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Research Article

The Effects of Salt-Lake Salt Solution on the Strength of Expansive Soil

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Expansive soils are widely distributed and often cause serious damage to structures. Hanzhong expansive soil and Yulin salt-lake solution were adopted to investigate the effect of salt-lake salt solution on the strength of expansive soil. Expansive soils modified with salt-lake salt solutions with different concentrations (0.1, 0.5, and 1.0 mol/L) were evaluated by X-ray diffraction (XRD), Atterberg limit, free swelling, no load swelling ratio, and triaxial compression tests. The improved expansive soil research using salt-lake salt solution was carried out based on the macroscopic mechanical characteristics. Test results showed that the addition of salt-lake solution effectively inhibited the expansibility of soil. With the increase of the concentration of salt-lake solution, liquid limit, plastic limit, plastic index, free expansion rate, no load swelling, cohesion, and internal friction angle of expansive soil were decreased in varying degrees, and stress-strain relationship curve gradually showed strain softening trend. The reason for the above results was believed to be that salt-lake salt solution reduced the force between particles on shear surface and reduced mutual hindrance.

1. Introduction

Expansive soils contain several mineral components such as montmorillonite and illite and are often applied as the foundation of roadbeds, embankments, and buildings [1]. Expansive soils are primarily composed of hydrophilic clay minerals such as montmorillonite, which have significant swelling and shrinking characteristics [2]. Because montmorillonite and illite have very high capacities of water-absorbing swelling, the internal structure of swelling soil is deformed during repeated water-absorbing swelling and water-loss shrinking processes, resulting in a great number of cracks finally destroying soil structure making it resistant to shear. Sudden drop in soil strength often causes serious damage such as building foundation uplift, roadbed cracking, and slope instability to structures causing huge economic losses [3]. The treatment of expansive soils is imperative for practical implications in engineering.

Due to the adverse nature of expansive soils, geotechnical engineers are constantly searching for different options to mitigate their unfavorable characteristics via soil stabilization technologies [4]. Two improvement methods, namely, mechanical and chemical, have been adopted to improve expansive soils. Mechanical methods using compaction, pre-wetting, wetting-drying cycles, reinforcement, and solid wastes have been evaluated by many researchers.

Traditional chemical agents for improving expansive soils include lime, cement, and fly ash, which are usually calcium-based substances [4]. Addition of lime and cement rapidly and significantly improves soil properties by reducing plasticity and eliminating swelling [5–11]. Some researchers have also applied fly ash and quarry dust as binders to stabilize expansive soil due to their sustainable construction and economic benefits [11–13]. However, issues such as the environmental impact of traditional production technologies have raised questions about their sustainability. Nontraditional chemical agents including nanomaterials [14], biochar [15], enzyme [16], jute fiber [17], and vetiver root [18] play important roles in enhancing expansive soil strength parameters.

Expansive soil strength is extremely sensitive to pore solution. When the physical and chemical environments of pore solution (including concentration, ion type, and pH value) change, due to the interactions of particles and pore solution, the particle arrangement, structural characteristics, and pore water occurrence state of the soil are changed, thus changing its macroscopic physical and mechanical properties (cationic–electrokinetic). Soil improvement has been shown to be an effective technique [19]. $MgCl_2$ solution, with the optimum concentration of 7%, is recommended as a viable soil improvement additive for both low- and high-swelling clays [20, 21]. KCl changes pore-water chemistry to improve its geotechnical properties [22]. Salt content can affect freezing temperature (FT) and unconfined compressive strength (UCS) of lime-treated subgrade clay [23]. The expansion deformation rules of soils immersed in salt and acid solution are similar to the rules of soaked soil [24]. Using Dead Sea salt as a stabilization additive significantly improved the engineering properties of expansive clays used as subgrade soil [25]. Therefore, taking into account possible geotechnical engineering problems such as geological hazards and soil slope stability, the mechanism of the effects of the kind of solute and concentration in pore water of expansive soil on physical and mechanical properties of soil urgently needs to be investigated. It is also necessary to study the influence of salt-lake solutions on expansive soil strength. It can provide efficient suggestions for disaster prevention in areas with expansive soil.

In this research, the effect of salt-lake salt (SLS) solution as an additive on the engineering properties of expansive soil has been investigated. To achieve this objective, different concentrations of SLS solution (0.1, 0.5, and 1.0 mol/L) were added to expansive soil samples. Fine-grained soil properties such as Atterberg limits (liquid limit (LL) and plastic limit (PL)) were tested, and free swell, no loading swelling ratio tests, and c, φ, τ, as well as stress-strain relationship, were investigated with and without the additive.

