Failure Characteristics and Mechanisms of Loess Structure Under Salt Weathering: Postprint

Authors: Duan Zhao, Li Ruiyi, Song Kun, Yan Xusheng, Zheng Licai, He Ziguang

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Abstract

This study investigates the damage characteristics of loess structure and the deterioration effects of loess strength under salt weathering (unidirectional moisture removal conditions), providing a reference basis for soil and water conservation and disaster prevention in the Loess Plateau region. Q2 loess from Fugu County, Shaanxi Province was selected, and macro- and micro-scale observations and shear strength tests were conducted under different sodium sulfate contents. The results show that: (1) At the macro scale, increasing salt content significantly exacerbates the apparent damage degree and swelling displacement of the specimens. Specimens with 1.0%~2.5% salt content all exhibited contour scaling damage characteristics, gradually transitioning from uneven surface crusting to large-area salt spots and swelling cracks, but no salt swelling, salt spots, or crusting phenomena were observed in specimens with lower salt content of 0.5%. Moreover, the entire salt weathering process experienced three stages: initial stage, growth stage, and stable stage. (2) At the micro scale, salt weathering caused an increase in aggregates and pores in the loess; additionally, the presence of sodium sulfate decahydrate crystals was clearly observed, which is a direct product of the salt weathering process. (3) After undergoing salt weathering, the shear characteristics of specimens transformed from strain-softening type to strain-hardening type, and salt weathering can significantly deteriorate the peak strength of specimens, causing a noticeable reduction in cohesion. With increasing sodium sulfate content, salt weathering intensifies the occurrence of "crystalline swelling" and "dry aggregation" in the loess, forming numerous swelling cracks and pores on its surface and interior, ultimately causing significant damage to loess structure and strength.

Damage Characteristics and Mechanisms of Loess Structures Under Salt Weathering

DUAN Zhao[1], LI Ruiyi[1], SONG Kun[1], YAN Xusheng[2], ZHENG Licai[3], HE Ziguang[4]

[1]College of Geology and Environment, Xi' an University of Science and Technology, Xi' an, Shaanxi, China
[2]Key Laboratory of Geotechnical and Underground Engineering of Ministry of Education, Tongji University, Shanghai, China
[3]Sanying Precision Instruments Co., Ltd, Tianjin, China
[4]College of Architecture and Civil Engineering, Huanghuai University, Zhumadian, Henan, China

Abstract

This study investigates the damage characteristics of loess structures and the deterioration of loess strength under salt weathering, with a focus on unidirectional dehumidification conditions. The findings provide valuable references for soil and water conservation, as well as disaster prevention strategies in the Loess Plateau. Q2 loess from Fugu County, Shaanxi Province, China was selected for macro- and micro-scale observations and shear strength tests under varying sodium sulfate contents. The results indicate the following: (1) Macroscopic effects: An increase in salt content significantly impacts the apparent damage degree and expansion displacement of the samples. Samples with salt contents ranging from 1.0% to 2.5% exhibited contour scaling damage characteristics, transitioning from uneven surface crusts to extensive salt spots and expansion cracks. In contrast, samples with a lower salt content of 0.5% did not show salt swelling, salt spots, or crust formation. The salt weathering process progresses through three stages: germination, growth, and stability. (2) Microscopic effects: Salt weathering leads to the formation of agglomerates and expansive pores within loess. Sodium sulfate decahydrate crystals were observed as a direct result of the salt weathering process. (3) Shear characteristics: The shear behavior of the samples transitioned from strain softening to strain hardening after salt weathering, with significant degradation in peak strength and reduced cohesion. As sodium sulfate content increased, salt weathering intensified the effects of "salt crystallization-induced expansion" and "soil drying-induced coagulation" in loess. This process generated numerous expansion cracks and pores both on the surface and within the loess, ultimately causing severe structural and strength deterioration.

