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**Abstract:** Dispersive soil has the characteristic of being dispersed and lost when encountering water. In engineering practice, lime and cement are often used to modify dispersive soil, but doing so often has such problems as environmental pollution. The Si/Ca compound system composed of nano silica sol and calcium chloride is selected as the modified material for dispersive soil. The effect of the modification is studied by pinhole test, mud ball test, and dispersion and disintegration test. The mechanism of dispersive soil modified by Si/Ca compound system is explored by physical and chemical properties tests. The results show that the dispersibility of soil can be completely eliminated by using nano silica sol alone at 25% dosage or using calcium chloride alone at 0.40% dosage. However, the Si/Ca compound system composed of 1% nano silica sol and 0.05% calcium chloride can also completely eliminate the dispersion of soil, which effectively reduces the dosage of the two materials used alone. The disintegration process of the soil modified by nano silica sol modified is different from that of dispersive soil, with a shorter final disintegration time and a more stable disintegration rate. The final disintegration time is further shortened and the disintegration rate increases when the nano silica sol and calcium chloride are used together. The mechanism of dispersive soil modified by Si/Ca compound system includes reducing the percentage of exchangeable sodium ions and the pH of the soil, and generating calcium silicate hydrate. The results demonstrate that the Si/Ca compound system composed of nano silica sol and calcium chloride can effectively modify the dispersive soil.

**Keywords:** dispersive soil; nano silica sol; calcium chloride; disintegration characteristics; modification mechanism

### 1 Introduction

Dispersive soil is a kind of special soil with water sensitivity. In the water with low salt content, the cohesion of dispersive soil can decrease or even disappear completely because the repulsive force between ions exceeds the attractive force, and the aggregated soil particles are dispersed into the original graded particles<sup>[1]</sup>. Under the action of flowing water, dispersive soil is prone to various forms of failure such as erosion, scouring, and piping, which poses a serious threat to the safety of hydraulic engineering. The necessary conditions for the dispersibility of cohesive soil are the high content of sodium in the soil and the strong alkalinity of the soil<sup>[2]</sup>. When the percentage of exchangeable sodium ions is high, the repulsive force between soil particles is greater than the attractive force, and the net potential energy is represented as the repulsive force, resulting in the dispersion of soil<sup>[1]</sup>. According to the dispersion mechanism, various methods can be used to reduce or completely eliminate the dispersion. At present, there have been many research achievements in this field. Studies have shown that inorganic salts such as calcium, magnesium and aluminum<sup>[3]</sup>, as well as materials such as lime<sup>[4]</sup>, cement<sup>[5]</sup>, fly ash<sup>[6]</sup> and silica fume<sup>[7]</sup> all can be used to modify dispersive soil. With the deepening of research and the application of new materials, high-molecular

compound such as calcium lignosulfonate<sup>[8]</sup>, Xanthan gum<sup>[9]</sup>, urease induced calcium carbonate precipitation technology<sup>[10]</sup>, and pseudo-karstification calcium bicarbonate technology<sup>[11]</sup> have also been used to modify dispersive soil, and have made some achievements.

Soil disintegration refers to a characteristic of soil that undergoes wetting and disintegration when encountering water. It is of great practical significance to study the disintegration characteristics of soil in the fields of geotechnical engineering and soil-water conservation. Jian et al.<sup>[12]</sup> and Luo et al.<sup>[13]</sup> conducted a detailed study on the disintegration characteristics of granite residual soil, as well as the effects of dry density, initial moisture content and temperature on the disintegration process. Through exploring the disintegration characteristics of loess, Li et al.<sup>[14]</sup> believed that disintegration of loess includes fragmentation process, breaking process and separation process. Chen et al.<sup>[15]</sup> studied the dispersibility and disintegration characteristics of dispersive soil under different soil-water-electrolyte systems and simulated the water stability of dispersive soil under different water environments. They demonstrated that water quality is one of the important factors affecting the water stability of soil. Zhang et al.<sup>[16]</sup> investigated the effect of moisture content on the disintegration characteristics of loam soil in Moscow, Russia, and found that the disintegration rate of soil samples was faster under

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low moisture content.

Achieving the goals of ‘carbon peak and carbon neutrality’ is a major national strategic decision in China. The traditional modified materials, such as lime and cement, consume a lot of energy and emit a lot of carbon dioxide in the process of production, causing great pollution to the environment. In the practice of geotechnical engineering, both researchers and engineers focus more on the search for environmentally friendly soil modification materials. The research and application of nanomaterials are considered to be the most important field of scientific and technological in the 21st century, which is conducive to meeting the requirements of sustainable development<sup>[17]</sup>. Nanomaterials have special surface area effect and volume effect, which make them different from macroscopic scale materials. Currently, nanomaterials widely used in geotechnical engineering include nano silica, nano clay, nano alumina, carbon nanotubes, etc.<sup>[18]</sup>.

Nano silica is a common additive or modifier in geotechnical engineering and has been widely used to improve the mechanical properties and durability of concrete. Nano silica can react with calcium ions to produce calcium silicate hydrate, promoting cement hydration and enhancing concrete compactness<sup>[19]</sup>. At present, there have been many studies and applications in the reinforcement of silt<sup>[20]</sup>, loess<sup>[21]</sup> and expansive soil<sup>[22]</sup>. Nano silica, including solid state and sol state, is non-toxic, odorless and has the characteristics of biochemical inertia, high adsorption, high durability, etc.<sup>[23]</sup>. The silica molecules in the nano silica sol are connected by siloxane linkage (-Si-O-Si-), and the siloxyl alcohol group (-SiOH) and silicate ions in the

colloidal solution form a double layer with a small amount of metal cations under electrostatic action, which can be stable at room temperature and pressure<sup>[24]</sup>. In this study, based on the properties of nano silica sol and the dispersion mechanism of dispersive soil, a new method for modifying dispersive soil by the Si/Ca compound system composed of nano silica sol and calcium chloride was proposed. The modification effect and mechanism of the Si/Ca compound system for modifying dispersive soil were investigated through the dispersibility discrimination test, dispersion and disintegration test, and physical and chemical properties test.

## 2 Test materials and methods

### 2.1 Soil specimens

The soil used in this study was taken from a construction site on the east side of Yangquan Road, Yangling District, Shaanxi Province, with a depth of about 5 m. Yangling Loess is a typical non-dispersive soil. The obtained soil samples were first air-dried, ground up, and then the residual plant roots inside the soil samples were removed. After that, the Na<sub>2</sub>CO<sub>3</sub> solution with 0.16% dry soil mass fraction was added to the soil sample. Then, the sample was prepared to a water content of the liquid limit, stirred evenly, and standed for a few days to make it dispersible<sup>[25]</sup>. The basic physical and chemical properties of the soil used in the tests are shown in Table 1. The discrimination results of the mud ball test, pinhole test, double hydrometer test and exchangeable sodium test are shown in Table 2, showing that the soil used in this study is classified as a dispersive soil.