2. Materials and Methods

2.1. Materials. Expansive soil samples used in the tests were collected from the landslide monitoring site in, Shaanxi. It is a highly plastic cohesive soil with obvious water absorption expansion and water loss shrinkage, as well as multifissure and overconsolidation. SLS samples were taken from Dingbian County, Yulin City, Shaanxi, as shown in Figure 1.

The soil was reddish-brown in color and was collected from the depth of 1~3 m. According to China's *Standard for geotechnical testing method (GB/T 50123-2019)*, the water content tests on soil samples were performed by drying method, density tests were conducted by ring knife method, and Atterberg limits were determined by liquid and plastic limit water content joint measurements. Basic physical property indexes are shown in Table 1. By X-ray diffraction (XRD) tests, clay mineral composition was determined to be as follows: illite 33.21%, kaolinite 9.35%, chlorite 7.24%, and Imonite mixed-layer mineral 6.97%. Also, free swell rate was 65.8%. According to the classification of *Technical code for buildings in expansive soil regions (GB50112-2013)*, our expansive soil samples were of medium expansive soil type.

Bulk SLS samples were crushed and dissolved in distilled water to obtain salt-lake solution. The properties of the obtained SLS solution were determined using standard X-ray fluorescence spectroscopy, as shown in Table 2. The concentration of sodium chloride (NaCl) in SLS solution was about 28%, while that in the salt of most oceans and seas is about 70%. Based on the abovementioned properties for SLS and the richness and high concentrations of divalent cations such as Mg^{2+} and Ca^{2+}, SLS can be used as a green chemical treatment supplement to replace lime and cement, which may cause the increase of global warming.

2.2. Atterberg Limits. According to the standard *GB/T 50123-2019*, the liquid limit, plastic limit, and plasticity index of modified expansive soil samples were measured by photoelectric liquid and plastic limit combined tester. Expansive soil samples were dried using a 0.5 mm sieve, and then, the water used in Atterberg limits was replaced with 0.1 mol/L, 0.5 mol/L, and 1 mol/L SLS solutions.

2.3. Free Swell Test. The effects of different SLS solution concentrations on the free swelling rate of expansive soil samples were also studied. According to the standard *GB/T 50123-2019*, undisturbed soil was cut and crushed using a 0.5 mm sieve, and 300 g of the as-prepared soil sample was taken and dried to a constant mass at 105~110°C. Three parallel tests were set for each sample. The prepared salt-lake solutions with concentrations of 0.1, 0.5, and 1 mol/L were added to each group of soil samples according to free swelling rate test procedure.

2.4. No Loading Swelling Ratio Test. No loading swelling ratio tests were performed using a WZ-2 dilatometer produced by Nanjing Ningxi Soil Instrument Factory. 61.8 mm × 20 mm standard small ring knife samples with a volume of 60 cm^3 were used for tests. SLS solutions with three concentrations of 0.1, 0.5, and 1 mol/L were prepared, and distilled water was adopted as the control group. The samples were configured based on their natural water content and placed in a moisture cylinder for 72 hours to make SLS solution fully migrate and react with mineral components in the samples. Then, according to test procedure, when the difference between the two dial indicator readings within 6 h was less than 0.01 mm, the expansion deformation of the sample was regarded as stable. Remove the dial indicator, push out the sample from the ring knife, weigh it after cooling, and calculate the water content and void ratio after expansion.

2.5. Triaxial Compression Test. In order to evaluate the effect of SLS solution concentration on the shear strength of expansive soil, the strength parameters and stress-strain curves of soil samples under different influencing factors were drawn by drained and consolidation shear tests. The TSZ series strain-controlled triaxial apparatus produced by Nanjing Ningxi Soil Instrument Factory was applied to

