Study on the Relationship between Microstructure and Strength of Stabilized/Solidified Silt

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***Abstract*—Silt is a kind of material with poor engineering properties, and stabilization/solidification is an effective method to improve its engineering properties. In order to explore the effect and mechanism of silt stabilization, three kinds of admixtures (lime, cement + lime and SEU-2) are chosen to stabilize silt. Unconfined compressive strength and scanning electron microscopy (SEM) tests of stabilized silt are carried out, and then the image processing analysis software Image-Pro Plus is used to quantitatively measure the values of some main microstructure parameters from SEM images. Stepwise regression method is used to select five main microstructure parameters and establish the regression equation between microstructure parameters and strength. Based on the regression equation the mechanism of silt stabilization is discussed from the point of microstructure change. This study will help to better understand the mechanism of silt stabilization.**

***Index Terms*—silt, stabilization/solidification, unconfined compressive strength, scanning electron microscopy, microstructure**

I. Introduction

Silt is a kind of building material with poor engineering properties such as low strength, large deformation, easily liquefied, difficult to compaction and so on. Stabilization/solidification is an effective method to improve silt engineering properties, which has been widely used in China. At present, many scholars have studied the macroscopic mechanical properties of stabilized silt [1]. In contrast, few people study the microstructure characteristics and stabilization mechanism of stabilized silt. In fact, the macroscopic mechanical properties of soil depend on the microstructure [2], so studying the microstructure helps to better understand the macroscopic mechanical behavior.

Since the late 1970s, due to the continuous improvement of computer technology, computer image processing system was introduced into the studies of soil microstructure, which brought the quantitative studies of soil microstructure to a new level. In the early, Tovey developed a digital computer techniques method for the quantitative analysis of clay particles orientation in electron micrographs [3]. Later Shi obtained the quantitative analytical results of soil SEM images using computer image processing system [4]. Similarly Martínez-Nistal developed a novel computerized procedure to study the orientation of clay particle based on SEM images [5]. After entering the new century, studies on soil microstructure based on computer image processing system developed more rapidly. New development mainly focused on two aspects: one was new, mature and integrated image processing software, and the other was application of new and advanced algorithm. On one hand, more new, mature and integrated image processing software was used to study soil microstructure. For example, Mahfouz determined the orientation of soil aggregates and pores with GEOIMAGE software [6]; Phillips utilized high resolution digital scans of orientated thin sections imported into a standard computer graphics package to measure the orientation of long axes of detrital grains [7]; Tang quantitatively analyzed the microstructure of Shanghai muddy clay before and after freezing using vectorization software [8]. On the other hand, new and advanced algorithm made the image processing techniques more accurate and effective. Ruan and Ward used Rietveld-based data processing technique to evaluate the mineralogy of clay-rich mineral matter in quantitative terms [9]; Kikkinides and Politis used standard and hybrid simulated annealing (SA) methods to stochastically reconstruct in three dimensions zeolite adsorbent structure [10]. In short, using computer image processing techniques to study soil microstructure has been very popular now.

The ultimate goal of qualitative and quantitative study of soil microstructure is to seek the unity of micro and

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macro, so as to reveal the mechanism of macroscopic mechanical properties. Many scholars have found that soil microstructure can significantly affect the mechanical properties and tried to establish the relationship between each other. Pore is an important constituent of soil microstructure, which is closely related to macroscopic mechanical properties. First of all, pore can reflect the compaction or consolidation of soil. Sridharan found changes in the pore-size distribution of kaolinite were followed as a function of increasing amount of static compaction, and Delage found in the process of soil consolidation the largest inter-aggregate pores were the first affected, and as the consolidation proceeds smaller and smaller pores were affected [11]. In addition, Nagaraj developed the relationship between the stress state and permeability (an important indicator reflecting pore characteristics) for saturated soils [12]. Also, the shape, size and other properties of pore can affect the mechanical properties. For example, Kilfeather described how till bulk porosity and pore shape, size and connectivity relate to deformation processes [13]; Tang discussed the relationship between microstructure (pore diameter, pore shape and orientation) and moisture migration [8].

