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Research Article

Experimental Study on the Modification Mechanisms of Dispersive Soil Treated with Hydroxyl Aluminum

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Dispersive soil is a special clay that is easy to disintegrate and disperse into particles and suspend in water, which can easily cause erosion and piping damage of dams, grooves, and road slopes. In this study, a new dispersive clay modifier hydroxyl aluminum (a positively charged aluminum hydroxide electrolyte) was proposed. Previous studies have shown that it can well coat montmorillonite in clay and combine with it to stabilize the properties of clay. The modification effect and interaction mechanism of hydroxyl aluminum on dispersive soil were studied through indoor dispersion discrimination, physical and mechanical, and micro mechanism tests (SEM and XRD). The experimental results indicate the following: With the increase of hydroxyl aluminum content, the dispersion of dispersed soil decreases and becomes nondispersive soil. Hydroxyl aluminum has an excellent inhibiting dispersion effect on dispersive soil, and it has the "agglomeration" and "cementation" effect on the dispersive soil particles. The addition of hydroxyl aluminum makes the dispersive soil agglomerated crystals arranged closely, and the number of pores between the particles reduces clearly, making the dispersed particles agglomerated. It can also reduce the alkalinity of the clay and make the clay structure more stable to restrain the dispersion of clay.

1. Introduction

Certain fine-grained soils are structurally unstable, with ease of dispersion, and therefore highly erodible. Soils in which the clay particles will detach spontaneously and go into suspension in quiet water are termed dispersive soils. Dispersive soil has existed in various climates in America, Mexico, Brazil, Australia, New Zealand, Spain, Greece, China, Iran, Malaysia, South Africa, etc. In China, dispersive soil is found in 16 provinces. Dispersion and easy erosion characteristics of dispersive soil cause serious erosion and piping failure for many engineering structures like dams, canal slopes, and road slopes [1, 2]: piping incidents of Grenada dam in Mississippi in 1949, the piping event of LAN Sulai dam in Thailand, dam failure event of Ling Luo reservoir in Hainan Province, and dam failure event of Heilongjiang diversion project in China.

It is complicated by the erosion effect on dispersive soil. It directly relates to the dispersion mechanism of dispersive soil and the electrochemical properties on the soil particle surface [3] [4], It has a high content of exchangeable sodium ions in dispersive soil, and montmorillonite is involved in the clay, which are essential affecting factors of its dispersion [5]. The surface of Na-montmorillonite in dispersive soil is liable to form a double electrical layer, which weakens the connection between mineral layers and the relationship between lamellar particles. It promotes large water entry freely. Then, the repulsion force between soil particles changes to be more significant than the attraction force, gradually resulting in the disintegration and shedding of the soil surface [6]. Some researchers developed that the relationships between the increment of the negative charge on the particle surface and pH value, pH value, and dispersion degree of the dispersive soil are all positive correlations [7].

Solving the dispersion problem of dispersive soil can reduce or eliminate related engineering accidents. To this end, aiming at the dispersion characteristics of dispersive soil in actual engineering, chemical stabilizers such as lime, cement, alum, and fly ash are added to dispersive soil.

Table 1: Physical and chemical properties of dispersive soil.

Project		Numerical value
Proportion		2.69
Natural moisture content/(%)		30.0
	Sand >0.075 mm	6.7
Particle composition/(%)	Silt 0.075~0.005 mm	49.8
	Clay particle <0.005 mm	43.5
Liquid limit (ω_L/%)		52.8
Plastic limit (ω_P/%)		20.5
Plasticity index (I_P)		32.3
Compaction parameters	Maximum dry density ρ_{dmax}/(g·cm^{-3})	1.62
	Optimum moisture content (ω_{op}/%)	21.8
	Soluble salts	2.84
Salt content/(g·kg^{-1})	Medium soluble salt	0.38
	Insoluble salt	50.60
	Organic matter	3.79
pH		9.25

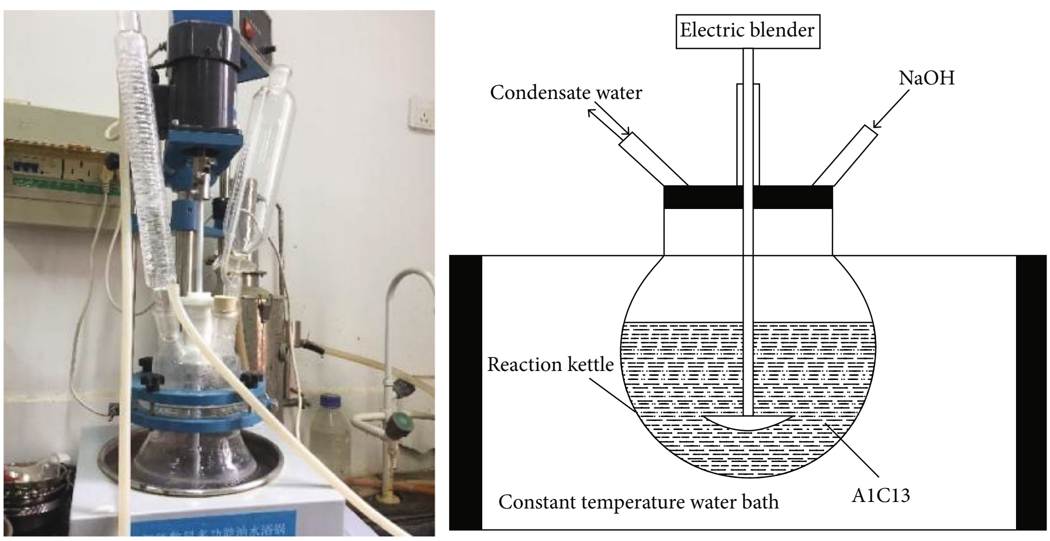


Figure 1: Device diagram and schematic diagram of the preparation of hydroxyl aluminum solution.

Figure 2: FDJ-20 direct shear apparatus.

Employing these manners, the dispersion of the dispersive soil reduces effectively, and the dispersive soil changes into nondispersive soil. In recent years, some experts have attempted to investigate new modifiers to treat dispersive soil in the laboratory, such as magnesium chloride [8, 9], slag [2], and ZELIAC (consists of zeolite, activated carbon, limestone, rice husk ash, and Portland cement) [10]. Some other experts also put forward new analysis methods for soil stability [11, 12].

Hydroxyl aluminum is a general term for the hydrolyzate produced after aluminum ions in the Al (III) solution hydrolysis equilibrium. Due to the abundance of the aluminum element, the large size, and the multichange of polyhydroxy aluminum ions, the hydroxyl aluminum system attracts researchers to explore its applications in specific

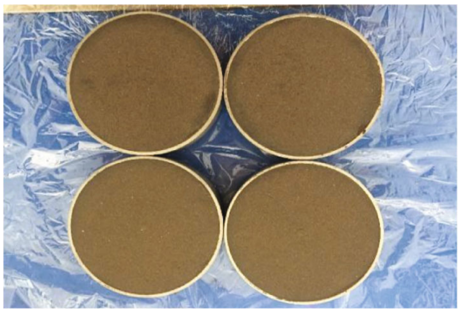


Figure 3: Soil samples of the test.