**Table 1 Basic physical and chemical properties of soil samples**

Specific gravity	Liquid limit	Plastic limit	Plastic index	Particle composition /%			Maximum dry density / (g · cm <sup>-3</sup> )	Optimal water content /%	Soluble salt content /%	Organic content /%	pH value
	/%	/%		>0.075 mm	0.075–0.005 mm	<0.005 mm					
2.71	29.9	18.5	11.4	1.3	63.5	35.2	1.77	16.5	0.17	0.53	9.75

**Table 2 Comprehensive discrimination of the dispersibility of soil samples**

Water head /mm	Pinhole test			Crumb soil test	Mud ball test	Percent dispersion of double hydrometer test /%	Percentage of exchangeable sodium R <sub>ESP</sub> /%	Comprehensive discrimination
	Time /s	Cloudiness	Hole size after test /mm					
50	300	Muddy	2.8	Dispersive soil	Dispersive soil	77.6	24.8	Dispersive soil

### 2.2 Test materials

In this paper, nano silica sol (hereinafter referred to as NS-S) is an acidic nano silica sol by Guangzhou Suize Environmental Protection Technology Co., Ltd. For this NS-S, the concentration is 30%, the average particle size is 10–13 nm, the specific gravity is 1.19–1.21, and the pH value is 2.5–3.5. The NS-S is in the form of a bright blue liquid. The calcium chloride used in this study was analytically pure anhydrous calcium chloride produced by Guangdong Guanghua Technology Co., Ltd., with a dosage of CaCl<sub>2</sub> greater than 96.0% and a pH value of 8.0–10.0.

### 2.3 Testing methods

The test parameters are listed in Table 3. In the test, nano silica sol and calcium chloride were selected as modifiers to examine the modification effects of the nano silica sol, calcium chloride and the compound system consisting of nano silica sol and calcium chloride (Si/Ca compound system) respectively on the dispersive soil, and to analyze the disintegration characteristics and mechanism of dispersive soil by the Si/Ca compound system.

The specific steps of soil preparation are as follows: a certain mass of sieved dispersive soil is first

taken, and a certain mass of nano silica sol and calcium chloride is calculated according to the test scheme and added to the soil sample. nano silica sol and calcium chloride are mixed evenly with the soil sample, and the water content is matched to the liquid limit. After air dried, the soil samples are ground and passed through a 2 mm geo-screen before testing.

**Table 3 Test parameters**

Type	Modifier dosage /%
Nano silica sol	0, 1, 3, 5, 7, 10, 15, 20, 25, 30
Calcium chloride	0, 0.05, 0.10, 0.15, 0.20, 0.30, 0.40

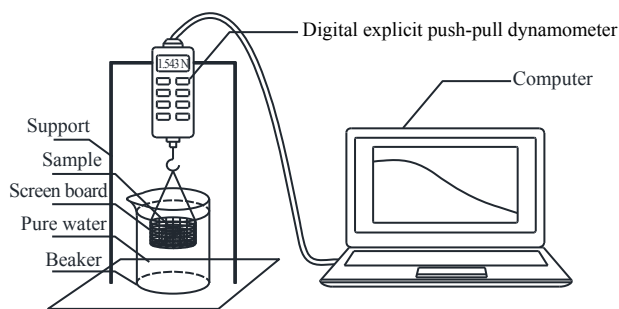
Note: Dosage refers to the percentage of the mass of nano silica sol or calcium chloride in the mass of dry soil.

### 2.3.1 Dispersibility discrimination tests

The pinhole test was conducted in accordance with the D4647-20<sup>[26]</sup> standard proposed by the American Society for Testing and Material (ASTM). The mud ball test was improved based on the crumb test according to ASTM D6572-20<sup>[27]</sup>. Specifically, the fine ground soil samples passing through the 2 mm sieve were prepared into uniform paste, then kneaded into about 1 cm<sup>3</sup> mud balls, and placed in deionized water to discriminate the dispersibility. This method can overcome the misjudgment caused by the displacement of colloidal particles in soil disturbed by gas burst in conventional crumb tests.

### 2.3.2 Dispersion and disintegration tests

The dispersion and disintegration test was carried out according to the Standard for Geotechnical Testing Method (GB/T 50123 – 2019)<sup>[28]</sup>. Following the device and method proposed in Fan et al.<sup>[29]</sup>, the disintegration rate of the soil sample under water immersion was measured. The test device used in this work is shown in Fig. 1.



**Fig. 1 Schematic diagram of disintegration testing apparatus**

### 2.3.3 Mechanism analysis test

The laser particle size analysis test was carried out using the Mastersizer 2000E laser particle size analyzer made in the UK. To avoid destroying the generated binding material, ultrasonic dispersion was not performed during the test. PHS-3C precision pH meter and DDS-11A conductivity meter produced by Shanghai Leimi Instrument Factory were selected for acidity and alkalinity test and conductivity test,

respectively. According to the method in Appendix F of ‘Study of dispersive soil’<sup>[1]</sup>, the exchangeable sodium percentage test was performed using ZA3000 atomic absorption spectrometer manufactured by Hitachi, Japan. The scanning electron microscope test was carried out using an S-4800 field emission scanning electron microscope produced by Hitachi, Japan.

## 3 Dispersibility test results

### 3.1 Effect of nano silica sol on the dispersibility

Due to the complexity of the dispersion mechanism of dispersed soil, it is difficult to accurately discriminate the dispersibility of soil samples only using one type of test. Therefore, the pinhole test and the mud ball test were used together to discriminate the dispersibility comprehensively. The test results of the nano silica sol modified dispersive soil are shown in Table 4, and the test results of dispersibility for typical modified soil are plotted in Fig. 2.

The results showed that the dispersibility of modified soil decreased significantly with the increase of nano silica sol dosage. When the dosage of nano silica sol was less than 10%, both the pinhole test and the mud ball test showed dispersion. When the dosage of nano silica sol was 10%, the pinhole test showed transitional behaviour, while the mud ball test showed dispersion. When the dosage of nano silica sol was 15% and 20%, both the pinhole test and the mud ball test showed transitional behaviour, and the transitional behaviour gradually weakened. When the dosage of nano silica sol was 25% and 30%, the dispersibility of the dispersive soil was eliminated, and both the pinhole test and the mud ball test showed non-dispersion.

