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The expansion deformation characteristics of expansive soil under acid pollution

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Abstract. Soil pollution incidents occur frequently in China. After contamination by acid, the expansion performance of expansive soil is further intensified, posing a significant threat to infrastructure. Using sulfuric acid as the contaminant source, expansion deformation tests of expansive soil under sulfuric acid immersion were conducted, followed by scanning electron microscopy and X-ray diffraction analyses to investigate the evolution of the microstructure and mineral composition of the samples under acidic conditions. The results demonstrated that the acidic environment increased the expansion rate of the samples, with higher sulfuric acid concentrations correlating to greater expansion rates. Under acidic conditions, cementing materials (e.g., free oxides) in expansive soil underwent varying degrees of dissolution and leaching, thereby weakening the connections between overlapping structures. This process resulted in a more dispersed arrangement of the surface-overlapping structures, accompanied by a continuous increase in both the volume and number of micropores. The post-acid-rain expansion deformation of expansive soil can be quantified using the e–p_e fractal relationship. Furthermore, the e–p_e fitting analysis of the experimental data revealed that the enhancement of expansion performance by acid rain primarily stems from the reduction in cementing content, leading to an increase in the expansion coefficient (κ).

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1. Introduction

Soil pollution incidents occur frequently in China. According to statistical data from relevant studies, 209 soil pollution incidents were recorded between 2005 and 2022, 51 of which involved acidic contaminants. Researchers have consistently observed that acidic contamination generally degrades the mechanical properties of soil. Under acidification, the dissolution of cementing materials and the dissociation of cations ($Ca^{2+}$and Mg^{2+}) in silicate minerals weaken interparticle bonding forces, promote pore development, and ultimately lead to reduced soil strength, increased deformation, and severe deterioration of mechanical performance. Empirical data indicate that a 1-unit decrease in the pH of the acid-etching solution corresponds to a 20–25 % [1] reduction in soil cohesion and an 18–26 % [2] increase in the compression index, triggering geotechnical hazards such as soil loosening, foundation subsidence, and slope instability [3–6]. Expansive soils, widely distributed in China with a coverage exceeding

100,000 km^2, affect regions inhabited by over 300 million people. Intensive human activities in these areas have heightened the frequency of acidic contamination incidents. These soils are primarily composed of hydrophilic clay minerals (montmorillonite and illite), whose unique crystal layer structures exhibit strong cation exchange capacity and hydration properties. Their characteristic “swell-shrink” behavior – expansion upon water absorption and contraction upon dehydration – represents a critical engineering challenge. Acidic solutions react chemically with components of expansive soils, significantly altering their swelling-shrinkage characteristics and jeopardizing the safety of regional infrastructure. Therefore, elucidating the effects of acid solutions on the swelling deformation behavior and microstructure of expansive soils, along with developing a scientifically robust model for predicting expansion deformation, is imperative for the safety assessment of acid-contaminated expansive soils.

For expansive soil, Chang et al. [7] found that a lower pH environment markedly increased the unloading expansion rate, expansion force, and shrinkage rate of Beise expansive soil. Microscopic analysis revealed that this was due to the dissolution of cementing agents, the development of porosity, and a consequent reduction in interparticle bonding strength. Li et al. [8] have consistently observed that acidic solutions lead to accelerated swelling rate, prolonged stabilization time, and noticeable chemical swelling phenomena in the expansive soils of the Mengzi region, China. Sivapullaiah et al. [9] also found that the expansion performance of black cotton expansive soil was significantly enhanced after being treated with sulfuric acid. By analyzing the microstructure, the researchers found that the specific surface area of expansive clay, after being corroded by acid solution, would increase significantly, even by 3 to 5 times [10]. When not acidified, expansive clay basically shows a flocculent structure of multiple layers of clay combined together, with strong agglomeration among them; while after acidification, the agglomeration of the original aggregate weakens, evolving from the surface-overlapping structure to the edge-edge structure, presenting a dispersed structure, and the volume and number of micropores also increase continuously, resulting in enhanced expansion performance [11]. Further analysis reveals that the main cause of the loose structure of acidified expansive soil is the acid leaching of cementing materials such as free oxides in the expansive soil. Unbound oxides residing in disordered configurations within the interparticle voids of soil matrices function as cohesive binders for clay mineral colloids, with their accumulation significantly reinforcing the intergranular adhesion forces in swelling clay soils [12, 13]. As the pH value of the acidic solution decreases, the free cements such as SiO_2, Al_2O_3, K_2O, MgO, Fe_2O_3, and CaO in the expansive soil will be eroded and leached to varying degrees, resulting in an increase [14–16] in expansive properties and a gradual weakening of the structural bonding between expansive aggregates [17], which is one of the main reasons why acidic solutions lead to an increase in expansive properties such as the expansion of expansive soil.

In addition, researchers have generally found that the reaction of acidic solutions with expansive soil can also cause changes in mineral composition, especially the changes in the content of hydrophilic minerals such as montmorillonite and illite have an important impact on expansive properties. However, the evolution of hydrophilic minerals under acidified conditions remains unclear. Some scholars believe that acids have an erosive effect on aluminum in montmorillonite crystals, which can destroy the crystal structure and cause a decrease in the content of hydrophilic minerals. Gratchev and Towhata [18] studied the consolidation and compression properties of three types of clay around the coast of Japan and found that sulfuric acid erosion had different effects on the consolidation and compression properties of different types of clay because different clays had different mineral compositions and had different initial microstructures of the soil. Liu et al. [19] found that acidic conditions led to the dissolution of montmorillonite, resulting in a significant reduction in its content. Gratchev and Towhata [11] also found the dissolution effect of sulfuric acid on montmorillonite in Kawasaki clay. However, some scholars have found that in acidic conditions, illite or illite-montmorillonite mixed layers are more likely to undergo potassium removal and transform into montmorillonite, resulting in an increase in montmorillonite content. Zhao et al. [20] experimental studies revealed that acidic precipitation accelerates the mineralogical transformation of illite and illite-smectite interstratified minerals in swelling clays through hydrolysis-driven alteration processes, and believed that this was one of the main causes of landslides in the Three Gorges Reservoir Area. Chang et al. [21] employed bulk mineralogical characterization combined with thermodynamic geochemical modeling to systematically decipher the hydro-chemo interaction dynamics of acidic leaching solutions with swelling clay strata, and concluded that some illite depotassium was transformed into montmorillonite clay minerals, resulting in a decrease in illite content and an increase in montmorillonite content.

