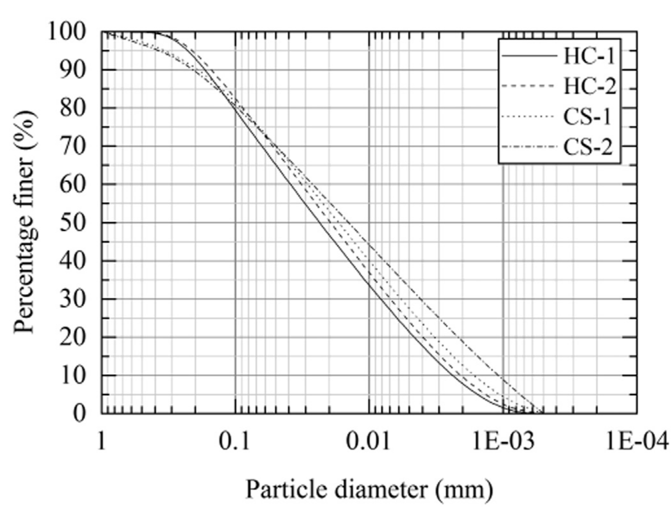

Fig. 2. Grain-size distributions of four representative saline soil samples.