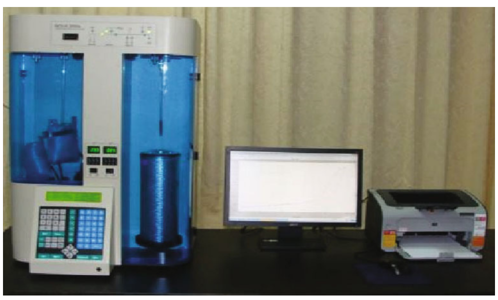


Figure 4: NOVA-1000 high-speed specific surface area and aperture analyzer.

fields. Several experts have studied the interaction between hydroxyl aluminum and montmorillonite. Hydroxyl aluminum can significantly reduce the exchange capacity for the cation of montmorillonite [13]. The cross-linking of hydroxyl aluminum with montmorillonite can form a more stable soil [14]. Clay minerals pillared by hydroxyl aluminum can change the cation exchange capacity in clay minerals, significantly increase interlayer attraction, and make it more significant than interlayer repulsion [15]. In addition, hydroxyl aluminum has a positive effect on clay consolidation that can reduce the surface acidity of montmorillonite [16]. Sludge was significantly acidified after the addition of hydroxyl aluminum. After the sludge flocs were conditioned with hydroxyl aluminum, the floc structure of the sludge was denser and more compact [17].

As experts ([5–7] said, the dispersion of dispersive soil is related to the presence of sodium montmorillonite and the acidity and alkalinity of the medium in the dispersive soil. Current studies have shown the advantages of hydroxyl aluminum in stabilizing soil properties and improving soil acidity, providing us with a research direction for effectively inhibiting the dispersion of dispersive soil. Traditional modification methods have achieved practical application effects in current engineering applications. However, there are some problems with the economy and timeliness of these traditional modifiers: choose the traditional modifier. It needs to excavate the subgrade filler and transport it to a specialized site. The modifiers are mixed into the subgrade filler to make it well-mixed and then transported to the engineering site for filling, which takes a lot of time, transportation, and labor costs. Once the hydroxyl aluminum is used as the modifier to realize engineering application, it can be prepared on a large scale. The hydroxyl aluminum can be sprayed directly on the subgrade surface filled in layers. The effect of modifying the subgrade filler can be achieved through an electrochemical reaction, which can save a lot of time and labor costs and make it more economical and environmental. Thus, in this paper, laboratory tests will be done to verify the inhibiting effect of hydroxyl aluminum on the dispersion of dispersive soil. The dispersive soil will be modified by hydroxyl aluminum. The laboratory tests of the modified soil samples will be done, including pH value, dispersion, limiting water content, permeability coefficient, cohesion, internal friction angle, shear strength, SEM, and XRD. The dispersibility, strength, and microstructure of dispersive soil with different content of hydroxyl aluminum are studied, which will provide theoretical and technical support for the engineering application of the new modifier hydroxyl aluminum.

2. Materials and Methods

2.1. Soil Samples. The soil samples are typical dispersive soil from a homogeneous dam in Northeast China and have been confirmed as dispersive soil in advance. Table 1 presents some engineering and chemical properties of dispersive soil measured in this study. According to the test results, the soil samples are divided into high plastic clay (CH). The pH value of the soil sample is 9.25, showing an alkaline state, which is a typical feature of dispersive soil.

2.2. Dispersive Soil Modifier. Hydroxyl aluminum ($Al(OH)_2^+$) is a general term for the hydrolysates of aluminum ions in Al (III) solution after reaching the hydrolysis equilibrium. It is rich in aluminum elements, large-scale polymerized hydroxyl aluminum ions, and multi charges. Hydroxyl aluminum enters the interlayer of montmorillonite through ion exchange, occupies the position of the exchangeable ions (Na^+), and improves the interlayer water rationality of montmorillonite. Hydroxyl aluminum has a significant positive charge, which can enhance clay's physical and chemical properties by neutralization reaction with clay particles (negative control) [18]. In addition, hydroxyl aluminum has also been proved to change soil's hydrophilicity and strength properties through physical and chemical reactions such as ion exchange, coating, and bonding with montmorillonite [19], significantly improving the physical properties and strength index of montmorillonite.

Different content of hydroxyl aluminum was selected to modify the dispersive soil, and the results were compared to verify the modification effect of hydroxyl aluminum. The main preparation methods of hydroxyl aluminum are as follows: adjust the ambient laboratory temperature to room temperature (20°C), add 40 ml with the concentration of 0.5 mol/l $AlCl_3$ solution into the glass reactor with an electric mixer, and reflux the condenser (Figures 1 and 2). The glass reactor is heated to the required temperature (80°C) using cauldron thermostat water bath.

50 ml NaOH solution with a concentration of 1.0 mol/l was added to the reactor through a buret at a specific dropping rate and mixed around intensely with a speed of 250 r/min. After the NaOH solution titration is finished, add

Table 2: Physical and chemical properties of the soil before and after modification with aluminum compounds.

Hydroxyl aluminum content/($mmol \cdot g^{-1}$)	The specific gravity of soil particle	Particle composition/(%) Sand 0.075 mm	Silt 0.075~0.005 mm	Clay particle <0.005 mm	pH
0	2.69	6.7	49.8	43.5	9.25
0.08	2.44	4.5	63.1	32.4	8.50
0.10	2.48	4.1	62.6	33.3	8.36
0.20	2.43	3.8	65.8	30.4	8.28
0.40	2.37	10.2	63.8	26.0	8.04

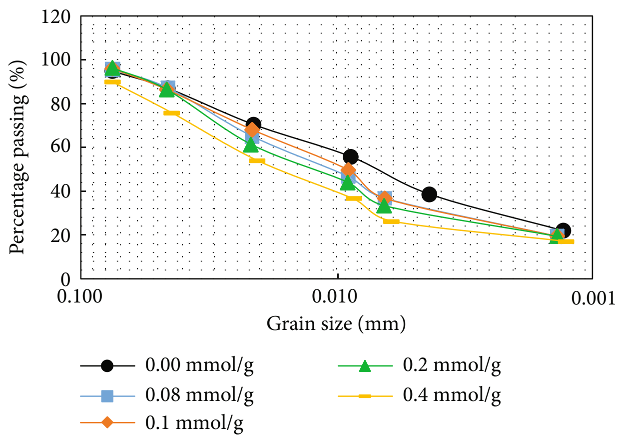


Figure 5: The curve of particle analysis under different hydroxyl aluminum contents.