In addition, acidic solutions can also trigger ion exchange in expansive soil. Prasad et al. [15] pointed out that cation exchange and changes in mineral composition in acidic conditions led to an increase in expansive properties of expansive soil. Chavali et al. [22] suggest that the enhanced expansion performance of expansive soil under the action of acid solution is closely related to the substitution of exchangeable cations by hydrated hydrogen ions, which can promote the dissociation of cations such as Ca^{2+} and Mg^{2+} in silicate minerals and reduce the electrostatic attraction effect of exchangeable cations on the clay surface.

The acidic environment profoundly compromises the engineering performance of expansive soils by dissolving cementing agents, altering the microstructure, and influencing clay mineral transformation. To mitigate these effects, future research and practice should prioritize the development of economical countermeasures, primarily through three avenues: material modification (e.g., incorporating lime or fly ash to neutralize acidity), the construction of impermeable barriers (e.g., using geosynthetics or clay liners to prevent acid infiltration), and enhancing chemical stability (e.g., via ion exchange and cementation). In line with the principles of a circular economy, there is a growing research focus on sustainable remediation using industrial and urban waste. For instance, Randhawa et al. [23] demonstrated that a blend of 60 % lime-stabilized soil, 20 % municipal solid waste incineration bottom ash (MSWI BA), and 20 % calcium carbide residue (CCR) could increase the unconfined compressive strength (UCS) and splitting tensile strength (STS) of expansive clay by up to 526.03 and 463.41 %, respectively, after 28 days of curing. Furthermore, Shen et al. [24, 25] showed that embedding MSWI BA columns into soft kaolinite clay – with a column penetration ratio (CPR) of 0.8 – increased shear strength by 58.66 %, attributable to the column's drainage and skeleton effects. A synergistic enhancement was achieved by mixing bottom ash with silica fume to form a composite column (BASF), which increased the shear strength by up to 88.59 % due to pozzolanic reactions and improved stiffness. Additionally, Ghalandarzadeh et al. [26] confirmed that encasing these columns with geotextiles further optimizes load transfer, confines lateral bulging, and enhances the overall stability of the composite foundation.

Some progress has been made in the study of the expansion properties of expansive soil under acidic solutions. Due to the differences in mineral composition and microstructure of expansive soil in different regions, the reactions with acidic solutions are somewhat different, resulting in different mechanisms of changes in expansive properties. Therefore, further research is needed on the mechanism of the change in expansive properties of expansive soil under acidic solution contamination. This paper takes expansive soil from areas with severe soil pollution in China as the research object, with sulfuric acid as the pollution source, and conducts an expansion test on the expansive soil soaked in sulfuric acid to test the variation of expansive properties with the concentration of sulfuric acid, By means of X-ray diffraction (XRD), scanning electron microscopy (SEM), and other testing methods, physical and chemical indicators such as mineral composition, cementation composition, and microscopic pore structure of expansive soil under sulfuric acid pollution are analyzed to reveal the mechanism of the effect of acid rain on expansive properties. At the same time, combined with the fractal theory of porous media surface, an expansion fractal model of expansive soil under the action of acidic solution is constructed for the scientific prediction of expansion performance, which can provide scientific guidance for the prevention and control of geological disasters in acid-contaminated expansive land areas.

2. Methods

2.1. Materials

Sulfuric acid is widely used in industry, agriculture, medicine, chemical engineering, and other fields. China produces about 100 million tons of sulfuric acid annually. Leakage is inevitable during the production and transportation of sulfuric acid, causing pollution to the soil. Therefore, in this study, sulfuric acid with concentrations of 1, 10, and 20 % (corresponding to molar concentrations of 0.102, 1.087, and 2.324 mol/L) was used as the acidic contaminant. Distilled water was also used as the control group. The 20 % maximum sulfuric acid concentration used in this study was dictated by the following considerations: (1) Environmental Relevance: The acidity of soil pore water in real-world contamination incidents is generally lower than this level; (2) Chemical Saturation: Preliminary tests indicated that concentrations above 20 % caused the expansion rate trend to flatten, implying that the dissolution of key cementing agents was nearing completion; (3) Operational Safety: Higher concentrations exhibit strong corrosivity, introducing substantial risks to laboratory personnel and procedures.

Kunming, Yunnan is the largest sulfuric acid production base in China, the sampling site was selected within the historical leakage area downwind of a sulfuric acid plant, ensuring it is representative of industrially impacted acidic environments. This region features widely distributed expansive soils, primarily composed of montmorillonite and illite, which exhibit strong swell-shrink potential and are representative of southwestern China. The mineral composition of the studied soil is similar to that of well-known expansive soils such as Baise clay and Indian black cotton soil as it is also rich in hydrophilic minerals like montmorillonite and illite. Therefore, it is representative in terms of its engineering geological characteristics. Preliminary analysis identified a high content of free oxides (e.g., Fe_2O_3, Al_2O_3, CaO), which are key cementing agents for structural stability. Their susceptibility to acid dissolution makes this soil highly sensitive to acidic environments, providing an ideal medium for investigating the relationship between cement dissolution and macroscopic swelling. Soil samples were collected from a 2-meter depth, avoiding zones of active root penetration and significant human disturbance to ensure the obtained samples were pristine and representative. Laboratory tests determined the soil's physical properties and mineral composition. Following the methods of Shen and Britto [27, 28], the permeability coefficient, maximum dry density, and optimum moisture content of the Kunming expansive soil were calculated as summarized in Table 1.

Table 1. Physical properties and mineral composition of expansive soil.