Key words: loess; sodium sulfate; salt weathering; shear strength; damage

1. Introduction

Under the unique continental monsoon climate of the Loess Plateau and the inherent characteristics of loess itself, salt weathering phenomena are widespread. Large amounts of soluble salts migrate to the surface through capillary action and accumulate there. Sodium sulfate is recognized as one of the most severe types of soluble salts for rock and soil material weathering. When sodium sulfate evaporates and crystallizes (at temperatures between 24.00~32.38 ℃), it combines with 10 water molecules to form sodium sulfate decahydrate, expanding to 3.1 times its original volume. This expansion undoubtedly causes severe damage to loess structures and triggers engineering diseases, exacerbating geological disaster formation. The crystallization pressure generated far exceeds the tensile strength of loess, reaching up to 12.57 MPa.

Loess, as a Quaternary loose sediment, features large pores, weak cementation, and well-developed vertical joints, providing important conditions for salt weathering occurrence. When environmental humidity, temperature, and salt solution concentration and type change, soluble salts accumulate and crystallize in loess, causing structural and strength damage. During wet-dry cycles, soluble salts repeatedly undergo crystallization-dissolution-recrystallization, significantly intensifying loess strength deterioration. Under freeze-thaw cycles, soluble salts cause loess to undergo salt expansion deformation due to temperature drop crystallization, and dissolution deformation upon warming. This causes surface salt content to rise sharply, promoting the salt weathering process.

Research shows that soluble salts significantly damage loess structures in China' s Loess Plateau region, representing an important factor contributing to soil erosion and frequent geological disasters. The loess slopes in Fugu County, Shaanxi Province, are frequently affected by salt weathering, with frequent landslides and collapses attracting widespread attention. This study selects Q2 loess from Fugu County, Shaanxi Province as the research object, conducting macro- and micro-scale observation tests and direct shear tests with sodium sulfate content as the variable to clarify the damage characteristics and mechanisms of loess structures under salt weathering, providing theoretical references for soil degradation research and new ideas for geological disaster prevention and control in loess areas.

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2. Experimental Materials and Methods

2.1 Test Materials

The Q2 loess samples used in this test were taken from the slopes on both sides of the Xingwangzhuang landslide in Fugu County, Shaanxi Province, at a depth of 1.5 m from the slope surface. Particle size distribution and conventional property tests showed the loess is low liquid limit clay (CL), composed of approximately 4.53% sand particles, 85.43% silt particles, and 10.04% clay particles. Specific results are shown in and [Figure 1: see original paper].

Before testing, to eliminate the influence of original salts in Fugu Q2 loess on test results, a water washing method was used for desalination pretreatment. The loess was crushed and immersed in deionized water for 24 hours, repeatedly washed until the filtrate conductivity was less than 0.001 $S \cdot m^{-1}$, then separated. The desalinated loess was considered completely desalinated. The desalinated loess was then oven-dried, crushed with a rubber hammer, passed through a 2 mm sieve, and finally sealed and stored at room temperature. The reagent used was anhydrous sodium sulfate analytical pure, with distilled water as the solvent. Salt content was calculated as the ratio of salt to dry soil mass, with water content as the test variable. Remolded loess was used for salt weathering observation tests and direct shear tests. The test environment temperature was maintained at 26$±$1 ℃.

2.2 Test Methods

2.2.1 Loess Structure Observation Tests To reduce the influence of water-salt migration on sample structure and strength, a lower target water content (10.0%~9.5%) was set for loess samples, with salt content ranging from 0.5% to 2.5%. Based on target values, 5 groups of sodium sulfate solutions with different concentrations were prepared. After oven-drying the loess, it was mixed with the 5 groups of sodium sulfate solutions, sealed and left to stand for 24 hours. Samples were prepared using the three-layer static pressure method to create 70 mm × 140 mm samples, controlling the sample void ratio at 0.85. After sample preparation, speckle patterns were quickly sprayed onto the samples, which were then placed on a balance for natural dehydration until water content dropped to 7.8% before observation tests were stopped. A camera continuously photographed the entire test process, recording macrostructural characteristics of samples at various times as water content changed.