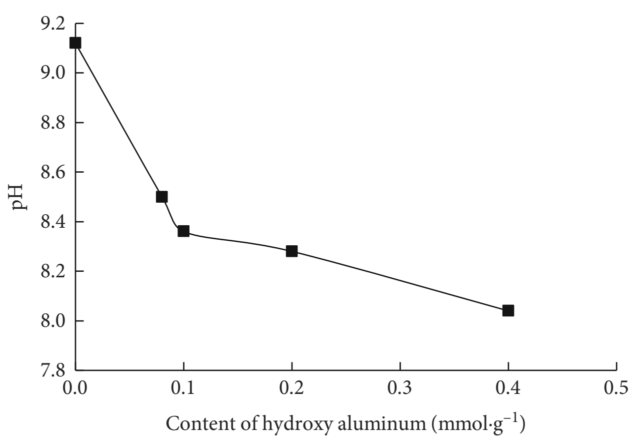


Figure 6: The curve of soil sample pH change with hydroxyl aluminum content.

110 ml distilled water through the buret, continue stirring the mixed solution for 20 min, and take samples after the hydroxyl aluminum solution turns to clear from turbidity, and leave the hydroxyl aluminum sample for one week.

The primary chemical reaction formula for the preparation of hydroxyl aluminum is shown in Formula (1). The device diagram and schematic diagram of the preparation of hydroxyl aluminum solution are shown in Figure 1.

$$Al^{3+} + 2OH^{-} \longrightarrow Al(OH)_2^{+} \quad (1)$$

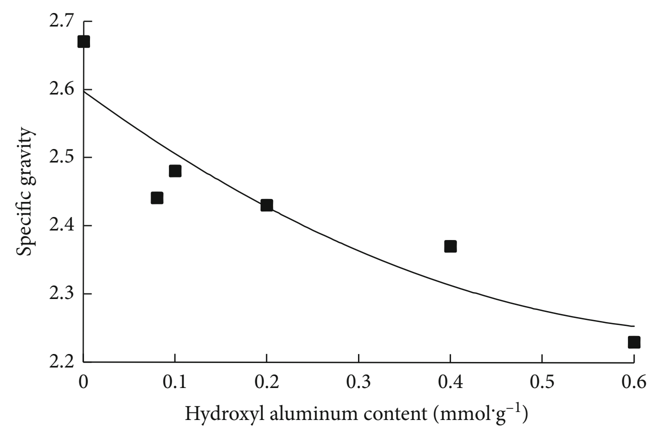
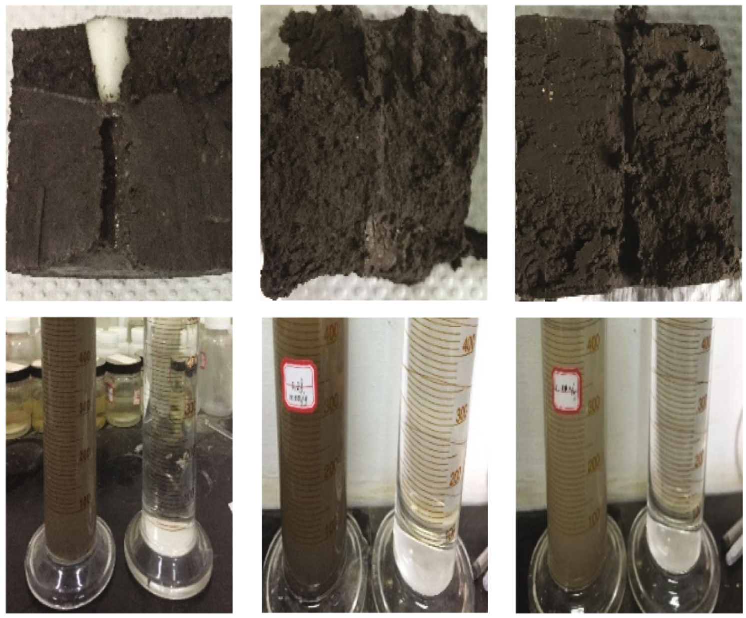


Figure 7: Variation of soil specific gravity with hydroxyl aluminum content.

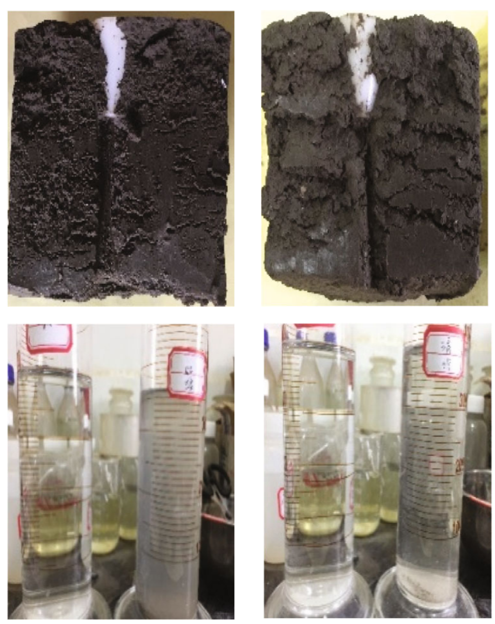
2.3. Soil Sample Preparation. In air-dry soil sample before the experiments, add different dispersant inhibitors: the hydroxyl aluminum solution with varying ratios of bauxite (0.08 mmol/g, 0.1 mmol/g, 0.2 mmol/g, and 0.4 mmol/g) mixed in the sample. The mixing samples are cured at room temperature for one week.

2.4. Main Test Items of Hydroxyl Aluminum Modified Dispersive Soil. Dispersion Discrimination Test: following the attainment of equilibrium and hydroxyl aluminum to these samples, based on the pinhole and crumb test methods given in ASTM d4647-93 and ASTM d421-99, the dispersibility of soil samples before and after modification was tested. And the modification effect with different modifiers was discussed. Other laboratory tests of the modified soil samples were done, including pH value, permeability coefficient, cohesion, internal friction angle, shear strength, SEM, and XRD. The dispersibility, strength, and microstructure of dispersive soil with different modifier content of hydroxyl aluminum were studied.

Shear Strength Test: the instrument used in the shear strength test is the FDJ-20 direct shear apparatus, as shown in Figure 2. The test soil sample is made of φ 61.8 mm × 20 mm (Figure 3). Each soil sample was sheared under different vertical pressures (100 kPa, 200 kPa, 300 kPa, and 400 kPa, respectively). The controlled shear rate is 0.08 mm/min, and the shear time is 10 min. The horizontal shear stress is applied to make the soil sample shear fail.