Optimal moisture content w (%)	Maximum dry density ρ (g/cm^3)	permeability coefficient k(m/s)	Plastic limit w_p (%)	Liquid limit w_L (%)	Free expansion rate δ_{ef} (%)	Mineral composition and content (%)				
						Montmor illonite	Illi te	Kaoli nite	Chlor ite	Quart z
23.5	2.32	4.26×10^{-10}	31.4	76.1	81.9	37.4	31.3	15.6	13.3	2.2

2.2. Expansion Test

Cut the original Kunming soil retrieved from the site into a sample in the shape of a circular knife section and place it in a stainless steel plate with polyethylene film at the bottom. Place a piece of filter paper and a permeable stone on each of the upper and lower sides of the sample in sequence. Install a dial indicator, record the initial reading, and apply the required load. Five loads of 6.25, 12.5, 25, 50, and 100 kPa were selected to simulate the force state of the soil at different depths. The load was applied at one time, that is, it remained constant during the test. Then pour sulfuric acid into the consolidation instrument to submerge the sample by about 1 cm. After that, record the changes in the dial indicator reading over time. When the dial indicator pointer changes less than 0.01 within 12 hours, it is considered that the expansion deformation has stabilized.

2.3. Characterization Tests

After the expansion test is completed, remove the sample saturated with acid solution and cut the sample in half. Transfer half of the sample to an aluminum container filled with liquid nitrogen for rapid freezing. Subsequently, the aluminum boxes containing expansive soil were placed in a freeze dryer (–50 °C) and vacuum-dried for 24 hours to remove moisture. Finally, the samples were taken out for SEM tests. At the same time, the other half of the sample was placed in a 50 °C oven to dry. The dried soil particles and precipitated minerals were ground and sifted through a 2 mm sieve, and the minerals and their chemical composition in the sample were measured using an X-ray diffractometer.

2.4. Test of Cementing Content

The cementing materials in expansive soil are mainly free oxides, but some free oxides are encapsulated in the surface of other silicate minerals or fill the pores and are difficult to separate. When testing free oxides, a suitable solution should be chosen to avoid affecting silicate minerals and to dissolve all types of free oxides. Existing studies have shown that sodium citrate-sodium dithionite ($C_6H_5Na_3O_7$–$Na_2S_2O_4$) performs well in selectively dissolving free oxides. Therefore, this method is used to test the cementing materials content, and the specific test process is as follows:

First, weigh about 2.0 g of the pre-treated soil sample and place it in a 100 mL centrifuge tube. Then, add 40 mL of 0.3 mol/L sodium citrate ($C_6H_5Na_3O_7$) solution and 6 mL of 1.0 mol/L $NaHCO_3$ solution. Heat the tubes in a water bath to 80 °C. Then, add 1.0 g of solid sodium dithionite ($Na_2S_2O_4$) to the centrifuge tube and stir constantly until the soil sample is completely grayish-white. Add 10 mL of saturated NaCl solution to facilitate the flocculation of the clay particles. After cooling, solid-liquid separation is carried out using a centrifuge, and the soil residue in the centrifuge tube is washed twice with 1.0 mol/L NaCl solution. It is then washed three times with distilled water, filtered, and weighed. The cementing content c_c can be calculated by the following formula:

$$c_c = \frac{m_1 - m_2}{m_1} \times 100\%. \quad (1)$$

In the formula: c_c represents the content of cementing in acidified expansive soil, m_1 represents the mass of expansive soil without $C_6H_5Na_3O_7$-$Na_2S_2O_4$ treatment, and m_2 represents the mass of the residue in the treated soil.

3. Results and Discussion

3.1. Expansion Deformation Test

Fig. 1 shows the relationship curves of the expansion rate of expansive soil in different sulfuric acid solutions under a load of 6.25 kPa over time. Experimental observations reveal that swelling clay specimens subjected to varying sodium sulfate concentrations exhibit analogous deformation trajectories, characterized by three consecutive phases: initial gradual expansion, subsequent accelerated growth, and ultimate stabilization [29, 30]: slow increase at first, then rapid increase, and finally stabilization. Fig. 1 shows that the expansion rate is the smallest in distilled water at 20.3 %, while the expansion rates are 23.1 and 24.6 % under 1 and 10 % sulfuric acid solutions, respectively, indicating that the expansion performance of the expansive soil is somewhat enhanced by sulfuric acid solutions.

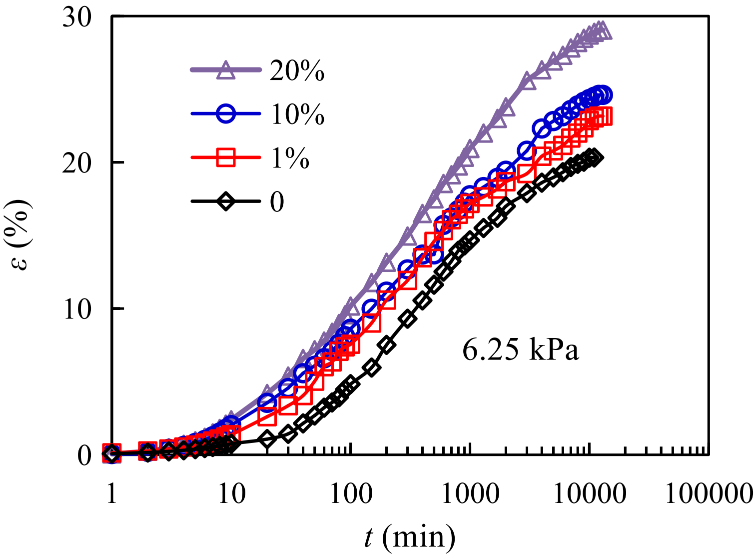


Figure 1. The relationship between the expansion rate of bentonite and time at 6.25 kPa.