In addition to pore, aggregate or particle is another important constituent of soil microstructure which affects the mechanical properties significantly. Shi Bin introduced two new quantitative indices to assess the aggregates orientation and applied the two indices to micro-mechanics model of soil creep [4]. Anandarajah found that the aggregates orientation and soil conductivity are related [14]. Hicher proved that mechanical behavior of clayed materials is largely dependent on the changes which occur at the scale of the particles [15]. The aggregates orientation can also affect the anisotropy of soil [6]. In general, although some scholars have studied the relationship between microstructure and macroscopic mechanical properties, the studies are still in exploratory stage, because there is not yet a theory or mathematical tool to unify the micro and macro effectively. A viable approach is using statistics.

As can be seen from the above research, studies on soil microstructure have stepped from qualitative stage into quantitative stage, and using computer image processing techniques to quantitatively study soil microstructure has been an effective method. The microstructure of soil, such as pores, aggregates or particles may affect the macroscopic mechanical behavior. Up to now, quantitative studies on the microstructure of stabilized silt have not been reported yet, so we carried out relevant research. In this paper, three kinds of admixtures that was lime, cement + lime, SEU-2 (a stabilizing agent invented by Zhu Zhiduo of Southeast University, China) were selected to stabilize silt, then the unconfined compressive strength (UCS) and SEM tests of the stabilized silt were carried out. The image processing analysis software IPP (Image-Pro Plus) was used to obtain the quantitative parameters values of microstructure from SEM images. A statistical method called multiple stepwise regression analysis was used to filter out main parameters of microstructure and establish the regression equation between microstructure parameters and UCS. Based on the regression equation the mechanism of silt stabilization was discussed.

II. Experiment

A. Experiment Materials

1) Silt

The soil used in the experiment was taken from the northern part of Jiangsu Province, China. The grain size distribution curve of soil is shown in Fig. 1. The contents of clay (<5μm), silt (5~75μm) and sand (>75μm) in soil are 8.78%, 58.79%, 32.43% respectively. The basic physical properties of soil are shown in Table I.

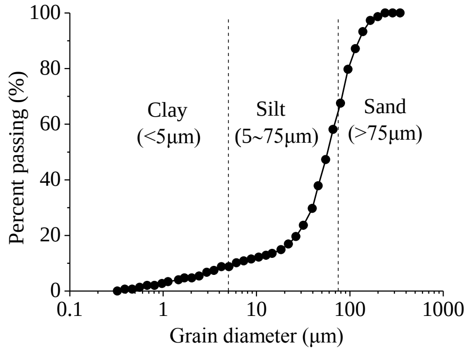


Figure 1. Grain size distribution curve of soil

TABLE I. Basic physical properties of soil

Water content (%)	Density (g/cm^3)	Specific gravity	Void ratio	Liquid limit (%)	Plastic limit (%)	Plasticity index (%)
27	1.97	2.7	0.779	27.18	21.51	5.67

2) Admixtures

Lime was purchased from a lime production plant in Nanjing. The lime is white and powdery, wherein the content of CaO is 67.47% and MgO is 3.1%.

Cement was ordinary Portland cement P.O32.5 purchased from Nanjing. The cement is off-white and powdery, in which the main chemical components are CaO (55.37%), SiO_2 (25.41%) and Al_2O_3 (10.09%). The initial setting time and final setting time of cement are 205 min and 260 min respectively. The compressive strength of the cement after curing for 3 days is 26.4MPa.

SEU-2 is an effective admixture for stabilizing silt, in which the main component is cementing materials composed of cement, fly ash and mineral powder, and the minor component is an appropriate amount of alkaline activating components, swelling components and surfactants.

B. Experiment Plan

The specific experiment plan was designed as shown in Table II. As can be seen from Table II, three admixtures were selected to stabilize silt: lime, cement + lime and SEU-2. For each admixture there were three different contents: 6%, 8% and 10%. For the sake of clarity, in this paper the symbol "An" is used to express the stabilized silt sample, where in "A" represents the type of admixture (L for lime, C for cement, S for SEU-2) and "n" represents for the content of admixture. For example, L6 represents silt mixed with 6% lime and C2L4 represents silt mixed with 2% cement and 4% lime.