After the macroscopic observation test ended, a small sample was cut from the central region of samples with 2.5% salt content. After vacuum freeze-drying, epoxy resin solution was slowly dripped onto the sample surface. Negative pressure was applied with a pipette to allow the epoxy resin solution to uniformly penetrate the soil body. After the soil sample completely solidified, it was pushed out. The sample was coarse-ground with sandpaper and diamond sand solution, then fine-polished on a polishing cloth with polishing solution until a thin section approximately 20 m thick was produced. After platinum plating the sample surface, final SEM samples were obtained. A field emission scanning electron microscope (JSM-7610F, JEOL Ltd., Japan) was used to observe sample microstructural characteristics at 1.3 nm resolution, comparing microstructural images at 2.5% salt content with salt-free samples.

2.2.2 Loess Strength Direct Shear Tests After the macroscopic observation test ended, a ring knife (Φ 61.8$×20*mm*)*wasusedtosampletheexactmiddleofthesamples*, *cutting*3*samples*
1}$.

3. Results

3.1 Macroscopic Damage Characteristics

As shown in [Figure 2: see original paper], with increasing salt content, the damage degree of loess under salt weathering gradually intensified. When water content decreased to 9.5%, the 0.5% salt content sample showed longitudinal cracks; when water content decreased to 8.5%, the 1.0% salt content sample locally showed slight swelling; the 1.5%~2.5% salt content samples all exhibited significant salt spots, swelling, and slight pulverization. The 1.0% salt content sample surface began crusting, the 1.5% salt content sample surface showed large-area salt spots and fine cracks, the 2.0% salt content sample showed zigzag expansion cracks, and the 2.5% salt content sample surface cracks gradually opened; when water content decreased to 7.8%, the 0.5% salt content sample still showed no obvious salt spots or swelling, while the deformation and damage degree of other salt content samples further intensified, with cracks gradually developing into the sample interior.

Under salt weathering, samples showed obvious expansion characteristics. The maximum distance of sample expansion to both sides was defined as expansion displacement. The obtained speckle image data was binarized and normalized, with the sample axis as the origin. The actual expansion displacement of the sample was 2 times the maximum horizontal displacement of the speckle. As water content decreased, expansion displacement showed staged characteristics ([Figure 3: see original paper]), roughly divisible into three stages: germination (water content from 10.0% to 9.5%), growth (9.5% to 8.5%), and stability (8.5% to 7.8%). Expansion displacement was smaller during germination and stability stages, and larger during the growth stage. The expansion displacements corresponding to 1.0%, 1.5%, 2.0%, and 2.5% salt content samples were 9.8 mm, 14.6 mm, 22 mm, and 6.0 mm respectively.

3.2 Microstructural Characteristics

To reveal the influence of salt weathering on soil microstructure, the central region of samples with 0%, 1.0%, 1.5%, 2.0%, and 2.5% salt content after salt weathering was selected for microstructural observation. As shown in [Figure 4: see original paper], with increasing salt content, the contact patterns between soil particles and pore structure changed significantly. At 0% salt content, soil particles mostly showed edge-to-edge contact with cementation bonding, and pores were small ([Figure 4a: see original paper]). At 1.0% salt content, pores were clearly larger with increased particle spacing ([Figure 4b: see original paper]). At 1.5% salt content, pore volume further increased, with clay particles aggregating and filling around silt and sand particles ([Figure 4c: see original paper]). At 2.0% salt content, expansion pores began to appear, increasing in number and volume, while numerous sodium sulfate decahydrate crystals distributed inside pores, with most particle contacts showing point-to-point contact ([Figure 4d: see original paper]). At 2.5% salt content, expansion pores further increased in number and volume, with sodium sulfate decahydrate crystals filling most pores, and particle contacts primarily showing point-to-point contact ([Figure 4e: see original paper]).