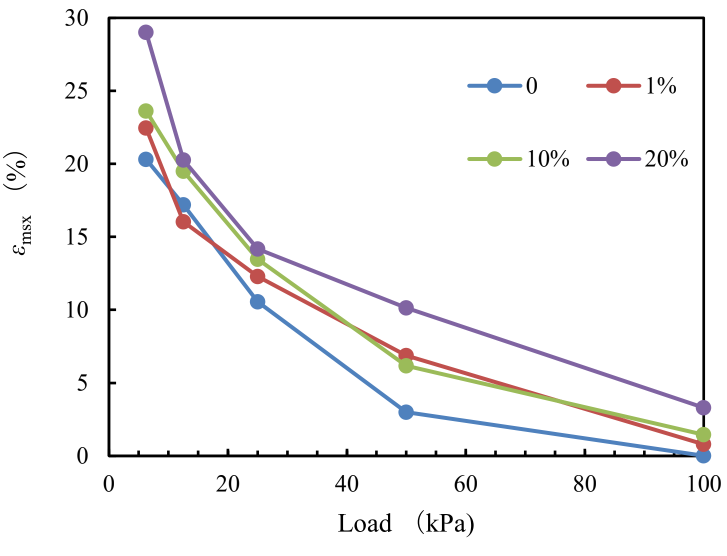
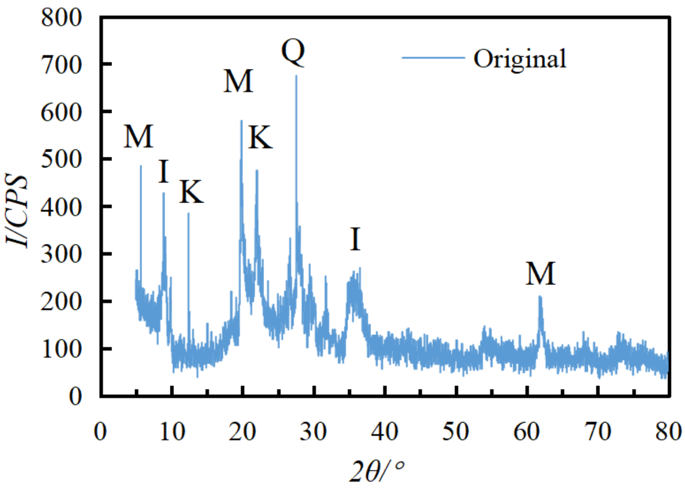


Figure 2. Relationship between maximum expansion deformation and load.

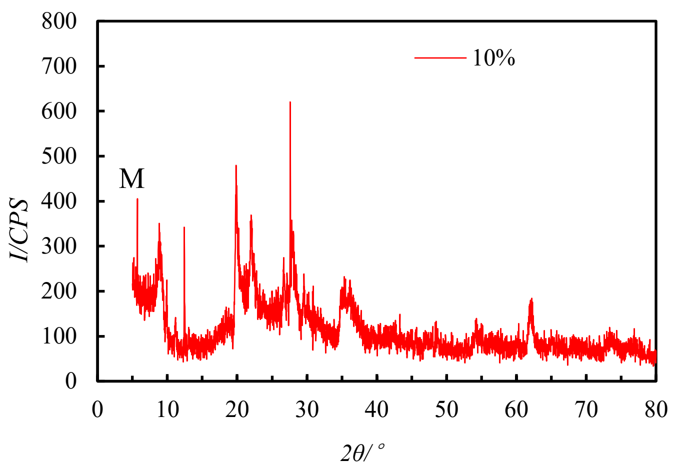
Fig. 2 illustrates the correlation between peak swelling strain in expansive soils and applied compressive stress. The figure shows that when the solution remains constant, the expansion rate gradually decreases as the load increases. When the load increased from 6.25 to 100 kPa, the maximum expansion rate decreased from 29.1, 24.6, 23.1, and 20.3 % to 3.4, 1.57, 0.768, and 0.127 %, respectively, indicating that the increase in load significantly affected the expansion of expansive soil. When the load was constant, the expansion rate curve of the expansive soil shifted upward with increasing sulfuric acid solution concentration, indicating that higher sulfuric acid concentrations enhanced the expansive properties of the soil. For example, under a load of 50 kPa, the maximum expansion rates of expansive soil in 0, 1, 10, and 20 % sulfuric acid were 2.98, 6.88, 6.17, and 10.14 %, respectively. The mechanism, by which sulfuric acid enhances the expansive properties of expansive soil, will be explained through composition analysis and microstructure tests.

3.2. Chemical Composition Changes

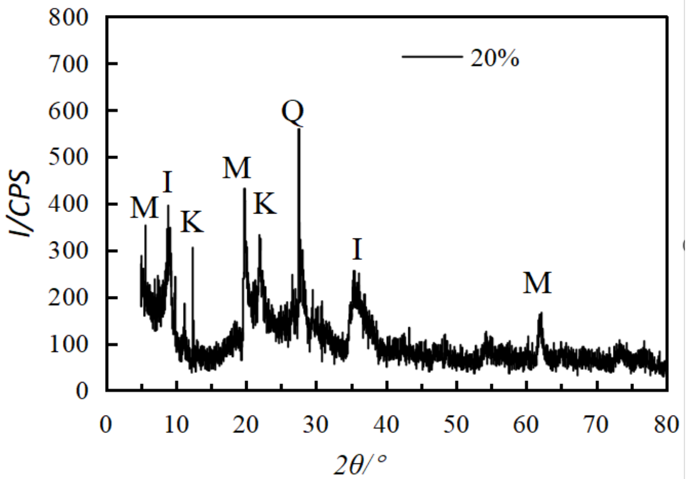
Fig. 3 shows the XRD comparison patterns of expansive soil under neutral and acidic conditions, where M denotes montmorillonite, I – illite, K – kaolinite, and Q – quartz. When the solution environment changed from neutral to acidic, the intensity of characteristic peaks at specific diffraction angles decayed, with this decay becoming more pronounced as environmental acidity increased. After soaking in 10 and 20 % sulfuric acid, the characteristic peak intensity of montmorillonite near 5.7 ° decreased from 485 (original soil) to 405.25 and 352.5, respectively. Similarly, the characteristic peak intensity of illite at 9.0° decreased from 317.5 to 292.5 and 270, while that of kaolinite at 20.9° decreased from 327.5 to 301.5 and 271.35. The underlying mechanism involves the attack of H^+ ions from the acidic solution on the mineral framework of expansive soils, particularly the octahedral sheets (e.g., Al-O-OH in montmorillonite and kaolinite). These ions react with cations such as Al^{3+}, Mg^{2+}, and Fe^{3+}, leading to their selective dissolution and a consequent "de-octahedralization." Simultaneously, the Si-O-Si or Si-O-Al bonds in the tetrahedral sheets may undergo protonation and breakage in a strongly acidic environment. This localized dissolution and degradation of the crystal framework reduce the overall crystallinity and diminish the proportion of well-ordered mineral structures. Macroscopically, this is evidenced by the universal attenuation of characteristic XRD peak intensities. Mineral composition, quantified using X'Pert HighScore Plus software (Table 2), shows subtle but indicative changes after acid soaking: the illite content decreased from 31.3 to 26.4 %, while the montmorillonite content increased from 37.4 to 40.8 %. This shift is attributed to the acid-driven enhancement of ion exchange. K^+ in the illite interlayer was likely replaced by solution cations like Ca^{2+} and subsequently leached out. This potassium release destabilizes the illite structure, thereby promoting its transformation into metastable montmorillonite, a pattern consistent with findings by Chang et al. [21]. Overall, however, the minor changes in hydrophilicity had negligible effects on expansion performance.