TABLE II. EXPERIMENT PLAN

Program numbering	Admixture	Content (%)	Curing time (d)	Experiment
L6	lime	6	7 28	UCS SEM
L8		8		
L10		10		
C2L4	cement + lime	2+4		
C2L6		2+6		
C4L6		4+6		
S6	SEU-2	6		
S8		8		
S10		10		

C. Experiment Methods

1) UCS

First, silt was naturally air-dried and passed through a 2 mm sieve to remove impurities. According to the proportion of experiment plan a certain quality of silt and admixture was mixed and stirred until homogeneous. Meanwhile according to the optimum moisture content (determined through the compaction test) a certain mass of distilled water was added to the mixture and then the mixture was sealed in a polyethylene plastic bag for 24 hours. Then the prepared mixture was poured into a steel mold and pressed into a cylindrical shape (diameter 5cm, height 10cm) using jack static pressure (ensure 96% degree of compaction). Next, the molded sample was released and cured for the designed age (curing conditions: temperature 20 ± 3 ° C, relative humidity ⩾ 95%). Finally, UCS tests of the cured samples were carried out using a strain-controlled unconfined compressive strength meter-YSH-2 (stress ring factor is 21 N/0.01mm, compression rate is 1% / min).

2) SEM

Samples used for SEM tests were prepared and cured in the same way as UCS tests. After curing the sample was carefully broken apart and a small piece (about 1 cm^3 in size) was picked out. This small piece was rapidly frozen using liquid nitrogen (-190 ℃) and then vacuumed for 24h using XIANOU-18N freeze-drying apparatus, by which to ensure that the water in the pores was completely sublimated and the piece was completely dry. Finally, SEM test of the dried piece was carried out using a scanning electron microscope-S-3000N (magnification 500-5000 times) produced by Hitachi, Japan.

III. EXPERIMENT RESULTS

A. UCS

The UCS results of stabilized silt are shown in Fig. 2. As shown in Fig. 2, the UCS increases as curing time increases, so the UCS of 28d is higher than that of 7d. It is also found that the UCS of lime stabilized silt is the lowest, and the UCS does not increase with the increase of lime content. On the contrary, the UCS of SEU-2 stabilized silt is the highest, and the UCS increases significantly with the increase of SEU-2 content. The UCS of cement + lime stabilized silt is in the middle, and the UCS also increases with the increase of cement + lime content. From the UCS of cement + lime stabilized silt after curing for 7d, it can be found that the UCS is almost unchanged when the admixture content increases from 6% to 8% (increasing 2% lime), conversely the UCS increases significantly when admixture content increases from 8% to 10% (increasing 2% cement), indicating that the early stabilizing effect of cement is better than that of lime.

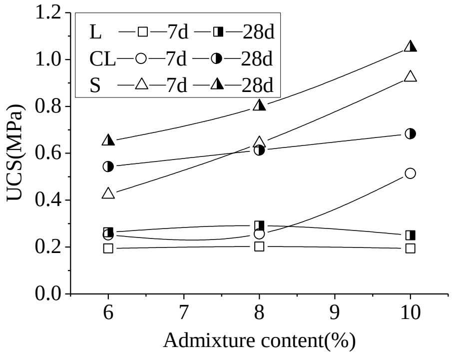
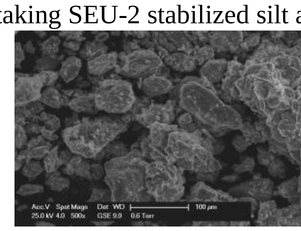
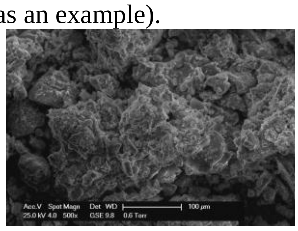


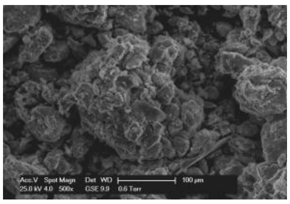
Figure 2. Relationships between UCS and admixture content of stabilized silt

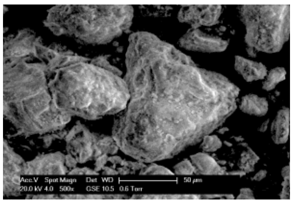
B. SEM

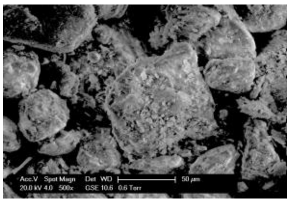
SEM images of stabilized silt are shown in Fig. 3(only taking SEU-2 stabilized silt as an example).