3.3 Mechanical Strength Characteristics

The shear strength of samples is shown in [Figure 5: see original paper] and [Figure 6: see original paper]. Salt weathering significantly reduced sample shear strength, with higher salt content causing more significant reduction. Taking the 100 kPa normal pressure as an example, the shear strengths of salt-free samples and samples with 0.5%, 1.0%, 1.5%, 2.0%, and 2.5% salt content were 87.03 kPa, 103.74 kPa, 92.00 kPa, 88.15 kPa, 82.87 kPa, and 75.9 kPa respectively. [Figure 5: see original paper] shows direct shear results for samples after salt weathering at 16% (undried) and 7.8% (after dehydration) water content under 100 kPa normal pressure. With increasing normal pressure and salt content, stress-strain curves gradually transitioned from strain softening to strain hardening. The 0.5% salt content sample had the highest peak strength at all normal pressures, requiring the smallest shear displacement to reach peak strength, showing significant strain softening. As sodium sulfate content increased, peak strength gradually decreased, and the shear displacement required to reach peak strength increased, with strain softening gradually weakening. However, increased sodium sulfate content did not significantly affect residual strength.

As shown in [Figure 6: see original paper], with increasing sodium sulfate content, both sample cohesion and internal friction angle decreased. The cohesions corresponding to 0.5%, 1.0%, 1.5%, 2.0%, and 2.5% salt content samples were 56.18 kPa, 53.22 kPa, 49.51 kPa, 42.26 kPa, and 39.92 kPa respectively, with internal friction angles of 24.39°, 21.79°, 21.47°, 22.58°, and 21.47° respectively. The 2.5% salt content sample showed cohesion decreasing by approximately 26.4% and internal friction angle decreasing by approximately 19.7% compared to the 0.5% salt content sample. Additionally, the cohesion and internal friction angle of salt-free samples at 16% water content (undried) were 43.62 kPa and 24.09° respectively.

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4. Discussion

4.1 Salt Weathering Stages and Characteristics

Soluble salts typically cause two types of weathering on rock and soil: contour scaling and powder disintegration. In this study, with salt content of 1.0%~2.5%, samples only showed varying degrees of crusting and slight powderization on the surface and near-surface, exhibiting contour scaling characteristics. The

0.5% salt content sample experienced the weakest salt weathering, showing no crusting or powderization.

Salt weathering experienced three stages during sample evaporation and dehydration: germination, growth, and stability. Throughout the process, sodium sulfate solution existed in the soil in the form of capillary water and gradually transformed into gaseous water through evaporation, causing solution concentration to gradually increase and eventually crystallize to form sodium sulfate decahydrate, resulting in sample structural damage.

During the germination stage (water content: 10.0%~9.5%), the sample surface was most strongly affected by evaporation, reaching supersaturation first. This caused sodium sulfate decahydrate crystals to appear first on the surface, with the sample surface beginning to crust. During the growth stage (water content: 9.5%~8.5%), crystals began migrating into the soil interior, growing outward layer by layer with capillary action. When insufficient meniscus force existed between soil particles to provide solution for crystal development, capillary action weakened and crystal growth stopped. Due to strong crystallization of sodium sulfate decahydrate during this stage, sample expansion displacement was maximum, forming a series of expansion cracks on the surface ([Figure 2: see original paper]). During the stability stage (water content: 8.5%~7.8%), this was the late stage of crystallization growth. Capillary action brought deeper soil moisture to the surface, where remaining solution slowly evaporated. The expansion caused by sodium sulfate decahydrate crystallization during this stage further expanded surface cracks.

4.2 Strength Deterioration Effects

Under salt weathering, increasing salt content significantly reduced sample peak strength but had little deterioration effect on residual strength. This occurred because salt crystals primarily destroyed cementation between soil particles. Additionally, salt crystal strength is far lower than minerals in loess, causing the residual strength reduction after shear failure to be less significant than the peak strength reduction. In fact, during salt weathering, the shear strength of salt-free samples gradually recovered as water content decreased. However, for salt-containing samples, salt weathering caused damage far exceeding the recovery portion from dehydration drying in salt-free samples, and this effect gradually intensified with increasing salt content, ultimately leading to complete strength loss.