a – water



b – 10% H_2SO_4



c – 20% H2SO4

Figure 3. XRD pattern of expansive soil samples: M – Montmorillonite, K – Kaolinite, I – Illite, Q – Quartz.

Table 2. Mineral composition of expansive soil soaked in sulfuric acid.

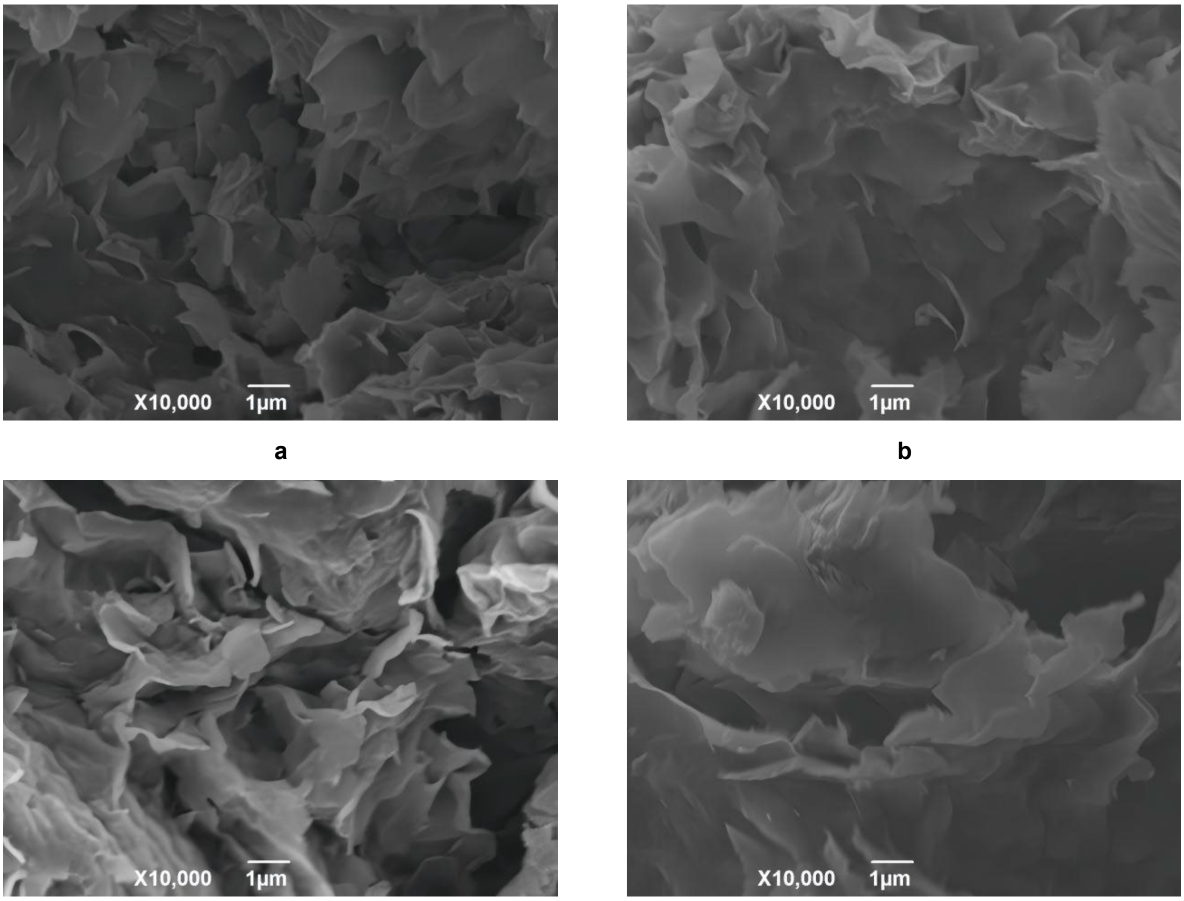
	Montmorillonite	Illite	Kaolinite	Chlorite	Quartz
Original soil	37.4	31.3	15.6	13.3	2.2
Soak in 10 % sulfuric acid	39.6	28.7	14.3	12.8	4.3
Soak in 20 % sulfuric acid	40.8	26.4	13.5	12.1	6.6

Natural expansive soil contains a certain amount of cementing materials, primarily free oxides, which mostly exist in amorphous forms and act as binding agents between clay particles. During water absorption, the interparticle distance remains stable, thereby limiting expansion. Thus, the presence of free oxides significantly influences the expansive properties of the soil. However, these oxides cannot be directly quantified from XRD images, and XRD-based mineral composition calculations do not account for their mass fraction. To address this, the $C_6H_5Na_3O_7$-$Na_2S_2O_4$ method was employed. The free oxide content measured 7.5 % in undisturbed soil, whereas values for expansive soil soaked in 1, 10, and 20 % sulfuric acid solutions decreased to 6.1, 4.5, and 3.8, respectively. These results demonstrate sulfuric acid's strong dissolving effect on free oxides. The reduced cementing content weakens interparticle bonding strength, allowing soil pores to respond more readily to moisture variations, which ultimately enhances the soil's expansion performance. Chemical reaction formula:

$$RO + H^{+} = Fe^{3+} + AI^{3+} + Ca^{2+}. \quad (2)$$

3.3. Microstructure

The effect of cementing content changes on the expansion properties of expansive soil is further evidenced by SEM images. As shown in Fig. 4a, the original soil sample (soaked in distilled water) displays a dense, face-to-face stacked microstructure. Well-organized plate-like clay aggregates form larger clusters with limited, small-sized pores. This dense fabric is attributed to cementation by free oxides (e.g., Fe_2O_3, Al_2O_3, CaO), which suppresses soil expansion upon water uptake. In contrast, samples soaked in sulfuric acid solution (Figs. 4b–d) exhibit significant structural loosening and dispersion. With increasing acid concentration (from 1 to 20 %), the high H^+ concentration dissolves the natural oxide cements (e.g., $Fe_2O_3 + 6H^+ \rightarrow 2Fe^{3+} + 3H_2O$), severely weakening or even destroying interparticle bonds. This causes the aggregated structures to disintegrate. As cementation diminishes, the stability of the face-to-face stacking decreases, allowing plate-like particles to separate at the edges and reassemble into more unstable edge-edge and edge-face configurations. Consequently, the overall structure becomes disordered and open, accompanied by a notable increase in the volume and number of micropores. These newly formed micropores provide additional channels and space for water intrusion, directly accounting for the increased macroscopic expansion rate. In summary, the SEM results are consistent with the binder content tests and XRD analysis. The dissolution of key cementing agents in acidic environments compromises the microstructural integrity of the expansive soil, transforming it from a dense aggregated state to a loose dispersed one with developed pore networks, thereby enhancing its macroscopic expansion.



a b c d

Figure 4. SEM images of expansive soil under each solution: a – water; b – 1 % H_2SO_4; c – 1 % H_2SO_4; d – 20 % H_2SO_4.

3.4. Measurement of Fractal Dimension by Nitrogen Adsorption Method

The surface dimension of expansive soil can be measured by the nitrogen adsorption test. Fig. 5 shows the N_2 adsorption-desorption isotherm of the expansive soil sample, presenting an upward convex curve in the low P/P_0 region; in the higher P/P_0 region, the adsorbate undergoes capillary coagulation, and the isotherms rise rapidly. Due to capillary coagulation, a hysteresis phenomenon can be observed in this region: that is, the isotherms obtained during desorption do not coincide with those obtained during adsorption, and the desorption isotherms are above the adsorption isotherms, forming a hysteresis loop. By using the FHH [35] equation, double logarithmic curves of adsorption capacity versus relative air pressure were plotted based on the N_2 isothermal adsorption lines of each powder sample in double logarithmic coordinates. And Fig. 6 shows the $\ln V_{\text{ads}}$–$\ln[\ln(p_0/p)]$ fitting curve. The surface fractal dimension results were calculated as shown in Table 3. It can be seen from the table that the surface dimension decreases with the increase in sulfuric acid concentration. The SEM image can fully explain this phenomenon. When the concentration of sulfuric acid solution is low, the hydration reaction of expansive soil is less intense and the surface is rougher (Fig. 4a), with the surface fractal dimension being larger. However, as the concentration of sulfuric acid solution increases, the hydration reaction becomes more intense and the surface of expansive soil tends to be smoother (Fig. 4d), resulting in a decrease in the surface fractal dimension.