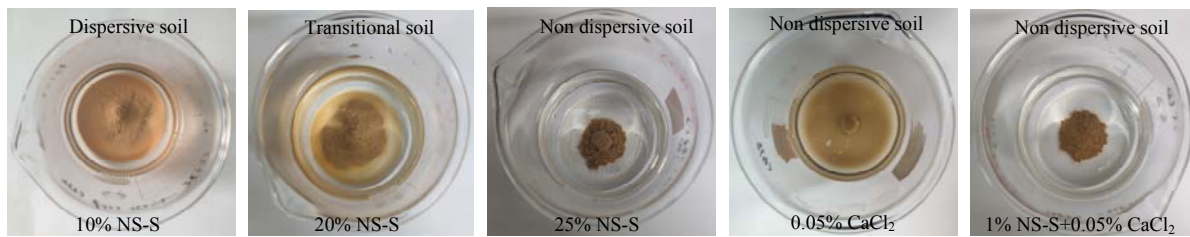
### 3.2 Effect of calcium chloride on the dispersibility

In the test, six different dosages of calcium chloride (CaCl<sub>2</sub>) were set. The results of the discrimination test for dispersibility are shown in Table 4. The dispersibility test results of the typical modified soil samples are shown in Fig. 2.

The results showed that when the dosage of calcium chloride was 0.30% or less, the dispersibility of soil samples could not be completely eliminated. When the content of calcium chloride was 0.05% and 0.10%, both the pinhole test and the mud ball test showed dispersion. When the content of calcium chloride was 0.20% and 0.30%, both the pinhole test and the mud ball test showed transitional behaviour. When the dosage of calcium chloride was 0.40%, both the pinhole test and the mud ball test showed non-dispersion, which is consistent with the results obtained by Zhao et al.<sup>[3]</sup> that the dosage of calcium chloride of 0.34% can be used to effectively modify the dispersibility of soil. The results also showed that in the case of using only calcium chloride, 0.15% or less of calcium chloride still could not effectively modify the soil dispersibility, and the dispersibility of soil can be eliminated only when the dosage of calcium chloride was at least 0.40%.

**Table 4** Dispersibility test results

Type	Group	NS-S dosage /%	Calcium chloride dosage /%	Pinhole test					Mud ball test	Comprehensive discrimination	
				Water head /mm	Time /s	Flow rate /( $\text{mL} \cdot \text{s}^{-1}$ )	Cloudiness	Hole size after test /mm			Results
Dispersive soil	—	0	0.00	50	600	0.29	Muddy	2.5	Dispersive	Dispersive	Dispersive
	—	1	0.00	50	600	0.35	Muddy	2.3	Dispersive	Dispersive	Dispersive
	—	3	0.00	50	600	0.32	Muddy	2.7	Dispersive	Dispersive	Dispersive
Nano silicon treatment	—	5	0.00	50	600	0.41	Muddy	2.1	Dispersive	Dispersive	Dispersive
	—	7	0.00	50	600	0.33	Muddy	1.7	Dispersive	Dispersive	Dispersive
	—	10	0.00	180	300	0.43	Muddy	1.1	Transitional	Dispersive	Dispersive
	—	15	0.00	180	300	0.38	Slightly muddy	1.5	Transitional	Transitional	Transitional
	—	20	0.00	1 020	300	1.22	Clear	1.2	Non-dispersive	Transitional	Transitional
	—	25	0.00	1 020	300	1.53	Clear	1.0	Non-dispersive	Non-dispersive	Non-dispersive
	—	30	0.00	1 020	300	1.49	Clear	1.0	Non-dispersive	Non-dispersive	Non-dispersive
Calcium chloride treatment	—	0	0.05	50	600	0.26	Muddy	2.5	Dispersive	Dispersive	Dispersive
	—	0	0.10	50	600	0.22	Muddy	1.8	Dispersive	Dispersive	Dispersive
	—	0	0.15	180	300	0.49	Muddy	1.7	Transitional	Dispersive	Dispersive
	—	0	0.20	180	300	0.33	Muddy	1.7	Transitional	Transitional	Transitional
	—	0	0.30	380	300	0.84	Muddy	1.6	Transitional	Transitional	Transitional
Si/Ca compound system treatment	—	0	0.40	1 020	300	1.72	Clear	1.0	Non-dispersive	Non-dispersive	Non-dispersive
	I	1	0.05	1 020	300	1.25	Clear	1.0	Non-dispersive	Non-dispersive	Non-dispersive
	I	3	0.05	1 020	300	1.53	Clear	1.0	Non-dispersive	Non-dispersive	Non-dispersive
	I	5	0.05	1 020	300	1.60	Clear	1.0	Non-dispersive	Non-dispersive	Non-dispersive
	I	7	0.05	1 020	300	2.00	Clear	1.0	Non-dispersive	Non-dispersive	Non-dispersive
	I	10	0.05	1 020	300	0.87	Clear	1.0	Non-dispersive	Non-dispersive	Non-dispersive
	II	1	0.10	1 020	300	1.80	Clear	1.0	Non-dispersive	Non-dispersive	Non-dispersive
	II	3	0.10	1 020	300	1.53	Clear	1.0	Non-dispersive	Non-dispersive	Non-dispersive
	II	5	0.10	1 020	300	0.95	Clear	1.0	Non-dispersive	Non-dispersive	Non-dispersive
	II	7	0.10	1 020	300	1.75	Clear	1.0	Non-dispersive	Non-dispersive	Non-dispersive
	II	10	0.10	1 020	300	1.00	Clear	1.0	Non-dispersive	Non-dispersive	Non-dispersive
	III	1	0.15	1 020	300	0.97	Clear	1.0	Non-dispersive	Non-dispersive	Non-dispersive
	III	3	0.15	1 020	300	1.37	Clear	1.0	Non-dispersive	Non-dispersive	Non-dispersive
	III	5	0.15	1 020	300	1.02	Clear	1.0	Non-dispersive	Non-dispersive	Non-dispersive
III	7	0.15	1 020	300	1.13	Clear	1.0	Non-dispersive	Non-dispersive	Non-dispersive	
III	10	0.15	1 020	300	1.75	Clear	1.0	Non-dispersive	Non-dispersive	Non-dispersive	



(a) Mud ball test results



(b) Pinhole test results

**Fig. 2** Typical dispersibility test results of modified soil

**3.3 Effect of Si/Ca compound system on the dispersibility**

For the Si/Ca compound system composed of nano silica sol and calcium chloride, the dosages of 0.05%, 0.10% and 0.15% calcium chloride were divided into groups I–III, and the dosage of nano silica sol in each group was 1%, 3%, 5%, 7% and 10%. The test results of using Si/Ca compound system to modify dispersive soil are shown in Table 4. The dispersibility test results of the typical modified soil samples are

shown in Fig. 2.