In addition to salt crystals destroying cementation between soil particles and generating numerous expansion pores within samples ([Figure 4: see original paper]), soil particles experienced "drying-induced coagulation" during salt weathering ([Figure 4: see original paper]), causing pores to further increase. This directly led to reduced sample cohesion. For internal friction angle, loess water content and particle morphology play important roles. Research shows sodium sulfate does not significantly affect particle morphology, and the low water content in this study’ s samples (7.8%) meant water lubrication was lacking during shearing. The combined effect of these factors resulted in minimal internal friction angle reduction under salt weathering.

4.3 Damage Mechanisms

In this test, the dual action of “crystallization expansion” and “drying-induced coagulation” was the primary cause of loess structural damage.

On one hand, during loess evaporation, nanometer-scale liquid films between salt and pore walls control crystallization pressure generation and stress release. The upper limit of separation pressure between liquid films is called crystallization pressure. Once crystallization pressure generates, salt crystals break through liquid films and contact pore walls. However, as breakthrough distance increases, liquid films are gradually consumed and crystal growth stops. Typically, salt crystallization pressure far exceeds loess tensile strength, especially sodium sulfate decahydrate crystallization pressure, which directly weakens cementation between soil particles, increases particle spacing, causes cementation damage and failure, and forms expansion pores within loess. Therefore, combined with microscopic characteristics of loess under evaporation conditions in this test, crystallization pressure-induced expansion is considered an important cause of loess structural damage.

On the other hand, clay particles generally exhibit negative charge. During loess evaporation and dehydration, increased sodium ion concentration in pore solution repels counter-ions in the diffusion layer, forcing them into the fixed layer. Simultaneously, some water molecules in the diffusion layer escape into bulk water, causing the diffusion layer to thin, increasing loess matrix suction. During this process, sodium sulfate destroys cementation between soil particles and generates numerous expansion pores within samples. Additionally, “drying-induced coagulation”causes some fine silt and clay particles to attract each other, forming aggregates. This phenomenon was observed in SEM tests ([Figure 4: see original paper]).

Furthermore, salt solution viscosity significantly affects loess structure. Increased viscosity notably influences salt solution flow and evaporation dynamics in loess, promoting “crystallization expansion”and “drying-induced coagulation” . Typically, loess salt solution viscosity is proportional to salt content. In this test, capillary flow velocity was higher in low salt content samples. In evaporation environments, salt solution migration from loess interior to surface was faster than salt evaporation crystallization speed, so the “evaporation front” was near the loess surface. Conversely, in high salt content samples, internal salt solution capillary flow velocity was slower, and crystallization occurred faster than migration, so the “evaporation front”gradually penetrated deeper into loess, causing deep cracking from crystallization pressure and gradual development of internal crystals and pores.

In summary, the dual action of “crystallization expansion” and “drying-induced coagulation” promotes pore volume expansion and increased quantity in loess, with increased salt content intensifying this effect, thereby damaging loess structure and strength. The damage mechanism of loess structure under salt weathering is shown in [Figure 7: see original paper].

4.4 Comparison with Freeze-Thaw

Due to climate change and land use, salt weathering is widespread in loess areas. Sodium sulfate in soil accumulates on slope surfaces (unsaturated zone) through long-term water-salt migration. Under evaporation, salt solution loses water to reach saturation, sodium sulfate decahydrate crystallizes and precipitates, expanding to 3.1 times its original volume. If water loss continues, sodium sulfate decahydrate crystals transform into anhydrous sodium sulfate, shrinking in volume. During this process, sodium sulfate destroys cementation between soil particles and generates numerous expansion pores within samples. Combined with “drying-induced coagulation”, some fine silt and clay particles attract each other, forming aggregates, and internal pores further expand, causing severe surface loess structure deterioration. This effect occurs repeatedly during summer and autumn with temperature and humidity variations.