(a) S6, 7d


(b) S8, 7d


(c) S10, 7d


(d) S6, 28d


(e) S8, 28d

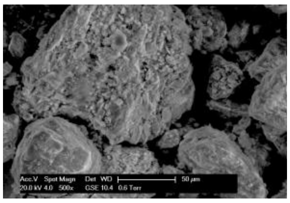

(f) S10, 28d

Figure 3. SEM images of SEU-2 stabilized silt

As can be seen from Fig. 3 with the increase of admixture content and curing time, the soil density and particles size increase, while the size and number of pores decrease. This is because with the increase of admixture content and curing time, hydration reaction and volcanic ash reaction will produce gel products, which will wrap soil particles or fill pores between particles, leading to greater soil particles and denser soil structure.

IV. Microstructure Quantitative Results

A. Microstructure Parameters

Microstructure parameters refer to the parameters that can quantitatively describe the microstructure characteristics of soil, which mainly contain two kinds, one is to reflect the particle characteristics, and the other is to reflect the pore characteristics.

1) Microstructure parameters about particle

Five microstructure parameters about particle are chosen to characterize the particles: particle equivalent diameter, particle circularity, particle size fractal dimension, particle surface relief fractal dimension and particle direction fractal dimension.

Only circle has a diameter, while in order to describe the size of the irregularly shaped particles, the particle equivalent diameter is introduced herein. Particle equivalent diameter means the diameter of a circle having the same area as the particle. The symbol Φ_p is used to represent particle equivalent diameter.

In addition to particle size, particle shape also has a great impact on the mechanical properties of soil. In order to characterize particle shape, particle circularity is introduced herein. Particle circularity is defined as

$$R_p = 4\pi S / L^2 . \quad (1)$$

Wherein R_p is particle circularity, S is particle area, L is particle perimeter. Particle circularity can reflect the degree of closing to a circle of the particle shape. The range of particle circularity is 0 to 1. The larger the R_p, the closer the particle shape to a circle; when R_p is 1, the particle shape is circular.

As far as we know, soil is very complex material with heterogeneity, so just using traditional geometric methods to quantitatively describe the geometric characteristics of particles is not enough. Many scholars have found that soil particles have fractal characteristics and using fractal theory to study soil microstructure is an effective method. So in this paper three parameters characterizing particle fractal characteristics are introduced: particle size fractal dimension (D_{ps}), particle surface relief fractal dimension (D_{pr}) and particle direction fractal dimension (D_{di}). Particle size fractal dimension can reflect the size distribution of soil particle, the larger the particle size fractal dimension, the more uneven the particle size. Similarly, particle surface relief fractal dimension can reflect particle surface fluctuation, the larger the surface relief fractal dimension, the larger the surface roughness. Particle direction fractal dimension can be used to reflect particle orientation, the greater the particle direction fractal dimension, the worse the orientation.

2) Microstructure parameters about pore

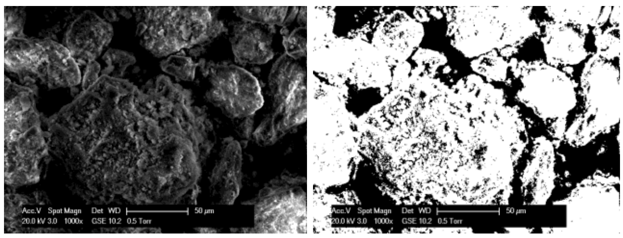
Four microstructure parameters are chosen to characterize the pore of soil: pore equivalent diameter, pore circularity, pore size fractal dimension and pore area ratio.

Similar to particle, pore equivalent diameter (Φ_b), pore circularity (R_b) and pore size fractal dimension (D_{bs}) are introduced to reflect the pore characteristics. The larger the pore equivalent diameter is, the larger the pore size is; the larger the pore circularity is, the closer the pore shape is to a circle; the larger the pore size fractal dimension is, the more uneven the pore size is.

Another important microstructure parameter is pore area ratio (A_f).The pore area ratio is defined as the ratio of the pore area to the total area in two-dimensional image. It is noteworthy that pore area ratio is based on two-dimensional image and is not equivalent to porosity of general concept. The larger the pore area ratio is, the looser the soil is.