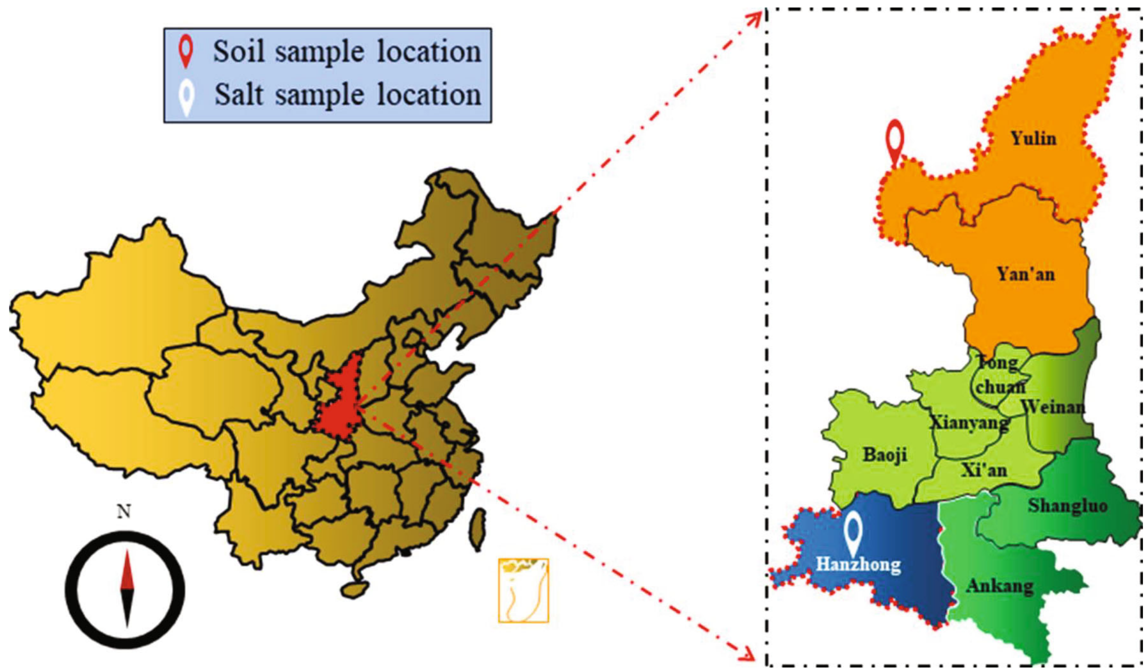


Figure 1: Schematic diagram of expansive soil and SLS sampling.

Table 1: Basic physical indexes of expansive soil samples collected from Hanzhong.

Natural density (g/cm^3)	Natural water content (%)	Liquid limit (%)	Plastic limit (%)	Free swell (%)
1.78	18.7	52	25	65.8

Table 2: Properties of SLS solution used in this research.

Property	Density (g/cm^3)	Water (%)	Solid salt (%)	NaCl (%)	$CaCl_2$ (%)	$MgCl_2$ (%)	KCl (%)
Quantity	1.24	65	35	27.7	12.3	48.8	7.5

perform these tests. The shear strength of expansive soil samples under different salt concentrations and confining pressure were also investigated. The shear strengths of remolded expansive soil samples were measured by triaxial compression shear tests under four confining consolidation pressures (50, 100, 200, and 300 kPa) and four SLS solution concentrations (0, 0.1, 0.5, and 1 mol/L). Then, based on the Mohr-Coulomb failure criterion, corresponding cohesion c and internal friction angle φ were calculated, and stress-strain relationship curve was drawn to evaluate the influence mechanisms of different consolidation confining pressures and SLS solution concentrations on the strength of expansive soil samples collected from Mian County, Hanzhong, southern Shaanxi.

3. Results and Discussion

3.1. Basic Physical Indicators. The test results given in Table 3 showed that SLS solution improved the expansibility

Table 3: Basic physical indexes of expansive soil samples under different concentrations of SLS solution.

Index	Plastic limit (%)	Liquid limit (%)	Plasticity index	Free swell (%)	No loading swelling ratio (24 h)
Concentration					
0 mol/L	25.2	51.6	26.4	65.8	1.48
0.1 mol/L	25.0	50.9	25.9	62.0	1.45
0.5 mol/L	23.0	43.8	20.8	56.2	0.93
1 mol/L	22.3	40.2	17.9	53.4	0.72

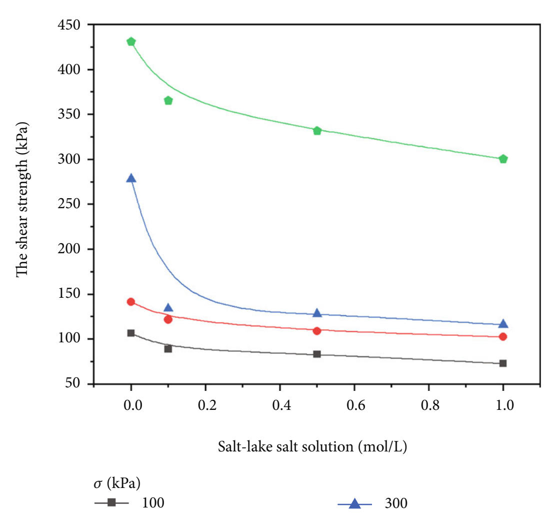


Figure 2: The relationship between shear strength and the concentration of SLS solution.

