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A study on the effect of the salt content on the solidification of sulfate saline soil solidified with an alkali-activated geopolymer

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HIGHLIGHTS

- Salt content significantly effect hydration reaction of alkali-activated geopolymer.
- The peak solidified soil UCS occurs at a salt content of 1.8%.
- The salt content changes cement chemical composition and pore structure.

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ABSTRACT

The salt content has a significant effect on the hydration reactions of alkali-activated geopolymers, thereby influencing the curing effect. The main objective of this paper is to study the changes that occur in the mechanical properties of sulfate saline soil solidified with an alkali-activated geopolymer due to varying the sulfate salt content. Sodium silicate, lime-fly ash, and the combination of lime-fly ash and sodium silicate were selected to solidify sulfate saline soils with different salt contents. An unconfined compressive strength test was conducted to study the variation in the compressive strength of the solidified soil at different salt contents. Moreover, the consistency characteristics, phase characteristics, chemical composition and microstructure of the solidified soil were evaluated. The results showed that as the salt content increased, the unconfined compressive strength of the three curing agents first increased and then decreased. Additionally, the peak strength occurred at a salt content of approximately 1.8%. Analyses of the phase characteristics, chemical composition and microstructure of the solidified soil indicated that the influence of the salt content on curing is reflected by changes in the cement chemical composition and the pore structure.

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1. Introduction

Saline soil is defined as soil in which the soluble salt content is higher than 0.3% and exhibits the engineering characteristics of depression, expansion and corrosion [1]. This soil type occurs widely around the world, covering an area of more than 1 billion hectares. In northwestern China, inland saline soil is widely distributed, especially sulfuric saline soil, which is a type of saline soil with a Cl^-/SO_4^{2-} ratio of less than 0.3 [2,3]. Natural sulfuric saline soil is regarded as an inferior construction material. Changes in the external environment (e.g., temperature and water content) are associated with many geotechnical problems and can lead to undesired engineering characteristics, such as frost boiling, salt heaving, etching, and frost heaving [4,5]. Therefore, it is important to solve or prevent these problems.

Numerous stabilization techniques have been implemented to improve the poor properties of sulfate saline soil. These techniques include soil replacement, vibratory compaction, and chemical stabilization [6,7]. The treatment of saline soil with inorganic materials such as lime, fly ash and cement has been widely implemented and is an effective method because of its suitability and cost effectiveness. For example, Al-Amoudi O S B [8] investigated the application of cement and lime at different dosages to improve the properties of sabkha soil. Chai et al. [9] studied the stabilizing effect of inshore saline soil with five compositions obtained by mixing various agents. Modifying the samples with lime, fly ash, and a small amount of polymer SH agent was found to improve the samples.

Geopolymers, which are materials that have been actively studied in recent years, comprise a subset of a broader category of

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Table 1
Basic physical properties of the soil.

Nature density (g/cm^3)	Atterberg limits (%)			Particle composition (%)			Maximum dry density (g/cm^3)	Optimum water content (%)
	Liquid limit	Plastic limit	Plasticity index	2–0.075 mm	0.075–0.005 mm	<0.005 mm		
2.70	26.4	14.9	11.6	37.18	47.12	15.70	1.85	13.8

Table 2
Soluble salt content in soil.

Negative ions (mg/kg)				Positive ions (mg/kg)			Total salt content	
CO_3^{2}	HCO_3^{-}	SO_4^{2-}	Cl^{-}	Ca^{2+}	Mg^{2+}	$Na^{+}+K^{+}$	(mg/kg)	(%)
63	161	12,121	6218	2318	1585	4107	26,573	2.63

alkali-activated binders [10]. Fly ash, which contains large quantities of reactive SiO_2 and Al_2O_3, was selected as a raw material to synthesize a proposed geopolymer [11]. Sodium silicate, an alkaline activator, has been successfully used in soil stabilization because of its low cost, adaptability, and nontoxicity. Some studies performed on soil found that the use of geopolymers can efficiently overcome various soil engineering problems. Lv et al. [12] conducted an experiment to assess the strength characteristics of sulfate saline soil solidified with lime, fly ash and sodium silicate and explored the mechanism of the geopolymer. However, due to secondary salinization, the salt content has a considerable influence on the type and content of the curing agent that can be used in the solidified saline soil. We et al. [13] described the effect of the salt content on the unconfined compressive strength of cured inshore saline soil. Li et al. [14] found that chlorine salt increased the quantity of coarse soil particles, decreased the total surface area and had adverse effects on the stability of lime-treated soil. In contrast, less research has been performed for inland saline soil.