The results showed that the pinhole test and mud ball test of the soil samples modified by the Si/Ca compound system in these three groups exhibited non-dispersive behavior. When the dosages of nano silica sol and calcium chloride were 1.00% and 0.05%, respectively, the Si/Ca compound system composed of nano silica sol and calcium chloride can eliminate the dispersibility of soil. This suggests that the Si/Ca compound system can effectively reduce the dosage of

each single material, namely nano silica sol and calcium chloride, and the modification effect is better.

The test results in this study provide a guiding ratio for the use of the Si/Ca compound system to modify dispersive soil. In practical engineering applications, according to the dispersibility of soil, exchangeable sodium ion content, soil particle composition and construction conditions, the ratio of nano silica sol and calcium chloride can be adjusted on the basis of the design dosage proposed in this study to ensure the modification effect. During construction, nano silica sol and calcium chloride can be prepared into the solution, and the dispersive soil on the surface can be in-situ modified using spraying vehicles, self-spraying pipes, etc. Pressure grouting can also be used to modify deep dispersive soil, and the specific construction application methods still need to be further studied in conjunction with engineering.

#### 4 Dispersion and disintegration test results of modified soil

Through a series of dispersion and disintegration tests, the disintegration characteristics of the soils modified by only nano silica sol of 10%–30% dosage, the soils modified by three different groups of Si/Ca compound system and the dispersive soil were investigated when they were exposed to water. The curves of disintegration rate over time is shown in Fig. 3, and the final disintegration time is shown in Table 5. The test results are shown below:

(1) The disintegration characteristics of dispersive soil were characterized by slow water absorption and spalling in the initial stage and rapid disintegration in the late stage. At the initial stage, the disintegration rate of dispersed soil was in the range of  $-1\%$ – $0\%$ , that is, the soil sample expanded by water absorption, and the surface of the soil sample presented spalling. Soil samples began to disintegrate when they absorbed water and expanded to a certain extent. Soil particles gradually dispersed and collapsed under the action of water, and a large number of cloud-like suspended clay particles began to appear in the water. As shown in Fig.3(a), there was a mutation point at 1 890 s of the curve, at which the soil sample collapsed rapidly and the disintegration rate reached the maximum. In the final stage, the disintegration rate slowed down because there were still a few small slowly falling soil blocks on the grid board. The overall structure of the soil sample had completely disintegrated at 2 200 s, and the disintegration rate reached 100% at 2 880 s. The rapid disintegration process lasted for 310 s in total.

(2) It can be seen from Fig.3(a) that the disintegration rate and final disintegration time of nano silica sol modified soil had little change with the increase of nano silica sol dosage. The disintegration rate was relatively small at the initial and late stages, and relatively large in the middle stages. The disintegration rate remained basically stable in the middle and late stages, with no obvious mutation points, and the curve tended to be smooth. At the initial stage, the disintegration rate did not show negative values, indicating that water absorption expansion and disintegration occurred simultaneously when the soil sample came into contact with water. The final disintegration time of nano silica sol modified soil was concentrated between 600 and 750 s. Since the soil sample still had a certain dispersibility when the dosage of nano silica sol was 10% and 15%, in the process of disintegration, fine particles still spalled off, and a small amount of cloud-like clay suspended in the water, but no rapid collapse occurred. When the dosage of nano silica sol was 20% and above, in the process of disintegration, the modified soil appeared as flake or block spalling, and there was no obvious cloud-like clay particles suspension in the water. The test results indicated that nano silica sol could play a cementation and consolidation role in the soil, promote the aggregation of soil particles, and form a bond between adjacent soil particles, making the soil particles difficult to disperse in water and stabilizing the soil sample disintegration process.

(3) From Figs. 3 (b) to 3 (d), it can be observed that for Si/Ca compound system, when the dosage of nano silica sol remained unchanged, the final disintegration time of soil samples became shorter with the increase of the dosage of calcium chloride, and a large number of block spalling occurred in the process of disintegration, suggesting that calcium chloride improved the disintegration rate of soil samples. While the disintegration characteristics did not change significantly with the increase of the dosage of nano-silicon when the dosage of calcium chloride was unchanged. At the initial stage of slow disintegration, the disintegration rate of the soil sample was slow, at which the soil sample would absorb water and expand. During this process, there was a difference of expansion pressure inside the soil samples, and the blocked air within the pores escaped due to the pressure, which was manifested as a large number of floating bubbles on the surface of the soil sample. Under this action, the cohesion between soil particles decreased, water gradually infiltrated into the soil through the pores, and cracks appeared in the structural weakness of the soil sample. Subsequently, flake or block disintegration occurred, and the disintegration rate increased gradually with time and continued until the soil sample completely disintegrated.

(4) After modification, the disintegration characteristics of dispersive soil changed significantly. On the one hand, the disintegration rate was accelerated, and on the other hand, the morphological structure of soil particles during disintegration changed from fine particle scaly spalling to block spalling, which is consistent with the findings in Chen et al.<sup>[15]</sup>. This is because under the action of cementation and agglomeration of nano silica sol and calcium chloride, the fine particles congregated into large particles, and under the action of static water, water entered the interior of the soil, causing the disintegration and collapse of the soil particles.