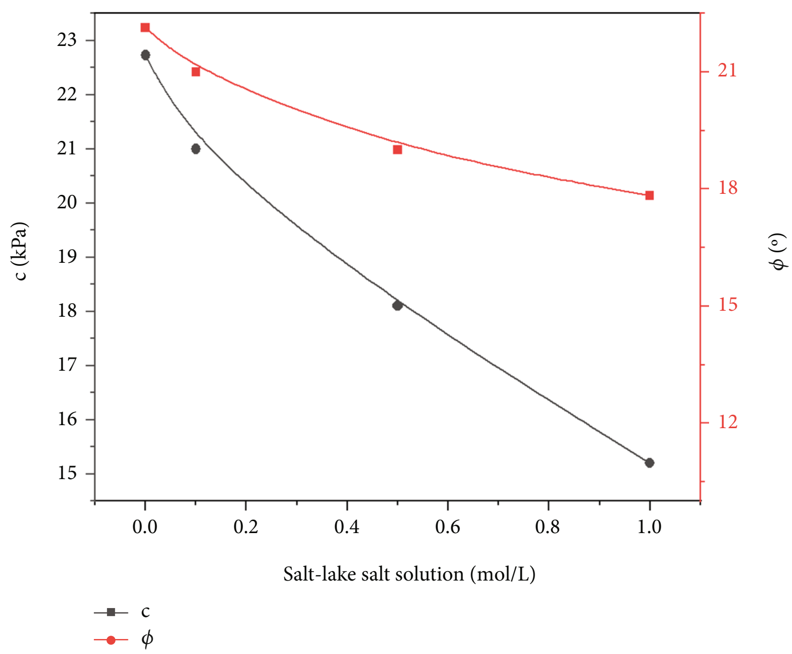


FIGURE 3: The relationship between c, φ, and SLS solution concentration.

of expansive soil samples collected from southern Shaanxi, and the effect of salt solution on inhibiting expansibility was related to solution concentration. Compared with unmodified expansive soil, the liquid limit, plastic limit, and plasticity indexes of modified expansive soil samples presented significant downward trends. Higher salt concentrations resulted in lower liquidity limit, plasticity limit, and plasticity indexes [26]. The liquid limit, plasticity, and plasticity indexes of expansive soil samples modified with 1 mol/L salt solution were decreased by 22.1%, 11.5%, and 32.2%, respectively, which presented the most strong improvement effect. This showed that SLS solution changed the particle size composition of expansive soil, i.e., increased the content of the coarse particle group and decreased water sensitivity, hydrophilicity, and specific surface area of soil. Clay particles tended to flocculate at high salt concentrations [27]. Flocculation could cause decreased specific surface area, free swell, and swell pressure [28]. As the concentration of SLS was increased, cationic concentration and combination value were increased; therefore, the gravity between particles was increased, repulsive force and double electric layer thickness were decreased, and soil particles flocculated, leading to the decrease of the liquid limit of expansive soil. After soil was flocculated, original particle gradation was changed. Particles with relatively dispersed and small sizes became concentrated and larger, and the content of coarse particles was relatively increased, decreasing plasticity index.

Due to different concentrations of SLS solutions, the free expansion rate of remolded expansive soil was decreased. When solution concentration was between 0.1 and 0.5 mol/L, expansion rate was decreased the fastest. The expansion type of expansive soil was also reduced from medium to weak expansive soil with the increase of SLS solution. Electrostatic repulsions among montmorillonite crystals in bentonite were weakened by infiltrated salt solution and the diffused double layer of bentonite became thinner [29]. It was concluded that the surface of expansive soil particles gradually formed uniform electric double layer structure under by the addition of SLS solution and electric double layer thickness was negatively correlated with ion concentration. Therefore, by the increase of the concentration of SLS solution, diffusion double layer thickness was decreased and the spacing between soil particles was gradually decreased, which inhibited the expansion of expansive soil.

With the increase of SLS solution concentration, the unloaded swelling rate of remolded expansive soil samples was significantly decreased. According to the change trend, it was seen that expansive soil could reach stable state more quickly under at high concentrations of SLS solution.

3.2. Shear Strength. Figure 2 shows the relationship between expansive soil shear strength and SLS solution concentration. Under the same confining pressure, higher concentrations of SLS solution resulted in lower shear strengths. Particle surface electrification created complex effects in clay particles at microlevel. When the physical and chemical environments of pore solution changed, due to the interaction of particles and pore solution, the particle arrangement, structural characteristics, and pore water occurrence state of soil were changed, thus changing its macro physical and mechanical properties. At clay particle scale, diffused double layer dictated the hydraulic and mechanical behaviors of clay [27]. Variation of pore solution environment in soil disturbed the original balance of soil particles at microscopic scale but changed soil strength at macroscopic scale.