(a) 0 mmol/g (b) 0.08 mmol/g (c) 0.1 mmol/g



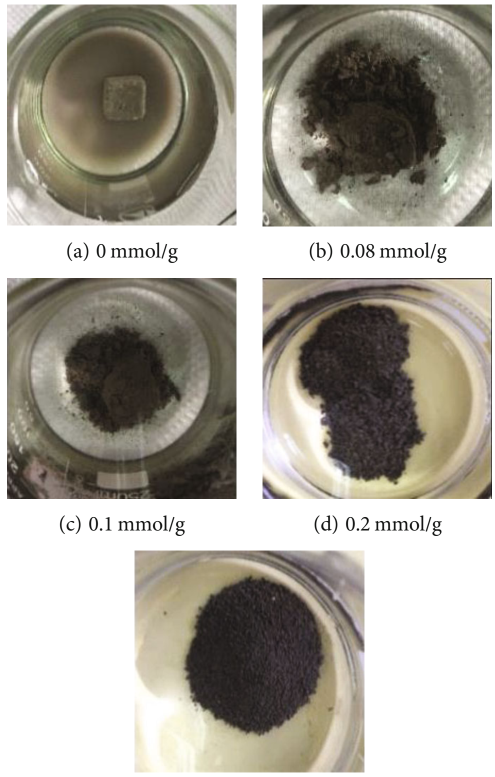
(d) 0.2 mmol/g (e) 0.4 mmol/g

Figure 8: Pinhole test before and after modification with different dosages of hydroxyl aluminum.

During the test, the unsaturated characteristics of the soil are not considered, and no air pressure is applied.

X-Ray Diffraction Test: the D8 advanced X-ray diffractometer of Bruker Company in Germany was used for X-ray diffraction analysis. X-ray diffraction tests were carried out on the samples before and after modification to study the changes in the phase composition of dispersive soil and crystal plane spacing of clay minerals before and after the modification of hydroxyl aluminum.

Specific Surface Area Test: according to BTE theory, all samples were analyzed using the N2 adsorption method on NOVA-1000 high-speed specific surface area and pore size analyzer of Quantan Chrome Company in the United States (in Figure 4). Working conditions are as follows: sample weight 100~500 mg, adsorbate N2 (>99.99%), carrier gas N2 (>99.99%), vacuum for 1.5 h, N2 adsorption temperature 77 K, and desorption temperature 393.15 k. Under these conditions, take the relative pressure as the abscissa and the adsorption capacity per unit sample mass as the ordinate, and draw the nitrogen adsorption isotherm and desorption isotherm. The specific surface area is calculated by the BET method, and the pore diameter is analyzed by the BJH method [20]. The T-method method obtained the micropore-specific surface area, mesopore (mesopore) specific surface area, and micropore volume. The specific surface area, particle size, pore size, and pore volume of the



(a) 0 mmol/g (b) 0.08 mmol/g

(c) 0.1 mmol/g (d) 0.2 mmol/g

(e) 0.4 mmol/g

Figure 9: crumb test before and after modification with different dosages of hydroxyl aluminum.

Table 3: Dispersion identification results of the soil before and after hydroxy aluminum modification.

Al/soil ratio/($mmol\cdot g^{-1}$)	Pinhole test			Crumb test		Comprehensive judgment
	Water head/ (mm)	Time/ (min)	Final aperture/ (mm)	Water	Soil sample	
0	50	5	≥6	Muddy	Disintegration	Dispersive soil
0.08	50	5	≥3	Muddy	Disintegration	Dispersive soil
0.10	50	5	≥2	Little muddy	Partial disintegration	Dispersive soil
0.20	50	5	≥1.5	Little muddy	Disintegration	Transition soil
0.40	50	5	1	Clear	Disintegration	Nondispersive soil

Criteria for dispersion: Double hydrometer test: nondispersive soil: dispersion <30%; transition soil: 50%~50%; and dispersive soil: the dispersity is greater than 50%. Pinhole test: nondispersive soil: under the water head - 1020 mm, the water is transparent and the final hole diameter is less than 1.5 mm; transition soil: under 50 mm water head, the outlet water is slightly turbid and the final aperture is less than 1.5 mm or under 380 mm water head, the outlet water is more transparent and the final aperture is greater than 1.5 mm; and dispersive soil: under the water head of 50 mm, the outlet water is turbid and the final pore diameter is greater than 1.5 mm. Fragment test: nondispersive soil: there is no reaction of dispersing colloidal particles. After hydrolysis, the soil blocks are stacked horizontally in the form of fine particles at the bottom of the measuring cup. The watercolor is clear or becomes clear soon after being slightly turbid; transition soil: there is a small amount of muddy water around the soil block after hydrolysis, but the diffusion range is small; and dispersive soil: after hydrolysis, the upper block is turbid and the soil quickly diffuses to the bottom of the whole measuring cup. The water is foggy and unclear for a long time.

modified dispersive soil were obtained by studying the specific surface area of the dispersive soil modified with different amounts of hydroxyl aluminum.

3. Test Results and Analysis

3.1. Physical and Chemical Properties of the Dispersive Soil. Dispersive soil always contains predominantly expansive lattice-type minerals such as montmorillonite. The treatment of aluminum hydroxide to dispersive soil is mainly with montmorillonite. In sensitive clay, the treatment effect of aluminum hydroxide in laboratory and outdoor in situ is better than that of hydrated lime [21]. Hydroxyl aluminum has a significant positive charge, improving clay's physical and chemical properties by neutralizing the reaction with clay particles with a negative charge and coating

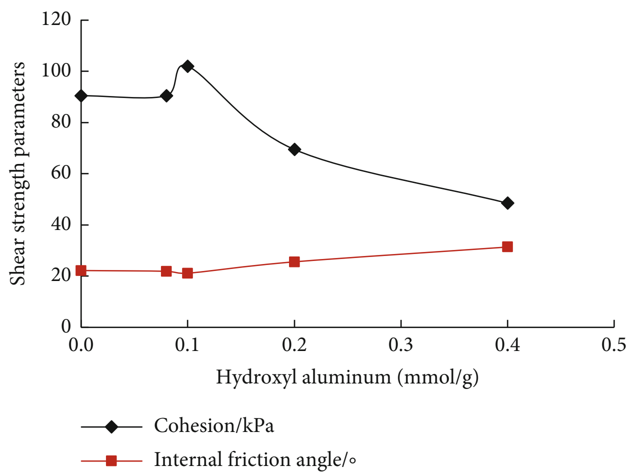


Figure 10: The adhesive force and internal friction angle change with aluminum compound content of modification clay sample.

adsorption [18]. Hydroxyl aluminum has also been proved to change soil's hydrophilicity and strength characteristics through ion exchange, coating, bonding, and other physical and chemical reactions with montmorillonite, significantly improving the physical properties and strength index of montmorillonite.