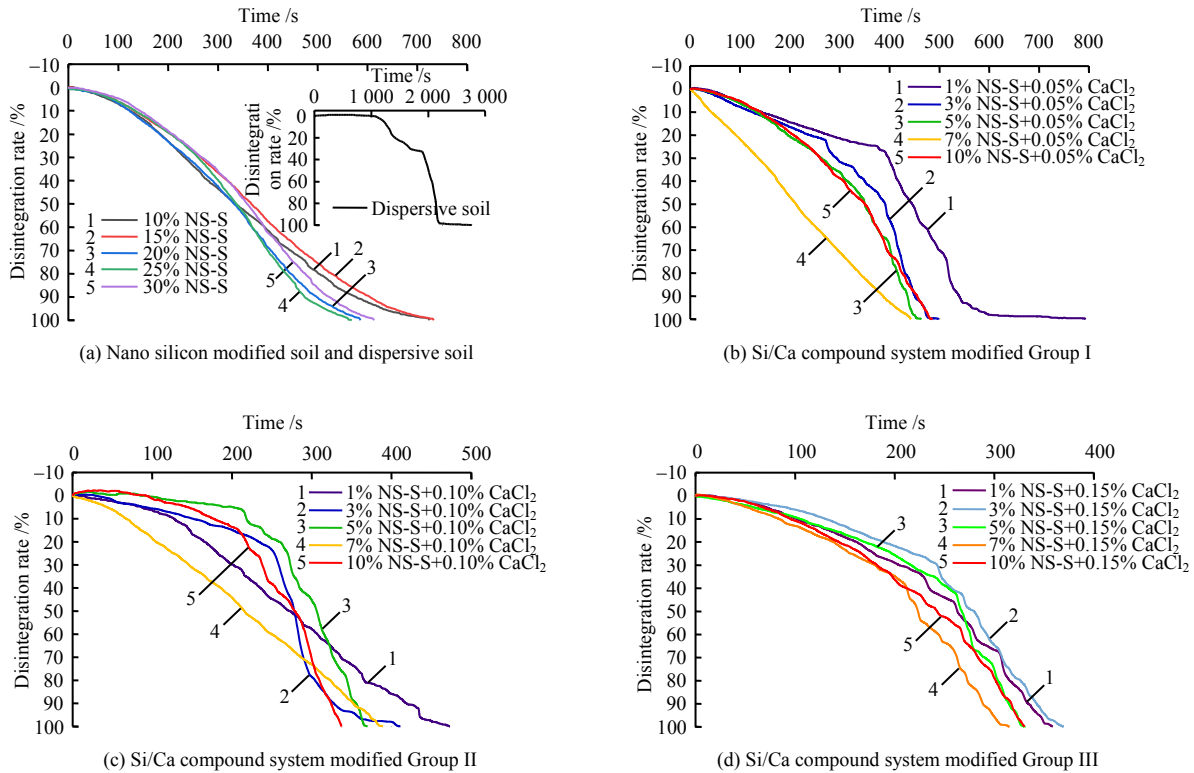


Fig. 3 Disintegration rate–time curves

Table 5 Final disintegration time

Type	Group	NS-S dosage /%	Calcium chloride dosage /%	Final disintegration time/s
Dispersive soil	—	—	—	2 880.0
Nano silicon sol treatment	—	10	—	731.2
	—	15	—	733.3
	—	20	—	586.2
	—	25	—	568.8
	—	30	—	613.3
Si/Ca compound system treatment	I	1	0.05	793.5
	I	3	0.05	499.3
	I	5	0.05	463.8
	I	7	0.05	442.8
	I	10	0.05	485.6
	II	1	0.10	472.1
	II	3	0.10	411.2
	II	5	0.10	369.7
	II	7	0.10	389.4
	II	10	0.10	337.6
	III	1	0.15	358.7
	III	3	0.15	369.7
	III	5	0.15	330.3
	III	7	0.15	315.1
	III	10	0.15	330.2

## 5 Mechanism for modifying dispersive soil by Si/Ca compound system

### 5.1 Laser particle size analysis test

The laser particle size analysis tests were carried out on the modified soil by only nano silica sol dosage of more than 15%, the modified soil by Si/Ca compound system, and the dispersive soil. The calculated particle volume composition is shown in Table 6. To obtain the distribution characteristics of the granular structure of the soil sample and avoid the destruction of the binding material generated by modification, the ultrasonic

dispersion was not performed on soil samples in the laser particle size analysis test.

Table 6 Composition of particle volume

Type	Group	NS-S dosage /%	Calcium chloride dosage /%	Proportion of particle volume /%		
				<5 μm	5–75 μm	>75 μm
Dispersive soil	—	—	—	9.8	71.1	19.1
Nano silicon treatment	—	15	—	4.8	56.4	38.9
	—	20	—	4.0	50.8	45.2
	—	25	—	4.4	51.3	44.3
	—	30	—	3.8	46.1	50.2
	Si/Ca compound system treatment	I	1	0.05	4.5	82.5
I		3	0.05	3.5	78.0	18.5
I		5	0.05	3.5	72.5	24.0
I		7	0.05	3.3	66.7	30.1
I		10	0.05	3.8	69.6	26.6
II		1	0.10	6.0	68.3	25.7
II		3	0.10	5.4	61.8	32.8
II		5	0.10	5.6	54.5	39.9
II		7	0.10	4.3	47.1	48.6
II		10	0.10	5.6	46.9	47.5
III		1	0.15	3.4	72.7	23.9
III		3	0.15	2.9	66.5	30.6
III		5	0.15	2.5	59.8	37.7
III		7	0.15	2.7	55.6	41.7
III		10	0.15	2.8	52.9	44.4

One can see from Table 6 that after the dispersive soil is modified by nano silica sol, the particles of dispersive soil below 5 μm and in range of 5–75 μm are reduced, and the particles larger than 75 μm are significantly increased. The higher the dosage of nano silica sol, the higher the content of particles above 75 μm. After drying and setting in soil samples, nano silica sol can form a large amount of binding material, wrapping



and aggregating dispersed small particles into large particles. Thus, the specific surface area of soil particles decreases, and the contact surface with water also decreases accordingly. This indicates that the agglomeration of nano silica sol can effectively inhibit the dispersibility of soil.

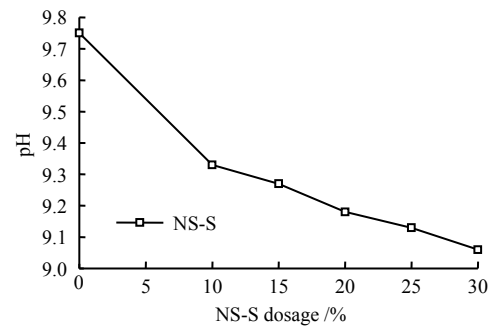
From the test results of Si/Ca compound system modified soil in groups I–III, it can be seen that the content of large particles increases with the increase of the dosages of both calcium chloride and nano silica sol. This suggests that the addition of calcium chloride on the basis of nano silica sol can further promote the agglomeration of soil particles through ion exchange, chemical reaction and shortening the gelation time of nano silica sol, which can effectively inhibit the dispersibility of the soil and significantly reduce the dosage of nano silica sol.

### 5.2 Acidity and alkalinity tests

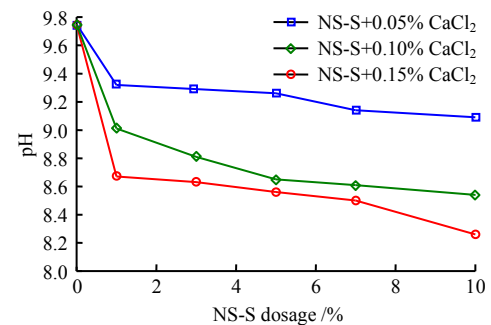
Acidity and alkalinity (pH) are important factors affecting the electrokinetic potential of soil, and the electrokinetic potential reflects the thickness of the double layer. Under alkaline conditions, clay particles form a stable negatively charged double layer, which adsorbs more  $\text{Na}^+$ . In this case, the electrokinetic potential increases, the thickness of the double layer and hydration film increases, and the clay particles tend to disperse<sup>[1]</sup>.

The acidity and alkalinity test results of the soil modified by only nano silica sol are shown in Fig. 4(a). Due to the acidity of nano silica sol used, the pH value of nano silica sol modified soil decreased from 9.75 to 9.06 with the increase of nano silica sol dosage. In the range of 10%–30% nano silica sol dosage, the pH value showed a linear relationship with the dosage of nano silica-sol.