When pore solution changed from distilled water to SLS solution, massive and granular structures appeared in expansive soil and the soil sample acquired loose flocculation structure. With the increase of the concentration of salt solution, the net gravity between particles was increased and

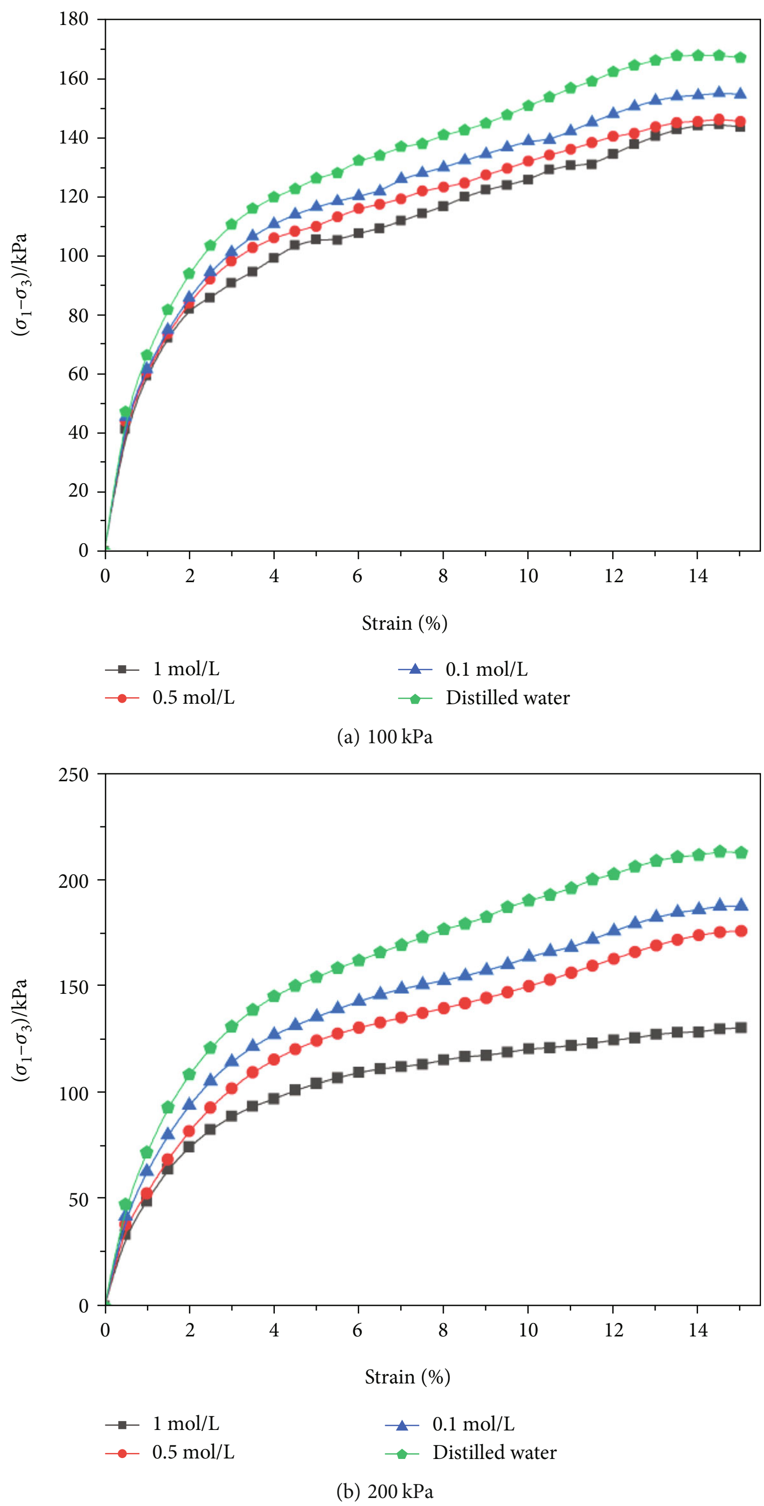
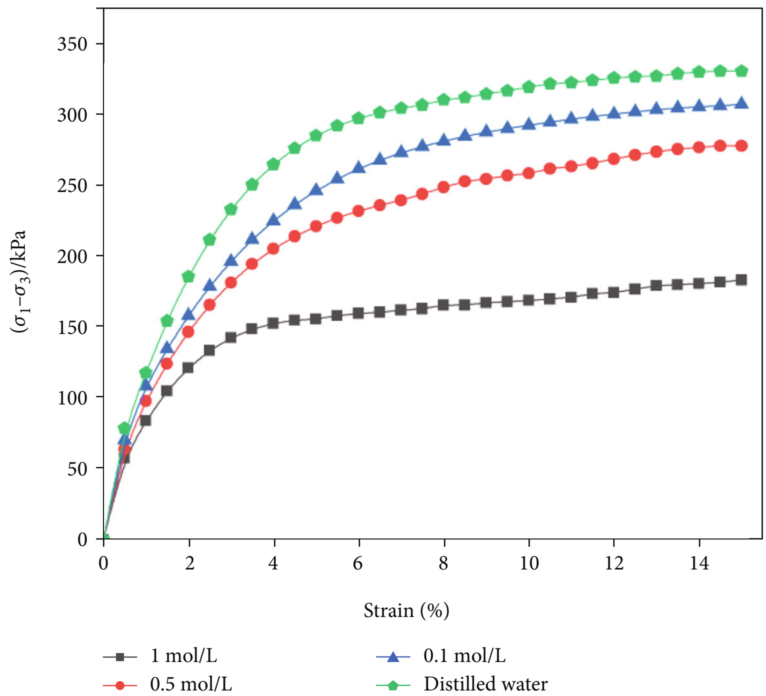
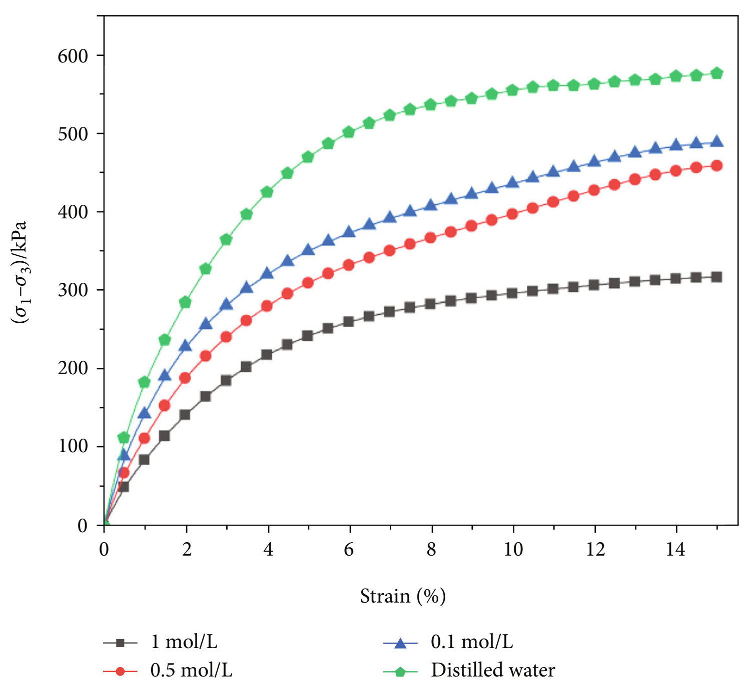