Based on the research team's previous micro experimental research results on hydroxyl aluminum-modified soil [22], different hydroxyl aluminum agent contents (0.08 mmol/g, 0.1 mmol/g, 0.2 mmol/g, and 0.4 mmol/g) are selected to be added into the dispersive soil. After modification by hydroxyl aluminum, specific gravity, particle analysis, pH test, and some other tests are carried out for the dispersive soil samples. The changes in the physical and mechanical properties of the soil samples are verified. The test results are shown in Table 2, which ululates that the physical and mechanical properties of the dispersive soil have some changes after modification.

The test results show that with the increase of hydroxyl aluminum content, the proportion and the clay content of the modified soil decrease, the silt content increases, and the alkaline weakens. After modification, the particle size increases (Figure 5), the specific surface area decreases, and the particles gather to form a more compact structure. Hydroxyl aluminum has the "agglomeration" and "cementation" effect on the dispersive soil particles, improving the dispersive soil's dispersion characteristics.

Dispersive soil is a high sodium soil formed by the secondary accumulation of weathering products due to evaporation. The pH value of the medium where the dispersive soil located is positively correlated with the degree of dispersion. The increment of negative charge on the particle surface is also positively correlated with the pH value [7]. The changing trend of pH value with the increase of hydroxyl aluminum content of the soil sample is shown in Figure 6. The result indicates that the pH of hydroxyl aluminum-modified soil decreases with hydroxyl aluminum content. The soil sample changes from strong alkali to weak alkali and even neutral with increasing hydroxyl aluminum content. It can be seen that the addition of hydroxyl aluminum changes the medium environment of the soil sample and increases the acidity of the soil sample.

Figure 7 shows the variation of soil-specific gravity with hydroxyl aluminum content. The range of soil-specific gravity is limited, generally between 2.6 and 2.8. After modifying hydroxyl aluminum, the ratio of aluminum to soil increases gradually, and the specific weight of soil particles decreases with the increase of the ratio of hydroxyl aluminum. The particular gravity value reduction range was 7.1%-16.5%, strengthening the connection between soil particles, the proportion of clay particles decreases, and the ratio of silt and sand increases. With the increase of large particle size, the particle weight per unit volume of the soil will be reduced accordingly, and the specific gravity of the soil becomes smaller.

3.2. Dispersion Change of Soil Sample Modification. Techniques are commonly used, such as the pinhole test, crumb test, and double hydrometer test. These tests may yield different results for the same soil samples; hence, multiple tests should be used to determine the dispersion of the soil [23, 24].

The results of the dispersion discrimination test of the soil samples with the modification of hydroxyl aluminum are shown in Figures 8 and 9. The results of the dispersion discrimination are shown in Table 3.

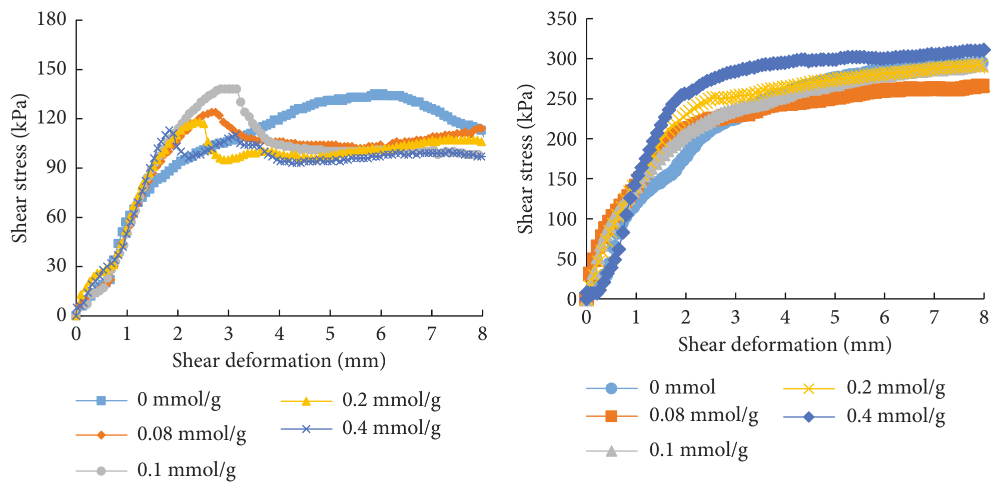
Pinhole Test: as the content of hydroxyl aluminum is 0.08 mmol/g, the pinhole diameter decreases, and the water flowing out from the pinhole is turbid; with the content of hydroxyl aluminum increasing, the pinhole diameter has a significant decreasing trend, and the turbidity degree of water flow out of the pinhole also decreases. When the content of hydroxyl aluminum is 0.4 mmol/g, the pinhole diameter hardly changes, and the water flow is bright.

Crumb Test: with the increase of hydroxyl aluminum content, all soil samples disintegrated to different degrees, but there was no turbidity in the beaker.

Double Hydrometer Test: with the increase of hydroxyl aluminum content, the dispersity of the soil sample decreases gradually. As the hydroxyl aluminum content is 0.08 mmol/g, the soil becomes transitional. As the hydroxyl aluminum content is 0.4 mmol/g, the soil turns into nondispersive soil. Hydroxyl aluminum also has a significant improvement effect on dispersive soil.

The dispersion discrimination test of hydroxyl aluminum-modified soil showed that the dispersion of soil samples had been restrained by different content of hydroxyl aluminum. With the increasing amount of modifiers, the diffusion of soil sample weakens clearly. The comprehensive test results showed that as the content of aluminum reaches 0.2-0.4 mmol/g, it has been dramatically suppressed because of the dispersion of the soil samples. Hydroxyl aluminum can bring about a good effect of restraining dispersion.

3.3. Shear Strength Changes of the Soil Samples. The adhesive force, internal friction angle, and the shear strength of the soil samples in different modifiers' content conditions are shown in Figure 10. It can be seen that the cohesion of the soil sample with different modifier content is all having an



(a) 100 kPa (b) 400 kPa

Figure 11: Stress-strain curve of hydroxyl aluminum-modified soil.

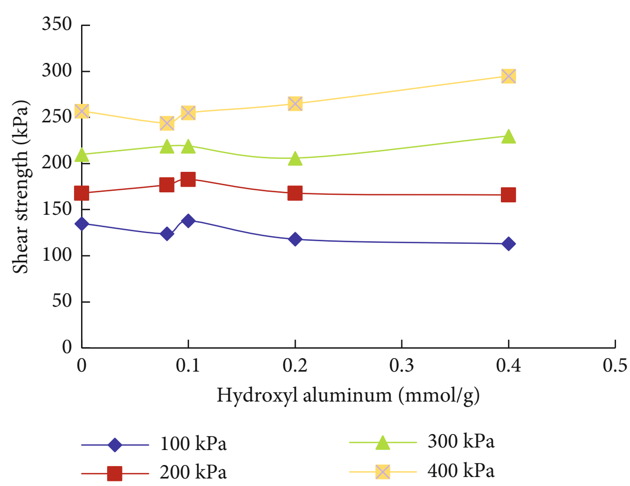


Figure 12: Shear strength changes of the modification clay sample.