The acidity and alkalinity test results of the soil modified by the Si/Ca compound system are shown in Fig. 4(b). It can be found that the pH of soil decreased with the increase of the dosages of nano silica sol and calcium chloride. Both nano silica sol and calcium chloride had the effect of reducing soil alkalinity. The higher the dosage of calcium chloride, the stronger the effect of reducing soil alkalinity. In the case of only adding nano silica sol, the pH value decreased to 9.06 when nano silica sol dosage was 30%. After adding calcium chloride, the pH value of the modified soil with 1% dosage of nano silica sol and 0.15% dosage of calcium chloride was reduced to 8.67. This is because calcium chloride is acidic after hydrolysis in water, reducing the pH value of the soil. This suggests that nano silica sol, whether used alone or in combination with calcium chloride, can promote the agglomeration and flocculation of soil particles and inhibit or completely eliminate the dispersibility of soil by reducing the soil alkalinity and the thickness of double layer and hydration film.



(a) pH value of nano silicon modified soil



(b) pH value of the soil modified by Si/Ca compound system

**Fig. 4 Variation curves of the pH of modified soil**

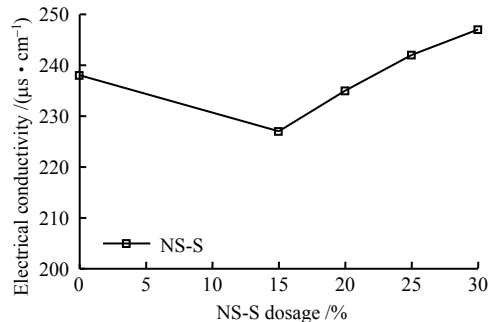
### 5.3 Conductivity tests

According to the soil-to-water ratio of 1:5, a certain mass of soil was first mixed with pure water to form the soil-water suspension, and then the electrical conductivity was measured by conductivity test, and the test results are shown in Fig. 5. Since the dispersibility of the soil was not significantly reduced when the dosage of nano silica sol was 10%, only the conductivity changes of soil samples at 15% to 30% dosage were examined.

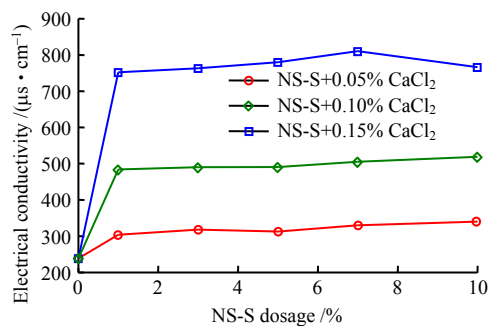
It can be seen from Fig. 5(a) that the conductivity of the soil sample varied within the range of  $\pm 5\%$ , indicating that there were fewer free ions in the nano silica sol, and the nano silica sol existed mostly in the form of binding material among the soil particles after being completely air-dried. As can be seen from Fig. 5(b), when nano silica sol and calcium chloride acted together, the conductivity was positively correlated with the dosage of nano silica sol and calcium chloride, and calcium chloride had a greater effect on the soil conductivity.

Kaya et al.<sup>[30]</sup> demonstrated that the increase in soil conductivity meant that the ion concentration increased, the dielectric constant decreased, and the thickness of the electric double layer became thinner under the neutralization of the surface charge of the soil particles. According to the double layer theory, as clay particles carry the negative charge, the low-valent  $\text{Na}^+$  ions adsorbed by the dispersive soil with high sodium content can increase the number of cations in the double layer, making the diffused layer and hydration film thicker, as a result, the clay particles show dispersive behavior. When high-valent  $\text{Ca}^{2+}$  ions are introduced,  $\text{Na}^+$  adsorbed by clay particles is replaced by ion exchange. More electricity

in the adsorption layer is neutralized by cations, the diffused layer and hydration film become thinner, thus the clay particles are easy to agglomerate. Calcium chloride can increase the conductivity of soil samples and reduce the thickness of the electric double layer of soil particles, eliminating the dispersibility of the soil.



(a) Electrical conductivity of nano silicon modified soil



(b) Electrical conductivity of the soil modified by Si/Ca compound system

**Fig. 5** Variation curves of the electrical conductivity of modified soil

#### 5.4 Exchangeable sodium percentage test

The exchangeable sodium percentage (ESP) refers to the ratio of exchangeable sodium adsorbed by the soil to cation exchange capacity (CEC). Generally, a higher ESP value of soil has a stronger dispersibility. The ESP values of the soil samples modified by only nano silica sol, the soil samples modified by Si/Ca compound system in group I, and two soil samples, with 5% nano silica sol dosage, modified by Si/Ca compound system in group II and III, were determined by the exchange sodium percentage test, and the test results are shown in Table 7.

**Table 7** Results of exchangeable sodium ion percentage test

Type	NS-S dosage /%	Calcium chloride dosage /%	Na <sup>+</sup> / (cmol · kg <sup>-1</sup> )	CEC / (cmol · kg <sup>-1</sup> )	ESP /%
Dispersive soil	—	—	4.5	17.9	24.8
Nano silicon treatment	10	—	2.7	24.0	11.3
	15	—	2.0	17.8	11.3
	20	—	1.8	17.0	10.4
	25	—	2.1	21.7	9.9
	30	—	1.9	20.5	9.2
compound system treatment	1	0.05	1.6	20.6	8.0
	3	0.05	1.6	20.2	8.0
	5	0.05	1.3	21.4	6.0
	7	0.05	1.4	24.6	5.8
	10	0.05	1.8	21.4	8.2
	5	0.10	1.9	27.9	6.7
	5	0.15	0.8	22.8	3.6

The test results showed that nano silica sol could effectively reduce the exchangeable sodium content of the dispersive soil, and the ESP value decreased from 24.8% to less than 12.0%. Under the optimal dosage of 25% nano silica sol, the ESP value decreased by 60.1%, suggesting that the nano silica sol was also involved in ion exchange reactions and chemical reactions in addition to the agglomeration. According to the acidity and alkalinity test, the H<sup>+</sup> ions existing in the sol environment can also neutralize the OH<sup>-</sup> in some soils, reducing the adsorption capacity of Na<sup>+</sup> by clay particles, hence exchangeable sodium is released into the pore solution environment, becoming free Na<sup>+</sup>.

The exchangeable sodium percentage of soil can be further reduced by cementation and ion displacement under the combined action of nano silica sol and calcium chloride compound system. When the dosages of both nano silica sol and calcium chloride were the lowest, the ESP value of soil can be reduced to 8.0%, and the ESP showed a decreasing trend with the increases of nano silica sol and calcium chloride dosages.