Figure 4: Continued.



(c) 300 kPa



(d) 400 kPa

Figure 4: Stress-strain relationship curves of expansive soil due to different SLS solution concentrations.

flake particles attracted each other, resulting in flocculation. Flocculation structure had large pores which were increased with the increase of gravity. Therefore, by increasing the concentration of SLS solution, more pore channels were generated between flocculating structures, thus reducing shear strength.

It is obvious from Figure 3 that the cohesion and internal friction angle of expansive soil were decreased by increasing SLS solution concentration, but the downward trend of internal friction angle was weaker than that of cohesion, indicating that SLS solution concentration had a great influence on expansive soil cohesion. This could be explained through DDL concept. Many chemical solutions tend to reduce DDL thickness, reducing repulsive forces among particles and forming a flocculated soil fabric [30]. By adding SLS solution, ion exchange processes increased attractive forces and reduced DDL thickness. Therefore, a structure was formed for the soil. By increasing SLS solution concentration, double electric layer thickness, net repulsion of expansive soil particles, effective contact surface between particles, and the ability to hinder displacement between particles were decreased. At the same time, SLS solution reacted with minerals in the soil, cementing material content was decreased, water film thickness was increased, the attraction of electric molecules was weakened, and mutual embedding and mechanical occlusion between expansive soil particles were reduced, Therefore, the cohesion and internal friction angle of expansive soil were decreased with the increase of SLS solution concentration.

3.3. Stress-Strain Relationship. According to the test requirements of similar sample moisture content and confining pressure, variations of stress-strain relationship curves of remolded expansive soil sample due to SLS solution at concentrations of 0.1, 0.5, and 1 mol/L are shown in Figure 4.

According to Figure 4, by increasing SLS solution concentration, corresponding principal stress difference was gradually decreased when the axial strain of expansive soil sample reached 15%, and stress-strain relationship curve of remodeled expansive soil sample showed a softening trend. This change law more comprehensively illustrated that when the concentration of SLS solution was increased, the number of cations in pore solution among soil particles was increased, which balanced negative charge on particle surface and reduced repulsion among soil particles. On the other hand, according to electron double layer adsorption theory, electron double layer thickness between soil particles was decreased with the increase of SLS solution concentration. Therefore, principal stress difference from stress-strain curve to failure standard was decreased with the increase of SLS solution concentration.