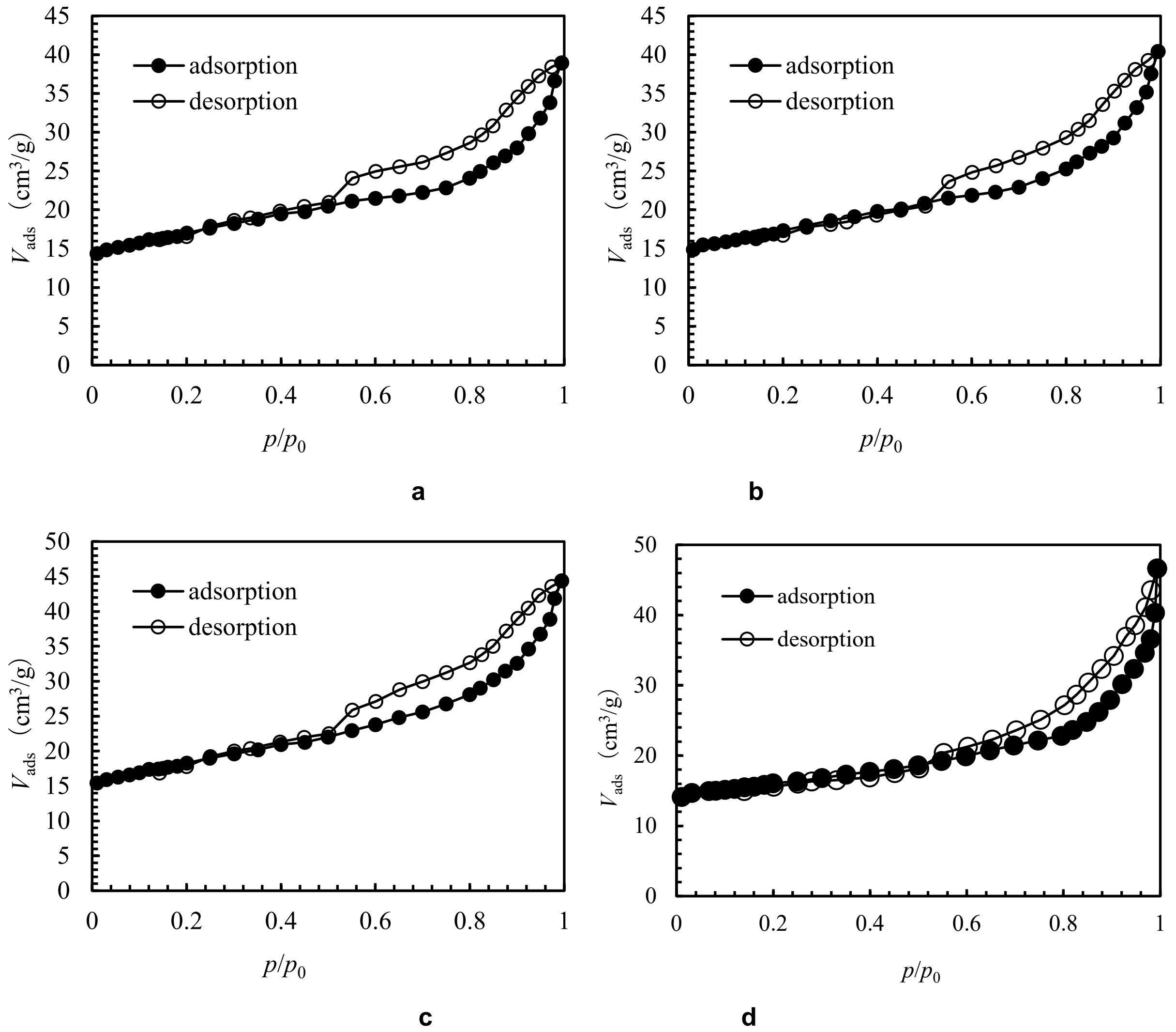


Figure 5. N_2 adsorption-desorption isotherms of the expansive soil samples: a – 0 %; b – 1 %; c – 10 %; d – 20 %.

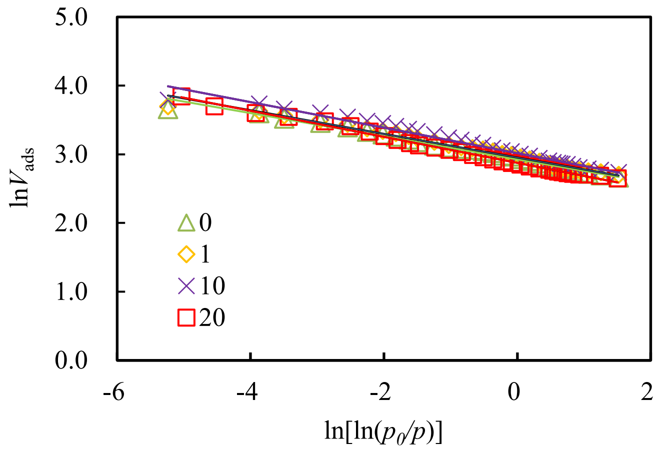


Figure 6. Equation curves of expansive soil samples after soaking in sulfuric acid solutions of different concentrations.

Table 3. Surface dimension division of expansive soil under nitrogen adsorption.

Sulfuric acid concentration	Fit the relationship	R^2	*D*
0	$\ln V_{ads}$ = 0.1684 ln [ln (p_0/p)] + 2.9265	0.9842	2.8316
1 %	$\ln V_{ads}$ = 0.1722 ln [ln (p_0/p)] + 2.9531	0.9831	2.8278
10 %	$\ln V_{ads}$ = 0.186 ln [ln (p_0/p)] + 3.0165	0.9767	2.814
20 %	$\ln V_{ads}$ = 0.1897 ln [ln (p_0/p)] + 2.8757	0.994	2.8103

3.5. Calculation Model

The swelling deformation of bentonite decreases as the effective stress p_e increases. Within the framework of fractal theory, the Debye–Hückel formula can be introduced to obtain the osmotic suction coefficient and calculate osmotic suction, thereby establishing a theoretical relationship between effective stress and swelling deformation. Analysis of the $e-p_e$ fitting curve was conducted to further explore the erosion mechanism of sulfuric acid solution on expansive soil.

Xu et al. [31] derived the relationship between the expansion deformation of bentonite and the corrected effective stress based on; the fractal theory:

$$e = \kappa p_e^{D_s-3}, \quad (3)$$

where e is the pore ratio of the sample and D_s is the fractal dimension of the bentonite surface; p_e is the corrected effective stress; κ is the coefficient of expansion. According to the fractal theory, the modified effective stress can be derived from the overlying pressure and the infiltration stress, and the calculation formula is as follows [32–34]:

$$P_e = \sigma + \pi \left(\frac{\sigma}{\pi} \right)^{D_s-2}, \quad (4)$$

where σ is the overlying pressure and π is the osmotic suction, $\pi = \varepsilon RTc\Phi$. ε is the number of ions decomposed by the solute (H_2SO_4: $\varepsilon = 3$); R is the generalized gas constant (8.314 J/mol/k); T is absolute temperature; c is the mass molar concentration of the solute; Φ is the osmotic suction coefficient. For solutions containing monovalent ionic electrolytes, the formula proposed by Li et al. [34] was used to calculate the osmotic suction coefficient Φ for 1, 10, and 20 % sulfuric acid, which were 0.791, 0.641, and 0.624, respectively, and the corresponding osmotic suction π was 599.69, 5178.87, and 10778.75, respectively.

The $e-p_e$ relationship of expansive soil in different sulfuric acid solutions can be obtained by fitting the test data using Equation (3) as shown in Fig. 7. It can be seen that the expansion deformation of expansive soil after soaking and erosion in the acid solution still conforms to the fractal relationship in Equation (3), and the corresponding $e-p_e$ relationship is listed in Table 4. It can be found that the fractal dimension after fitting the experimental data is basically consistent with the results of the nitrogen adsorption test.

As can be seen from Table 4, an increase in the concentration of sulfuric acid solution will, on the one hand, increase the effective stress of saturated expansive soil, which leads to a decrease in expansive deformation; on the other hand, the coefficient of expansion κ increases significantly with the increase in the degree of acid erosion. As can be seen from Fig. 7, the increase in sulfuric acid concentration leads to an increase in the effective stress p_e, but the porosity *e* also increases accordingly, thus increasing the expansion deformation. A good linear relationship between the expansion coefficient κ and the cementation was found in Fig. 8. As the expansion coefficient increases, the cementing content decreases. However, the decrease in cementing content weakens the bonding strength between the particles, making the soil pores more prone to change with moisture, thereby increasing the expansion deformation. To sum up, an increase in the concentration of sulfuric acid solution leads to an increase in the expansion performance of expansive soil.

By comparison, we found that the measured values obtained by previous researchers [36–38] were in excellent agreement with the theoretical values calculated by the $e-p_e$ fractal model in this paper. The results are shown in Fig. 9. This verifies the scientificity and accuracy of the model.