Table 4: Variations of the crystal face space of montmorillonite (D001).

Hydroxyl aluminum content/($mmol\cdot g^{-1}$)	0	0.08	0.1	0.2	0.4
Distance between crystal faces of montmorillonite d_{001}/(Å)	14.21	14.79	14.504	14.327	15.41

apparent downward trend, and the internal friction angle of the modification soil samples has a slight increase with the increase of the modifier content. Still, the increasing extent is smaller than that of cohesion. The increase of internal friction angle indicates that the particles can be occluded and inlaid, form some new large particle, and then increases the internal friction angle. However, the decrease of cohesion shows that aluminum's physical and chemical reactions include hydroxyl aluminum solution entering into the particles with negative electricity, such as agglomeration and coating, which change the particle size distribution of the soil sample. As the clay particles in the soil sample achieve mutual adhesion, the content of clay particles in the soil sample is reduced, and the cohesion of the modified soil is reduced.

Figures 11 and 12 show the stress-strain curves of hydroxyl aluminum-modified soil under different vertical pressures. The stress-strain curves of soil are stress hardening with the load increasing. Under the same load condition, the shear strength of soil has no noticeable linear change with the increase of hydroxyl aluminum content. When the vertical load is 100 kPa, the stress-strain curve of the soil

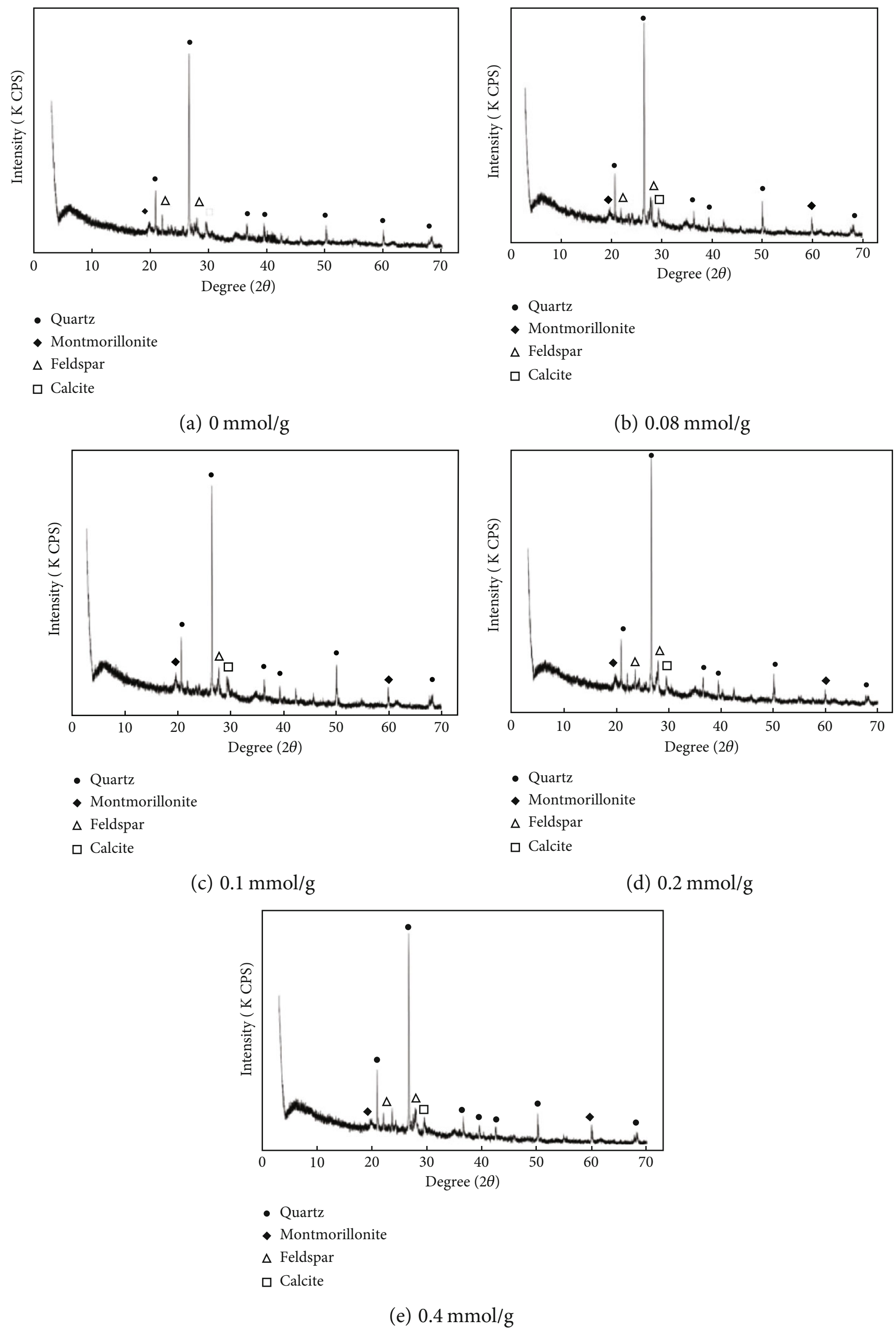


Figure 13: X-Ray diffraction pattern of soil samples with different contents of hydroxyl aluminum.

Table 5: Changes of specific surface area and pore size of hydroxyl aluminum-modified soil.

Hydroxyl aluminum content/ (mmol·g^{-1})	Specific surface area/ (m^2·g^{-1})	Cumulative pore volume/ (cm^3·g^{-1})	Average aperture/ (nm)
0	53.002	0.07089	2.6750
0.08	48.876	0.06808	2.7858
0.1	46.241	0.06083	2.7309
0.2	46.441	0.06376	2.7460
0.4	46.084	0.05892	2.8573

before modification is strain hardening type, and there is no obvious peak value of the stress-strain curve. After adding hydroxyl aluminum solution, the stress-strain curve of the modified soil increases rapidly with the increase of strain. When the stress peak value is reached, the stress decreases with the increase of shear displacement, and there is a prominent peak value characterized by strain softening. As the shear strength is significant (300 kPa and 400 kPa), the shear strength of the modified soil with 0.4 mmol/g hydroxyl aluminum content is significantly higher than that of the modified soil with other contents.