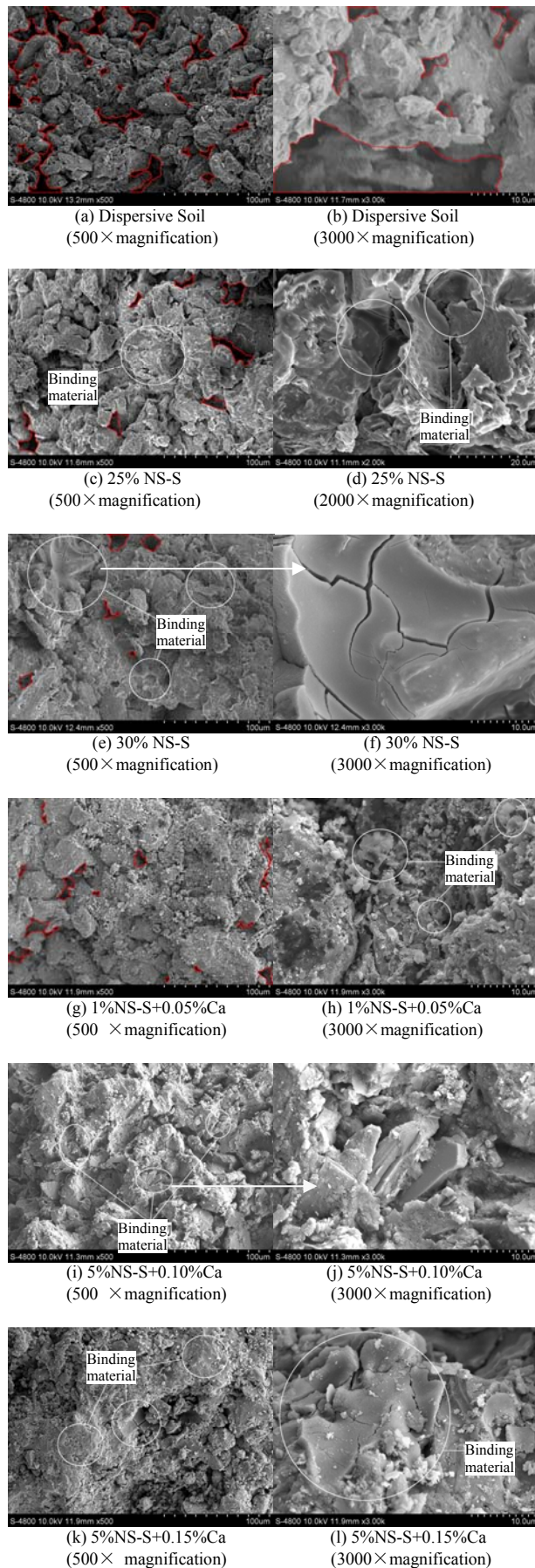
#### 5.5 Scanning electron microscope (SEM) tests

The dispersive soil samples, the soil samples modified with 25% and 30% nano silica sol, and the samples modified by the Si/Ca compound system with 1% NS-S+0.05%CaCl<sub>2</sub>, 5% NS-S+0.10%CaCl<sub>2</sub>, and 5%NS-S+0.15%CaCl<sub>2</sub> were selected for scanning electron microscope tests. The pore characteristics of the soil and the morphology of binding material in the soil before and after modification were observed. The SEM images are shown in Fig. 6, where the pores are circled in red, and the binding materials is circled in white.

In Figs. 6 (a) and 6 (b), it can be observed that the dispersive soil mostly presents an elevated pore structure, with a more obvious skeleton structure of large particles. There is less binding material between particles, and particles are mostly in edge-to-edge contacts, resulting in good spatial connectivity. Figs. 6(c) and 6(e) present the results of nanosilica sol modified soil samples. As the dosage of nano silica sol increases, the pores between soil particles significantly decrease, and nano silica sol effectively fills intergranular space, forming a dense network structure. Obvious binding materials can be observed in Figs.6 (d) and 6(f), exhibiting the morphological characteristics of encapsulation and filling. This indicates that nano silica sol has a strong agglomeration and filling effect, which can enhance the integrity of the soil sample, effectively reduce the large pores, form a dense binding material, make the spatial connectivity deteriorate, reduce the contact area between soil particles and water, thus inhibiting the dispersibility of the granular structure.

As shown in Figs. 6 (g), 6 (i), and 6 (k), it can also be observed that after modified by the Si/Ca compound system, the porosity of soil samples is reduced, and the bonding between soil particles is enhanced, and the obvious binding material shown in Figs. 6 (h), 6 (j), and 6 (l) are also formed. By combining the results of the laser particle size analysis tests, it can be concluded

that the integrity and density of soil samples can be further improved by the Si/Ca compound system.



**Fig. 6 Scanning electron microscope images**

Calcium chloride can promote the hard-coagulation reaction of nano silica sol, which rapidly generates colloids with agglomeration in the soil structure and exhibits a mosaic-covered morphology. At the same time, calcium chloride can chemically react with silicon dioxide to form hydrated calcium silicate or calcium silicate, which plays a binding and filling role.

### 5.6 Modification mechanism of Si/Ca compound system

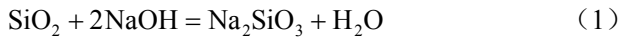
Based on the above test results, the modification mechanism of Si/Ca compound system on dispersive soil has the following aspects:

(1) When the dosage of nano silica sol is high, sol itself undergoes colloidal flocculation. After air drying, the nano silica sol can play a binding/filling role, and the pores between the soil grains can be filled by it, during which the porosity decreases, particle aggregation and mosaicism are enhanced, the soil becomes denser, the specific surface area of the clay particles also decreases. Therefore, the clay particles are not easily dispersed in the environment of running water.

(2) nano silica sol can reduce the thickness of the electrical double layer of soil particles by reducing the alkalinity and the ESP of the soil. The  $H^+$  ions in nano silica sol neutralize  $OH^-$  in some soil, reducing soil alkalinity and destroying the necessary conditions for the dispersibility of the soil<sup>[2]</sup>. The negative charge carried on the surface of clay particles is reduced<sup>[1]</sup>, the adsorption of  $Na^+$  is weakened, and the content of exchangeable sodium is reduced. Through the above action, the agglomeration ability of clay particles can be improved, the spacing between soil particles can be reduced, and the compactness of the soil structure can be improved.