4. Conclusions

In order to explore the influence of SLS solution concentration on the strength characteristics of expansive soil, Atterberg limits, free swell, no loading swelling ratio, and triaxial compression tests were carried out on expansive soil samples with different concentrations (0.1, 0.5, and 1.0 mol/L). The results showed that

(1) SLS solution had obvious inhibitory effect on the swelling of expansive soil and different concentrations of salt-lake solution had different inhibitory effects

(2) expansive index tests were carried out on expansive soil by using SLS solutions. The results showed that when SLS solution concentration was 1 mol/L, its improvement effect was the most obvious, and liquid limit, plastic limit, and plastic indexes were decreased by 22.1%, 11.5%, and 32.2%, respectively. The free expansion rates of modified expansive soil samples were decreased by 12.4% compared with those of unmodified expansive soil. The change trend of no loading swelling rate was also gradually decreased by SLS solution

(3) Cohesion and internal friction angle were decreased with the increase of SLS solution concentration, showing a good linear relationship, of which the influence on internal friction angle was smaller. According to the change rule of cohesive force and internal friction angle of expansive soil, shear strength was negatively correlated with SLS solution concentration. With the increase of SLS solution concentration, the stress-strain relationship curve of expansive soil gradually showed strain softening

Research results verified the inhibitory effect of SLS solution on the shrinkage deformation of expansive soil. However, the microstructure mechanism of expansive soil samples modified with SLS solution and its long-term effects need to be further studied. This will be the focus of my next research work. The article will serve to civil and geotechnical engineers.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

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References

[1] F. E. Jalal, Y. Xu, B. Jamhiri, and S. A. Memon, "On the recent trends in expansive soil stabilization using calcium-based stabilizer materials (CSMs): a comprehensive review," *Advances in Materials Science and Engineering*, vol. 2020, Article ID 1510969, 23 pages, 2020.

[2] B. X. Shi, C. F. Zheng, and J. K. Wu, "Research progress on expansive soil cracks under changing environment," *The Scientific World Journal*, vol. 2014, Article ID 816759, 2014.

[3] G. M. Kamel, G. Idriss, and B. Benchaa, "Effet de chaux, ciment et sel sur le potentiel de gonflement des argiles gonflantes des régions arides en Algérie," *European Journal of Environmental and Civil Engineering*, vol. 17, no. 5, pp. 315–328, 2013.

[4] C. C. Ikeagwuani and D. C. Nwonu, "Emerging trends in expansive soil stabilisation: a review," *Journal of Rock Mechanics and Geotechnical Engineering*, vol. 11, no. 2, pp. 423–440, 2019.

[5] M. Al-Mukhtar, A. Lasledj, and J.-F. Alcover, "Behaviour and mineralogy changes in lime-treated expansive soil at 20 °C," *Applied Clay Science*, vol. 50, no. 2, pp. 191–198, 2010.

[6] Y. Xue, J. Liu, P. G. Ranjith, Z. Zhang, F. Gao, and S. Wang, "Experimental investigation on the nonlinear characteristics of energy evolution and failure characteristics of coal under different gas pressures," *Bulletin of Engineering Geology and the Environment*, vol. 81, no. 1, article 38, 2022.

[7] S. A. Bourokba Mrabent, A. Hachichi, H. Souli, S. Taibi, and J. M. Fleureau, "Effect of lime on some physical parameters of a natural expansive clay from Algeria," *European Journal of Environmental and Civil Engineering*, vol. 21, no. 1, pp. 108–125, 2017.

[8] A. R. Goodarzi, H. R. Akbari, and M. Salimi, "Enhanced stabilization of highly expansive clays by mixing cement and silica fume," *Applied Clay Science*, vol. 132, pp. 675–684, 2016.

[9] J. Liu, Y. Xue, Q. Zhang, H. Wang, and S. Wang, "Coupled thermo-hydro-mechanical modelling for geothermal doublet system with 3D fractal fracture," *Applied Thermal Engineering*, vol. 200, article 117716, 2022.

[10] M. Al-Mukhtar, S. Khattab, and J.-F. Alcover, "Microstructure and geotechnical properties of lime-treated expansive clayey soil," *Engineering Geology*, vol. 139, pp. 17–27, 2012.

[11] Y. Xue, J. Liu, X. Liang, S. Wang, and Z. Ma, "Ecological risk assessment of soil and water loss by thermal enhanced methane recovery: Numerical study using two-phase flow simulation," *Journal of Cleaner Production*, vol. 334, article 130183, 2022.

[12] A. K. Sharma and P. V. Sivapullaiah, "Ground granulated blast furnace slag amended fly ash as an expansive soil stabilizer," *Soils and Foundations*, vol. 56, no. 2, pp. 205–212, 2016.