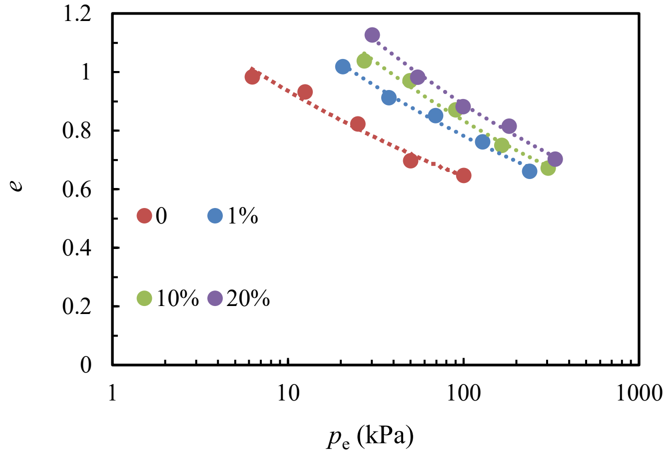


Figure 7. e–p_e relationship of expansive soil in different sulfuric acid solutions.

Table 4. e–p_e relationship under different concentrations of sulfuric acid solutions.

Sulfuric acid concentration	e–p_e relationship	κ	D
0	$e = 1.36 p_e^{-0.162}$	1.36	2.838
1 %	$e = 1.72 p_e^{-0.171}$	1.71	2.829
10 %	$e = 1.97 p_e^{-0.187}$	1.97	2.813
20 %	$e = 2.12 p_e^{-0.188}$	2.12	2.812

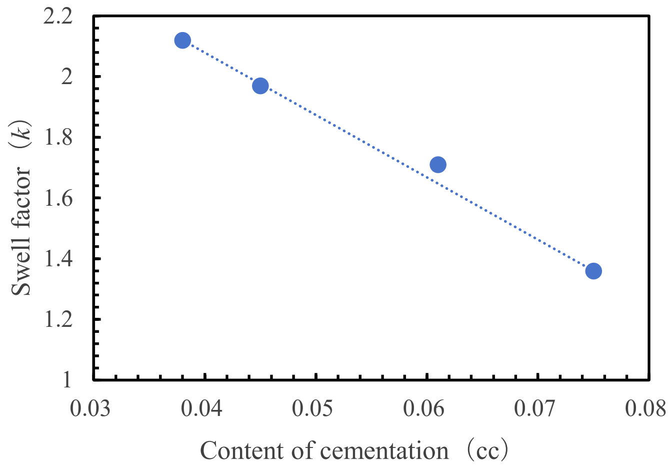


Figure 8. Relationship between expansion coefficient and cementing content.

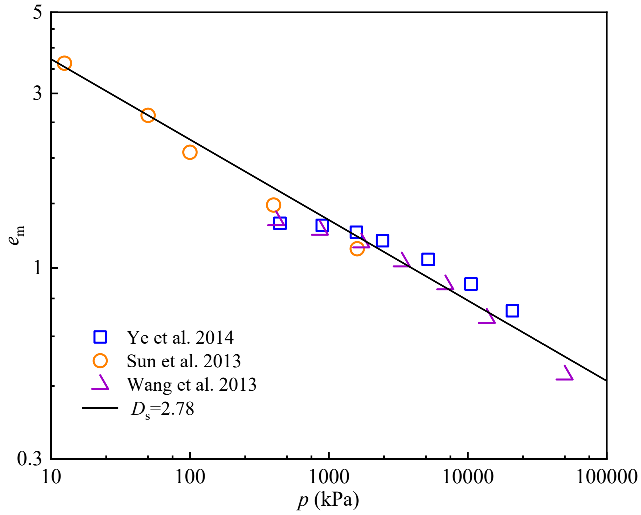


Figure 9. Model validation.

4. Conclusions

1. The initial expansion rate of expansive soil increases after being eroded by sulfuric acid and increases with the concentration. After being treated with 1, 10, and 20 % sulfuric acid, the expansion rate of expansive soil at 6.25 kPa increased from 20.32 % (distilled water) to 22.45, 23.63, and 29.02 %, respectively. When the load increased, the expansion rate decreased in all samples, especially in the samples treated with a high concentration of sulfuric acid.
2. By XRD and SEM analysis, it was found that the content of mineral components other than montmorillonite in the expansive soil after sulfuric acid treatment decreased. The montmorillonite content increased slightly, possibly due to the formation of montmorillonite resulting from the depletion of K^+ in illite. As the concentration of sulfuric acid increases, the free oxides in the expansive soil react with H^+, resulting in a decrease in the cementation content in the sample, weakening the bonding strength between the particles, increasing the porosity of the soil and the seepage channels available for the solution to penetrate the soil, thereby increasing the expansion deformation.
3. The expansion deformation of expansive soil treated with sulfuric acid can be calculated by the $e - p_e$ fractal model. The experimental data after erosion with the acid solution still conform to the $e - p_e$ fractal model. At the same time, with the increase in sulfuric acid concentration, on the one hand, the increase in effective stress p_e inhibits the expansion deformation of expansive soil, but on the other hand, the expansion coefficient κ shows a significant linear increase with the decrease in cementing content, further indicating that the mechanism by which sulfuric acid enhances the expansion performance of expansive soil is mainly due to the dissolution of free oxides and the decrease in cementing content.
4. While the developed $e - p_e$ fractal model effectively describes the swelling behavior of acid-etched expansive soils, some limitations exist. Firstly, its applicability to other soils, especially kaolinite-dominated expansive soils, remains unverified and may yield less accurate predictions. Secondly, the model cannot self-optimize with new data due to the absence of a feedback mechanism. Thirdly, the model has only been validated at the laboratory scale and requires field testing to identify potential deviations in practical applications.

Addressing the significant engineering risks posed by widely distributed acidic contaminated soils, this paper has focused on the fundamental theory for predicting swelling deformation. Future efforts should aim at developing sustainable remediation strategies and enhancing model robustness. Key directions include: leveraging industrial wastes (e.g., calcined lime slag, steel slag) for chemical stabilization; implementing a data-driven feedback mechanism, where long-term field data are used to dynamically calibrate the model parameters to maintain accuracy; and conducting multi-factor coupling studies (e.g., acid-heat-stress interactions) to decipher complex soil behavior and improve the model's performance in intricate field conditions.

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