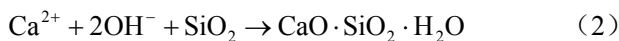
(3) Nano silica sol has a electric double layer structure<sup>[31]</sup>, and there are groups carrying the polyvalent negative charge, such as siloxanol groups in the colloids, which can generate electrostatic interaction with a small number of metal cations to maintain stability<sup>[32]</sup>. Studies have shown that if the concentration of metal cation is too high, the electric double layer structure is compressed and thin, and the colloid becomes unstable and agglomerates, forming a network of colloidal particles containing silicon-oxygen bonds that can firmly adhere to the surface of the particles<sup>[24]</sup>. For example, a large number of ions are generated in the cement hydration reaction, and the nano silica sol is prone to undergo condensation reaction on the surface of cement particles, forming a gel to encapsulate cement particles<sup>[33]</sup>. According to the mosaic encapsulation morphology of cement in SEM images, it can be inferred that due to the distribution of exchangeable cations such as sodium, potassium, calcium and magnesium on the surface of clay particles in dispersive soil, nano silica sol can adsorb clay particles and flocculate, and form amorphous gel

products on the surface of soil particles after the sol is air-dried.  $\text{SiO}_2$  reacts with  $\text{Na}^+$  and  $\text{OH}^-$  in the dispersive soil in an alkaline environment to produce sodium silicate, which consumes  $\text{Na}^+$  in the soil to a certain extent. Therefore, the ESP also shows a downward trend under the modification of only nano silica sol. The reaction equation is as follows:



(4) The combination of nano silica sol and calcium chloride into the Si/Ca compound system can give full play to their advantages in modifying dispersive soil. Calcium chloride is a strong acid and weak alkali salt, which is easily soluble in water and it can generate a large amount of free  $\text{Ca}^{2+}$  during hydrolysis. Nano silica is negatively charged in the stable sol state. The introduction of electrolytes such as cation  $\text{Ca}^{2+}$  can reduce the repulsive force between nano silica particles and promote the transformation of liquid nano silica sol into gel solid. Therefore, the viscosity of nano silica can be rapidly enhanced in a very short time, and the nano silica sol slurry gradually thickens and finally forms a solid with a certain stiffness<sup>[34]</sup>. Calcium chloride can be used as an accelerator to shorten the gel time of nano silica sol<sup>[35]</sup>. Under the combined action of the Si/Ca compound system, dense cementation is formed between the pores of soil particles, which can play a role in wrapping clay particles and inhibiting their dispersibility and disintegration.

Under the combined action of the Si/Ca compound system, the pH of soil can be further reduced, the conductivity can be increased, and the thickness of the electric double layer can be reduced to eliminate the dispersibility of soil. Nano silica can react to form hard-coagulation type C-S-H gel through  $\text{Ca}^{2+}$  adsorption and extend the length of the gel silicate chain<sup>[36]</sup>. Using the pozzolanic activity and adsorption of nano silica as well as the  $\text{Ca}^{2+}$  provided by calcium chloride to the soil, in an alkaline environment, nano silica sol and calcium chloride in the dispersive soil can undergo a chemical reaction as shown in Eq.(2) to generate C-S-H gel with the same cementation properties:



Meanwhile, there is still  $\text{Ca}^{2+}$  in the soil that is not fully reacted. The CEC of the soil increases, and the percentage of exchangeable  $\text{Na}^+$  decreases. The exchange capacity of cations in solution is related to the valence state of ions, and the ion exchange capacity of  $\text{Ca}^{2+}$  is stronger than that of  $\text{Na}^+$ <sup>[37]</sup>. Therefore, the free  $\text{Ca}^{2+}$  in the pore solution can undergo an ion exchange reaction with the exchangeable  $\text{Na}^+$  adsorbed on the surface of the soil particles. Under the combined effect of these two factors, ESP also decreases significantly. The microstructure model, reflecting the microscopic mechanism of dispersive soil, is shown in Fig. 7.

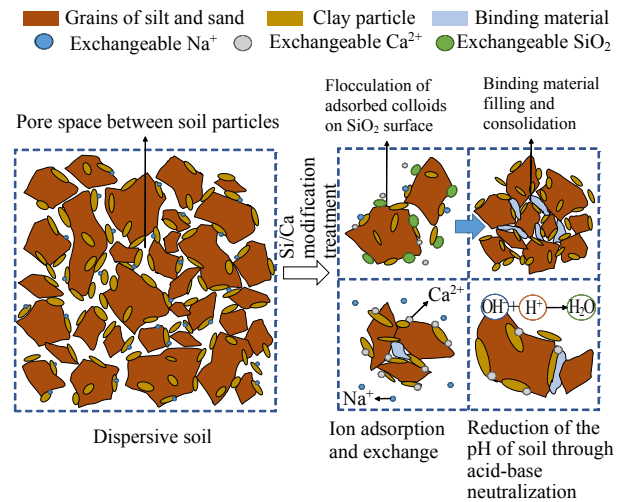


Fig. 7 Microstructure model of the dispersive soil modified by Si/Ca compound system

## 6 Conclusions

(1) Nano silica sol can effectively inhibit the dispersibility of soil. When the dosage of nano silica sol is below 25%, the soil dispersibility can be completely eliminated, and the modification effect is stable. When the dosage of calcium chloride is above 0.40%, the dispersibility of soil can be eliminated. The Si/Ca compound system composed of nano silica sol and calcium chloride can strengthen the modification effect and effectively reduce the dosages of nano silica sol and calcium chloride. The soil dispersibility can be completely eliminated by adding 1% nano silica sol and 0.05% calcium chloride. It is suggested that the dosage of nano silica sol can be increased appropriately when treating physically dispersive soil with less clay or binding material, while the dosage of calcium chloride can be reduced appropriately when dealing with high-sodium dispersive soil with strong alkaline.

(2) The disintegration process of dispersive soil is characterized by slow water-absorbing swelling in the initial stage and rapid disintegrating in the late stage. There is a mutation point in the disintegration rate, and the soil disintegrates rapidly in a short time. The disintegration rate and final disintegration time of the modified soil with nano silica sol do not change much with the dosage of nano silica sol. The final disintegration time is shorter than that of dispersive soil, but the overall disintegration rate is stable. The disintegration process of Si/Ca modified soil shows the characteristics of slow disintegration in the initial stage and rapid disintegration in the later stage, and its final disintegration time is shorter than that of the nano silica sol modified soil and decreases with the increase of calcium chloride dosage.

(3) The mechanism of using nano silica sol to modify dispersive soil mainly includes cementation and filling, reducing soil alkalinity, and reducing ion adsorption and ion exchange, which can improve the aggregate structure of dispersive soil, reduce soil porosity, and make it denser. When nano silica sol and

calcium chloride are used together, calcium chloride can provide a calcium source, create conditions for silica reaction to generate C-S-H gel, and promote the coagulation and solidification of nano silica sol. At the same time, the Si/Ca compound system has the effect of reducing the alkalinity of soil and ion exchange.

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