In contrast, freeze-thaw damage to slope loess mainly occurs at the saturated zone at slope toes. In short periods (few cycles), freezing also causes soil volume expansion from frost heave, but structural damage from freezing is far less severe than salt weathering. When soil freezes at low temperature, solid ice firmly cements soil particles together, strengthening mechanical properties. Loess structure and strength deterioration occurs mainly during warming when soil undergoes structural remodeling from thaw settlement under self-weight and external loads. This effect primarily occurs in winter and spring. Thus, salt weathering and freeze-thaw action differ significantly in their location on loess slopes, short-term intensity, and seasonal occurrence.

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5. Conclusions

(1) During salt weathering, sample surface and internal structures are damaged by salt crystallization expansion, generating expansion cracks and pores. Samples with 1.0%~2.5% salt content showed contour scaling and slight powderization damage characteristics, while 0.5% salt content samples showed no damage.

(2) Sample expansion displacement shows three stages with decreasing water content: germination, growth, and stability, with maximum expansion displacement during the growth stage.

(3) Salt weathering causes strain hardening phenomena in samples, significantly deteriorating shear strength and cohesion.

(4) Under salt weathering, samples undergo "salt crystallization expansion" and "drying-induced coagulation", with increased salt content significantly intensifying structural and strength damage.

This study aims to reveal loess damage characteristics caused by single sodium sulfate salt crystallization under continuous evaporation. However, in natural environments, soil contains various soluble salts and chemical substances from atmospheric, rainwater, groundwater, and chemical waste pollution. Their effects on soil are profound and complex, involving agricultural production, earthen heritage protection, and geotechnical engineering, becoming a key scientific issue for researchers. This study' s results can contribute valuable insights for future research and prevention of sodium sulfate salt damage.

References

[1] Lü Hongbo, Su Qingguo, Wu Xuyang, et al. Landform features of salt weathering in different climatic zones in China[J]. Geological Review, 2017, 63(4): 911-926.

[2] Ren Kefa, Xie Zhenbin, Wang Ling, et al. Salt weathering mechanism and climate response in Niujiaozhai Grottoes, Renshou, Sichuan[J]. Geological Review, 2023, 69(4): 1368-1386.

[3] Zhou Fengxi, Ran Yue, Wan Xusheng, et al. Water-salt phase transition of saline soils during evaporation[J]. Chinese Journal of Geotechnical Engineering, 2024, 46(5): 1030-1038.

[4] Guo Min, Li Xinhu, Wang Hongchao, et al. Effect of salt crust thickness on distribution characteristics of soil water and salt[J]. Arid Land Geography, 2023, 46(8): 1303-1313.

[5] Jin Zhiliang, Chen Gangquan, Xia Yin, et al. Sodium sulfate behind earthen relics salt damages: From micro to macro[J]. Sciences of Conservation and Archaeology, 2016, 28(1): 54-62.

[6] Liu Yanhui. A study on expansion characteristics of carbonate saline soil[J]. Bulletin of Soil and Water Conservation, 2012, 32(1): 119-121.

[7] Xu Jian, Zheng Xiang, Wang Zhangquan. Investigation for water and salt migrations on spalling disease of loess slope caused by salification erosion[J]. Journal of Engineering Geology, 2018, 26(3): 741-748.

[8] Duan Z, Cheng W C, Peng J B, et al. Interactions of landslide deposit with terrace sediments: Perspectives from velocity of deposit movement and apparent friction angle[J]. Engineering Geology, 2021, 280(5): 105913, doi: 10.1016/j.enggeo.2020.105913.

[9] Dong C X, Duan Z, Li R. Impact liquefaction mechanism of sandy silt with a change in impact energy[J]. Quarterly Journal of Engineering Geology and

Hydrogeology, 2023, 56(3): qjegh2022122, doi: 10.1144/qjegh2022-122.