The main objective of this paper is to study the changes that occur in the mechanical properties of sulfate saline soil solidified by an alkali-activated geopolymer based on varying the sulfate salt content. Sodium silicate, lime-fly ash, and the combination of lime-fly ash and sodium silicate were selected to solidify sulfate saline soils with different salt contents. An unconfined compressive strength test was conducted to study the variation in the compressive strength of the solidified sulfate saline soil for varying salt contents. Moreover, the consistency characteristics, phase characteristics, chemical composition and microstructure of the solidified soil were evaluated for different salt contents. Various instrumental techniques, such as moisture content limit analysis, X-ray diffraction (XRD), Fourier transform infrared spectroscopy (FTIR) and physical adsorption tests, were used. In addition, the mechanism associated with the effect of the salt content on the compressive strength was discussed.

2. Experimental procedure

2.1. Materials

The sulfate saline soil used in the tests was collected from Yinma Farm, which is located in Jiuquan, Gansu Province. Yinma Farm is situated in arid and semi-arid regions of China. Table 1 shows the basic physical properties of the saline soil obtained in the laboratory by following the ASTM standard methods. Particle composition analysis showed that the sample primarily consists of silt particles, with a fraction of 47.12%, which is classified as fine-grain saline soil. According to the unified soil classification system (USCS), the sample soil has low plasticity. The average soluble salt content of the soil is presented in Table 2. According to the Code for the Investigation of Geotechnical Engineering (GB50021-2001), which is the PRC National Standard, the sample soil is sulfurous saline soil, a form of strong saline soil.

Numerous inorganic stabilization materials have been implemented to improve poor soil properties. In this paper, quick lime, fly ash and sodium silicate are selected to solidify sulfate saline soil. The physical properties and chemical compositions of quick lime and fly ash are listed in Table 3. The mass fraction of the effective CaO + MgO of the quick lime was found to be more than 90%, with at least 80% CaO. Thus, the lime is characterized by high activity. The fly ash used, which was collected from a thermal power plant in Lanzhou City, China, meets the standard of second-class pulverized powder. Additionally, the main chemical components of the ash were SiO_2, Al_2O_3, and Fe_2O_3. Sodium silicate is a widely used alkali-activated geopolymer [15]. The sodium silicate used in this experiment was collected from Lanzhou Fuming Chemical Co., Ltd. The concentration of the sodium silicate was 20 °Bé, and the modulus was 3.2.

Table 3
Physical properties and chemical compositions of lime and fly ash.

Chemical analysis	Lime (wt%)	Class F fly ash (wt%)
SiO_2	1.65	54.73
Al_2O_3	0.88	24.78
Fe_2O_3	0.35	7.89
CaO	85.73	2.64
MgO	6.26	1.08
K_2O		0.68
Na_2O		0.31
SO_3	0.43	0.21
Physical properties		
Specific gravity		2.6
Loss on ignition (%)	6.02	6.09
Practical size	75% of 75 μm	73% of 75 μm

2.2. Sample preparation

The saline soil samples were desalinated repeatedly until the electrical conductivity and salt content were less than 1000 s/cm and 0.3%, respectively [16]. The plain soil was treated with different percentages (0.3%, 0.8%, 1.3%, 1.8%, 2.3%, and 2.8%) of anhydrous sodium sulfate to obtain saline soils with different salt contents. According to the quality ratio, three types of curing agents (20 °Bé sodium silicate, 9% lime + 18% fly ash and 9% lime + 18% fly ash + 20 °Bé sodium silicate) were selected to solidify sulfate saline soils with different salt contents.

The samples were prepared according to the optimum water content and the maximum dry density of the compacted soil. A curing agent was added to the plain soil, and the mixtures were then stirred evenly using a glass stirring rod and stirred again after these being sprayed with anhydrous sodium sulfate. These mixes were placed in hermetic bags for 24 h to make the water distribution in the samples be uniform. The mixes were weighed, and each mixture was compacted in layers using the bidirectional static compaction method. Each mixture was forced into a test mold for 3 min, demolded, and then made into a cylinder of 5 cm in diameter and 5 cm in height. Next, each cylinder was wrapped in cling film and placed in a sealed container to ensure that the water content remained unchanged. At the curing age of 30 d, the samples were removed from the film. Next, the samples were mechanically characterized via an unconfined compressive strength test and the Atterberg limit test and were mineralogically and microstructurally studied using XRD, Fourier transform infrared spectroscopy (FTIR) and physical adsorption tests.

2.3. Experimental methods

According to the prevalent standard (Chinese Standard for Soil Test Methods, GB/T 50123-1999, which is the same as BS 1377-2-1990 and ASTM D4318-05), all samples underwent Atterberg limit and unconfined compressive strength testing in the laboratory using a digital soil liquid-plastic limit combined measuring instrument and a CSS-WAW300 electrohydraulic universal testing machine. The XRD

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