[13] S. Sudhakar, E. Duraisekaran, G. Dilli Vignesh, and G. D. Kanna, "Performance evaluation of quarry dust treated expansive clay for road foundations," *Iranian Journal of Science and Technology, Transactions of Civil Engineering*, vol. 45, no. 4, pp. 2637–2649, 2021.

[14] Y. Shang and Y. Fu, "Experimental study of the mechanical properties of expansive soil with added nanomaterials," *Arabian Journal of Geosciences*, vol. 11, no. 8, 2018.

[15] S.-G. Lu, F.-F. Sun, and Y.-T. Zong, "Effect of rice husk biochar and coal fly ash on some physical properties of expansive clayey soil (Vertisol)," *Catena*, vol. 114, pp. 37–44, 2014.

[16] J. Pooni, F. Giustozzi, D. Robert, S. Setunge, and B. O'Donnell, "Durability of enzyme stabilized expansive soil in road pavements subjected to moisture degradation," *Transportation Geotechnics*, vol. 21, article 100255, 2019.

[17] Y.-X. Wang, P.-P. Guo, W.-X. Ren et al., "Laboratory investigation on strength characteristics of expansive soil treated with jute fiber reinforcement," *International Journal of Geomechanics*, vol. 17, no. 11, 2017.

[18] G. Wang, Y. Huang, R. Li, J. Chang, and J. Fu, "Influence of vetiver root system on mechanical performance of expansive soil: experimental studies," *Advances in Civil Engineering*, vol. 2020, Article ID 2027172, 11 pages, 2020.

[19] W. S. Abdullah and A. M. Al-Abadi, "Cationic-electrokinetic improvement of an expansive soil," *Applied Clay Science*, vol. 47, no. 3-4, pp. 343–350, 2010.

[20] N. Latifi, A. S. A. Rashid, S. Siddiqua, and S. Horpibulsuk, "Micro-structural analysis of strength development in low- and high swelling clays stabilized with magnesium chloride solution – a green soil stabilizer," *Applied Clay Science*, vol. 118, pp. 195–206, 2015.

[21] P. Hou, Y. Xue, F. Gao et al., "Effect of liquid nitrogen cooling on mechanical characteristics and fracture morphology of layer coal under Brazilian splitting test," *International Journal of Rock Mechanics and Mining Sciences*, vol. 151, article 105026, 2022.

[22] T. E. Helle, S. Nordal, and P. Aagaard, "Improved geotechnical properties in salt-treated highly sensitive landslide-prone clays," *Proceedings of the Institution of Civil Engineers - Geotechnical Engineering*, vol. 171, no. 3, pp. 232–242, 2018.

[23] L. Liu, Z. Li, X. Liu, and Y. Li, "Effect of salt content on freezing temperature and unconfined compression strength of lime-treated subgrade clay," *Applied Clay Science*, vol. 158, pp. 65–71, 2018.

[24] Z. Li, C. Tang, R. Hu, and Y. Zhou, "Experimental research on expansion characteristics of Mengzi expansive soil with water, salt and acid immersion," *Environmental Earth Sciences*, vol. 72, no. 2, pp. 363–371, 2014.

[25] O. Al Hattamleh, H. Aldeeky, S. Rabab'ah, and M. Taamneh, "The effect of Dead Sea salt solution on the engineering properties of expansive subgrade clayey soil," *Arabian Journal of Geosciences*, vol. 13, no. 11, 2020.

[26] A. Smaida, B. Mekerta, and M. K. Gueddouda, "Physico-mechanical stabilization of a high swelling clay," *Construction and Building Materials*, vol. 289, article 123197, 2021.

[27] T. Y. Elkady and A. M. Al-Mahbashi, "Effect of solute concentration on the volume change and shear strength of compacted natural expansive clay," *Environmental Earth Sciences*, vol. 76, no. 483, pp. 1–13, 2017.

[28] I. Yilmaz and M. Marschalko, "The effect of different types of water on the swelling behaviour of expansive clays," *Bulletin of Engineering Geology and the Environment*, vol. 73, no. 4, pp. 1049–1062, 2014.

[29] Y. He, W. M. Ye, Y. G. Chen, K. N. Zhang, and D. Y. Wu, "Effects of NaCl solution on the swelling and shrinkage behavior of compacted bentonite under one-dimensional conditions," *Bulletin of Engineering Geology and the Environment*, vol. 79, no. 1, pp. 399–410, 2020.

[30] A. R. Estabragh, A. Soltani, and A. A. Javadi, "Effect of pore water chemistry on the behaviour of a kaolin–bentonite mixture during drying and wetting cycles," *European Journal of Environmental and Civil Engineering*, vol. 24, no. 7, pp. 895–914, 2020.