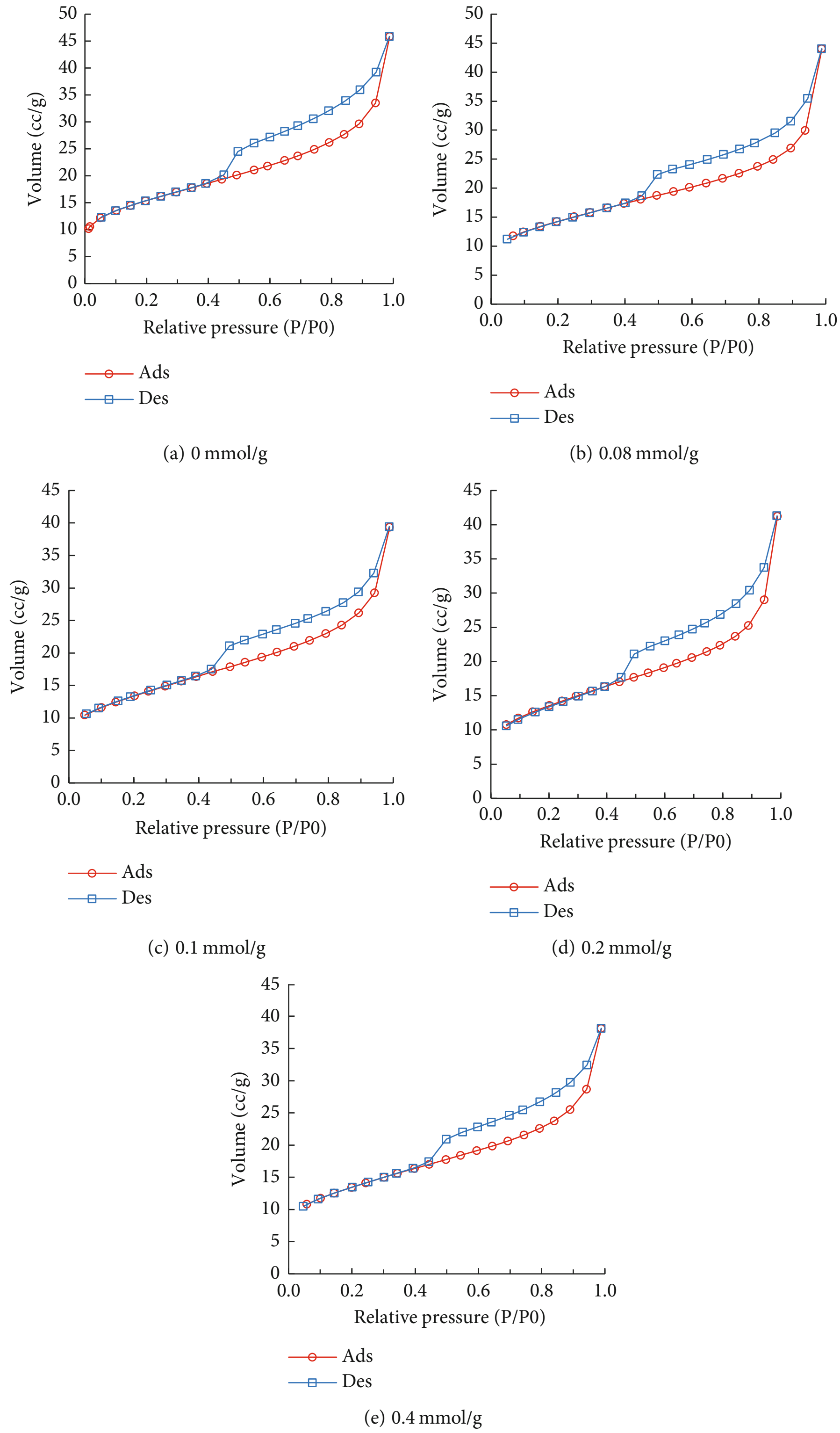
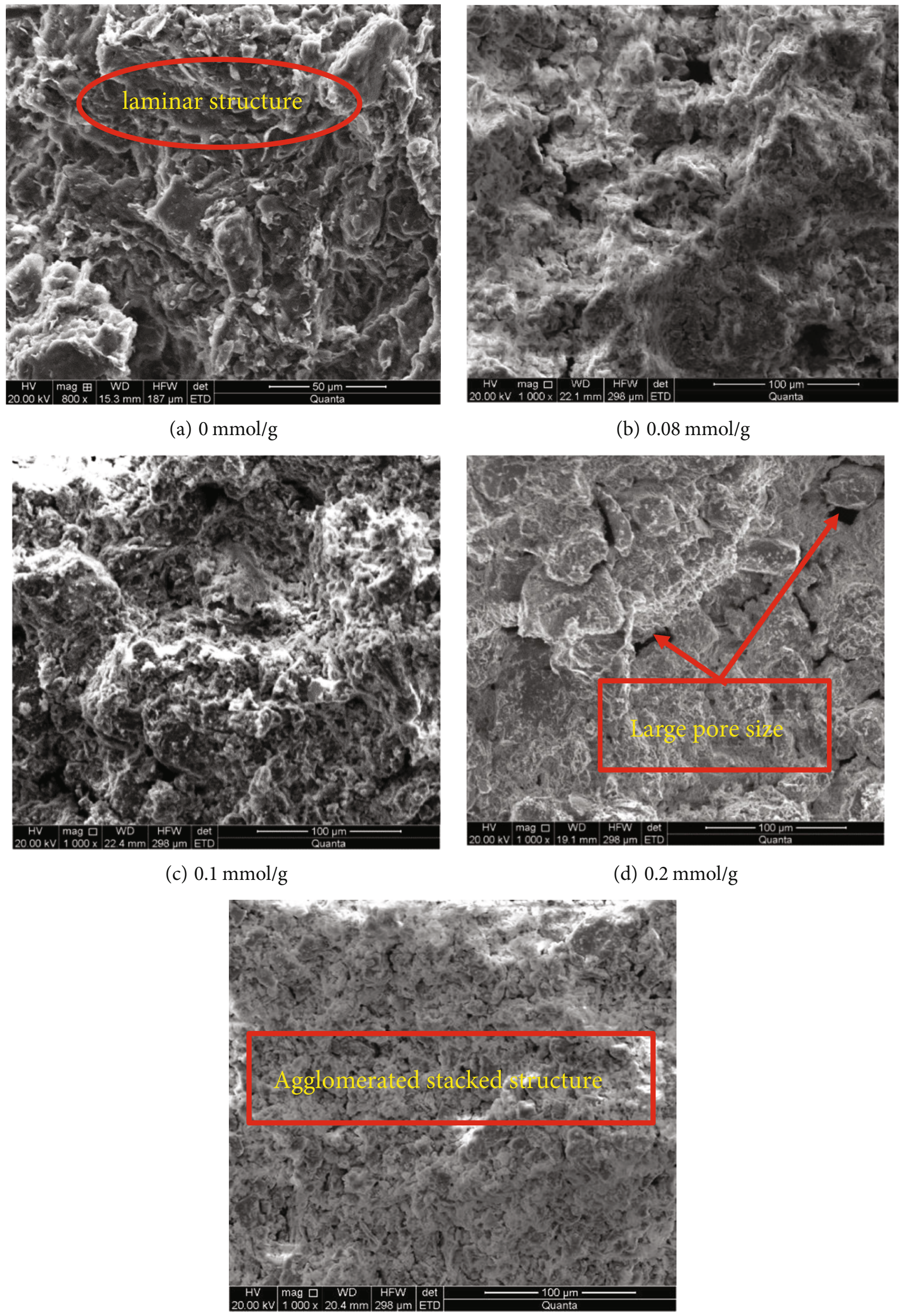


Figure 14: N2 adsorption-desorption isotherms with different amounts of hydroxyl aluminum.