[10] Espinosa Marzal R M, Scherer G W. Crystallization of sodium sulfate salts in limestone[J]. Environmental Geology, 2008, 56(3): 605-621.

[11] Wu S, Wu D, Huang Y. Evaluation of the crystallization pressure of sulfate saline soil solution by direct observation of crystallization behavior[J]. American Chemical Society Omega, 2021, 6(27): 17627-17634.

[12] Li Chunqing, Liang Dechen, Zhang Yuxu, et al. Study on the test of tensile strength of remolded loess[J]. China Earthquake Engineering Journal, 2014, 36(2): 233-238, 248.

[13] Zehnder K, Arnold A. Crystal growth in salt efflorescence[J]. Journal of Crystal Growth, 1989, 97(2): 513-521.

[14] Tang Yang, Li Xinhu, Guo Min, et al. Formation process of soil salt crust and its influence mechanism on evaporation under different initial salt concentrations[J]. Arid Land Geography, 2022, 45(4): 1137-1145.

[15] Agudo E R, Mees F, Jacobs P, et al. The role of saline solution properties on porous limestone salt weathering by magnesium and sodium sulfates[J]. Environmental Geology, 2007, 52(2): 269-281.

[16] Dai S, Shin H, Santamarina C J. Formation and development of salt crusts on soil surfaces[J]. Acta Geotechnica, 2016, 11(5): 1103-1109.

[17] Espinosa Marzal R M, Scherer G W. Advances in understanding damage by salt crystallization[J]. Accounts of Chemical Research, 2010, 43(6): 897-905.

[18] Jin Zhiliang, Liu Duanduan, Zhang Yongke, et al. Salt migrations and damage mechanism in cultural heritage objects[J]. Sciences of Conservation and Archaeology, 2017, 29(5): 102-116.

[19] Huang Youfen, Wu Daoyong, Wu Shiyu. Experimental study on deformation of remolded sulfate saline soil under freeze-thaw cycles[J]. Journal of Glaciology and Geocryology, 2022, 44(2): 602-611.

[20] Wang Ce, Mu Fangyuan, Liu Donghao, et al. Progress in salt expansion crystallization test of sulphuric acid saline soil[J]. Low Temperature Architecture Technology, 2021, 43(11): 120-124.

[21] Xu Zhangjian, Lin Zaiguan, Zhang Maosheng. Loess in China and loess landslides[J]. Chinese Journal of Rock Mechanics and Engineering, 2007, 26(7): 1297-1312.

[22] Ma Jianquan, Qiu Yongqiang, Zhao Xiaojie, et al. Effects of salinity and moisture content on the strength of loess in Heifangtai, Gansu Province[J]. China Earthquake Engineering Journal, 2023, 45(4): 819-825, 886.

[23] Masato S, Tsuyoshi H. A laboratory experiment on salt weathering by humidity change: Salt damage induced by deliquescence and hydration[J]. Progress in Earth and Planetary Science, 2018, 5(1): 41-47.

[24] Mokni N, Olivella S, Alonso E. Swelling in clayey soils induced by the presence of salt crystals[J]. Applied Clay Science, 2009, 47(1): 35-47.

[25] Lü Qingfeng, Gu Liuyang, Guo Lianxing, et al. Effect of sulfate content on clay characteristics of loess[J]. Journal of Engineering Geology, 2023, 31(1): 12-20.

[26] Xu Jian, Ren Chang, Gao Jingyu, et al. Influence of dry-wet cycles on hydraulic conductivity and microstructure of saline undisturbed loess with sodium sulfate[J]. Journal of Central South University (Science and Technology Edition), 2021, 52(5): 1644-1654.

[27] Nie Y, Ni W, Tuo W, et al. Collapsibility deterioration mechanism and evaluation of compacted loess with sodium sulfate under dry-wetting cycles[J]. Natural Hazards, 2023, 115(1): 971-991.

[28] Duan Z, Li Z Y, Wu Y B, et al. Mechanical and microscopic properties of soil according to the rate of increase in pore water pressure[J]. Soil and Tillage Research, 2023, 225: 105530, doi: 10.1016/J.STILL.2022.105530.

[29] Lai Y, Wan X, Zhang M. An experimental study on the influence of cooling rates on salt expansion in sodium sulfate soils[J]. Cold Regions Science and Technology, 2016, 124: 67-76.

[30] Fu J, Hu X, Li X, et al. Influences of soil moisture and salt content on loess shear strength in the Xining Basin, northeastern Qinghai-Tibet Plateau[J]. Journal of Mountain Science, 2019, 16(5): 1184-1195.

[31] Meng Huimin, Zhan Chesheng, Hu Shi, et al. Research progress on simulation of soil water-salt transport in large-scale irrigation districts[J/OL]. [2024-08-04]. http://kns.cnki.net/kcms/detail/65.1103.X.20240403.1005.001.html.

[32] Li Zhiqiang. Research on the laws of water and salt transport in salt marsh wetland of Loess Plateau under the coupling action of irrigation and evaporation[D]. Chengdu: Chengdu University of Technology, 2021.

[33] Bing Hui, Wu Junjie, Deng Jin. Variations of physical and mechanical properties of saline loess before and after desalting[J]. Journal of Glaciology and Geocryology, 2011, 33(4): 796-800.

[34] Tang Daxiong. Rock and soil engineering[M]. Beijing: Geology Press, 1999: 30-43.

[35] Charola A E. Salts in the deterioration of porous materials: An overview[J]. Journal of the American Institute for Conservation, 2000, 39(3): 327-343.

[36] Tang Chaosheng, Shi Bin, Gu Kai. Experimental investigation on evaporation process of water in soil during drying[J]. Journal of Engineering Geology, 2011, 19(6): 875-881.

[37] Meng J, Li X A. Effects of carbonate on the structure and properties of loess and the corresponding mechanism: An experimental study of the Malan loess,

Xi' an area, China[J]. Bulletin of Engineering Geology and the Environment, 2019, 78: 4965-4976.

[38] Hu W, Cheng W C, Wen S, et al. Effects of chemical contamination on microscale structural characteristics of intact loess and resultant macroscale mechanical properties[J]. Catena, 2021, 203: 105361, doi: 10.1016/J.CATENA.2021.105361.

[39] Moore R J. The chemical and mineralogical controls upon the residual strength of pure and natural clays[J]. Geotechnique, 1991, 41(1): 35-47.

[40] Kang X, Zou X, Sun H, et al. Molecular dynamics simulations of microstructure and dynamic shearing behaviors of kaolinite-water-salt system[J]. Applied Clay Science, 2022, 218: 106414, doi: 10.1016/J.CLAY.2022.106414.

[41] Tang Chaosheng, Shi Bin, Liu Chun. Study on desiccation cracking behaviour of expansive soil[J]. Journal of Engineering Geology, 2012, 20(5): 663-673.

[42] Li Haiyan, Wang Zhengwei, Liu Yalun. Study on mechanical strength of saline frozen soil on a plateau highway[J]. Subgrade Engineering, 2024(2): 95-100.

[43] Ni Wankui, Shi Huaqiang. Influence of freezing-thawing cycles on microstructure and shear strength of loess[J]. Journal of Glaciology and Geocryology, 2014, 36(4): 922-927.

[44] Ye Wanjun, Li Changqing, Yang Gengshe, et al. Scale effects of damage to loess structure under freezing and thawing conditions[J]. Rock and Soil Mechanics, 2018, 39(7): 2336-2343, 2360.

[45] Zhang Dianfa, Wang Shijie. Mechanism of freeze-thaw action in land salinization process: As a sample in west Jilin Province[J]. Bulletin of Soil and Water Conservation, 2000(6): 14-17.

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