4. Microscopic Changes of Hydroxyl Aluminum-Modified Soil

4.1. X-Ray Diffraction Test. Variations of the crystal face space of montmorillonite are listed in Table 4. As shown in Figure 13, montmorillonite is the main clay mineral composition, while the nonclay mineral composition is quartz, calcite, and feldspar. In the main clay mineral in the soil, the crystal surface spacing of montmorillonite increases with the content of hydroxyl aluminum increasing, which indicates that after the interaction of hydroxyl aluminum and soil samples, aluminum ions enter the interlayer of the soil



(a) 0 mmol/g

(b) 0.08 mmol/g

(c) 0.1 mmol/g

(d) 0.2 mmol/g

(e) 0.4 mmol/g

Figure 15: SEM test results of soil samples with different contents of hydroxyl aluminum.

and replace the interlayer water, reducing the amount of water absorbed by the soil, to reduce its hydrophobicity.

The diffraction pattern is the same before and after the interaction of hydroxyl aluminum with the soil sample. No new peak appears and disappears, which indicates no new phase appears. It can be explained that the physicochemical reaction between hydroxyl aluminum and dispersive soil is mainly the ion exchange adsorption on the surface of soil particles and the formation process of hydrogen bonds between the groups carried by polymer organic compounds and the crystal surface of minerals. Hydroxyl aluminum does not react with the soil to form new crystal compounds.

4.2. Specific Surface Area Test. The specific surface areas of soil samples with different hydroxyl aluminum contents are shown in Table 5.

Figure 14 shows the N2 adsorption-desorption isotherms with different amounts of hydroxyl aluminum; with the increase of hydroxyl aluminum content, the specific surface area and pore volume of dispersive soil gradually decrease, while the average pore size gradually increases. This result is because that hydroxyl aluminum promotes the connection between particles in the soil after entering the dispersive soil; the agglomerated particles increase. The pore volume also decreases gradually due to the stronger polymerization between soil particles and the increase of agglomerated particles. It also indirectly makes the grading of soil poor and increasing of the pore size. The adsorption isotherm of the modified soil given in Figure 13 belongs to a type II isotherm. It can be seen that the modified soil with different content shows the typical situation of multilayer adsorption of porous media. The hysteresis loop belongs to the H3 type, indicating that the pore shape is similar to the slit formed by parallel plates. The slope of the adsorption isotherm before modification is slightly more significant in the relative pressure range of 0.98~1.0. After modification, the slope decreases, indicating that the number of pores in the modified soil sample decreases. It also indirectly shows that the modification increases the large agglomerated particles in the soil, reducing the number of pores between the particles.

4.3. SEM Test Analysis. The micro view of dispersive soil modified with hydroxyl aluminum was tested by scanning electron microscope.

Figure 15 shows the SEM image of the soil sample at 1000 times magnification under different contents of hydroxyl aluminum. It can be seen that the connection between the particles of the soil sample with low content of hydroxyl aluminum is relatively loose, and the pores are strongly developed. The soil sample shows a laminar structure with large and thin clay flakes and clay minerals' typical soil morphology, agreeing with Ouhadi and Goodarzi [25]. With the addition of hydroxyl aluminum solution, the structural unit of the soil sample is mainly composed of the agglomerated stacked structure. The agglomerated crystals are arranged closely, and the number of large pores between the particles reduces clearly. The particles are stacked together to form a tight structure. The agglomeration, cementation, and other effects of hydroxyl aluminum on the dispersive soil make the content of significant and coarse powder increase and the content of clay decrease—the connection between the soil samples becomes closer. The structure becomes more stable to restrain the dispersion of soil samples. The scanning electron microscope shows that with the increase of hydroxyl aluminum content, the pore size of particles in the soil increases, and the significant aggregate particles increase. The results also directly verify the calculation results of specific surface area and pore diameter given in Table 5.

5. Conclusion

In this study, a new type of dispersive soil modifier, hydroxyl aluminum, is introduced. The effects of treating dispersive soil samples with different hydroxyl aluminum additive contents are investigated. The following conclusions of this study can be summarized from the test results:

(1) The test soil sample is highly dispersed. The dispersibility of the soil sample modified by hydroxyl aluminum decreases significantly and changes into nondispersive soil with the content increase of the modifier. In addition, with the increase of modifier content, the internal friction angle of the soil sample increases slightly, which shows that the modified soil particles are occluded and embedded to form new large particles to increase the internal friction angle. The clay particles in the soil sample adhere to each other, and the content of clay particles in the soil sample decreases, resulting in the cohesion decrease of the soil sample

(2) Under the same load condition, the shear strength of soil has no noticeable linear change with the increase of hydroxyl aluminum content. However, as the shear strength is large (300 kPa and 400 kPa), the shear strength of the modified soil with 0.4 mmol/g hydroxyl aluminum content is significantly higher than that of the modified soil with other contents

(3) The SEM and X-ray analyses depict a laminar structure with large and thin clay flakes of the sample without the additive. And the structural unit of the soil sample is mainly composed of the agglomerated stacked structure of the model with the additive. The addition of hydroxyl aluminum caused the sample agglomerated crystals to be arranged closely, and the number of large pores between the particles was reduced. This result is explained by the flocculation of the clay and the subsequent increase in particle size with the addition of the additive. This change in the microstructure corresponded to changes in the geotechnical properties of the soil

(4) The successful modification of dispersive soil by hydroxyl aluminum is expected to provide a scientific basis for the later engineering application of hydroxyl aluminum. The method of electrochemical injection of hydroxyl aluminum can be considered to treat the dispersed soil in situ. Hydroxyl aluminum solution diffuses to the extreme under electric pressure and cementates with dispersed clay to the greatest extent to realize the in situ treatment of dispersed clay subgrade. The application of hydroxyl aluminum will significantly improve the on-site project's economic, human and material costs and realize rapid treatment

Data Availability

Some or all data, models, or codes that support the findings of this study are available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this article.

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