B. Quantitative Results

The software IPP (Image-Pro Plus) is a powerful image processing and analysis tool. In this paper, IPP was used to quantitatively measure the microstructure of stabilized silt. Before the measurement a threshold value was determined to carry out binarization processing of microstructure images. After the binarization processing, the particles in the images become white and the pores become black, as shown in Fig. 4, therefore IPP can measure the microstructure of particles and pores respectively. It is undeniable that the selection of the threshold value is critical to the measurement accuracy, but there is not yet a widely accepted "perfect method". In this paper, a simple and effective method - visual method (by constantly changing the threshold and comparing the original image and processed image to obtain the optimal threshold) was used to obtain the optimal threshold. The quantitative results of the microstructure of the stabilized silt are listed in Table III.



(a) Before processing (b) After processing

Figure 4. Binarization processing of SEM images

TABLE III. QUANTITATIVE RESULTS OF MICROSTRUCTURE

Numbering	Curing time (d)	Φ_p (μm)	R_p	D_{ps}	D_{di}	D_{pr}	A_f	Φ_b (μm)	D_{bs}	R_b	UCS (MPa)
L6	7	5.731	0.567	0.901	0.853	1.134	0.366	4.804	0.916	0.307	0.194
	28	5.821	0.529	0.917	0.841	1.143	0.305	3.237	1.296	0.292	0.263
L8	7	6.083	0.582	0.916	0.838	1.142	0.312	3.525	1.467	0.304	0.202
	28	6.168	0.531	0.921	0.826	1.146	0.269	3.595	1.255	0.247	0.291
L10	7	6.134	0.586	0.893	0.805	1.131	0.323	5.309	0.993	0.289	0.194
	28	6.255	0.541	0.909	0.696	1.176	0.265	4.138	1.145	0.169	0.250
C2L4	7	5.561	0.541	1.050	0.796	1.147	0.338	5.897	1.641	0.186	0.252
	28	5.992	0.508	1.153	0.804	1.153	0.306	3.478	1.531	0.265	0.543
C2L6	7	6.201	0.561	1.120	0.782	1.133	0.303	3.756	1.246	0.374	0.256
	28	6.257	0.536	1.207	0.792	1.148	0.282	4.144	1.372	0.217	0.613
C4L6	7	6.541	0.536	1.221	0.777	1.149	0.301	4.249	1.599	0.338	0.514
	28	6.709	0.493	1.302	0.812	1.135	0.281	3.502	1.415	0.267	0.683
S6	7	6.127	0.561	1.066	0.787	1.147	0.280	3.084	1.533	0.231	0.424
	28	6.321	0.527	1.161	0.839	1.132	0.243	3.455	1.406	0.332	0.651
S8	7	6.327	0.542	1.234	0.860	1.153	0.240	3.267	1.423	0.204	0.643
	28	6.657	0.462	1.301	0.880	1.127	0.203	3.149	1.336	0.380	0.800
S10	7	6.591	0.537	1.284	0.900	1.146	0.216	3.288	1.467	0.234	0.923
	28	7.469	0.422	1.409	0.907	1.112	0.177	3.078	1.360	0.434	1.051

V. RELATIONSHIP ANALYSIS

A. Multiple Stepwise Regression Analysis

Soil strength is the comprehensive reflection of the entire microstructure. There are many microstructure parameters that may affect the strength, but each microstructure parameter affects the strength differently, with some parameters having a significant effect and others having only a very slight effect. On the other hand, the effect of each microstructure parameter on the strength may not be independent, that there may be cross-effects between different parameters. In order to establish an accurate regression relationship between microstructure and strength, the main microstructure parameters must be selected and cross-effects between different parameters need to be considered, and multiple stepwise regression analysis is such an effective method to solve this problem. Multivariate stepwise regression analysis is a mathematical statistical method which can be used to analyze the relativity of dependent variable and multiple independent variables. The analytical model is

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \cdots + \beta_k X_k . \quad (2)$$

Wherein Y is dependent variable, X_i is independent variable, β_0 is regression constant, β_i is the partial regression coefficient of X_i, and k is the number of independent variables.

The basic steps of multiple stepwise regression analysis are shown in Fig. 5. The basic steps: First of all, calculate the partial regression square sum of variable that is not yet in the equation in turn and consider whether the variable can be introduced into the regression equation, if the variable can be introduced into the regression equation then continue, if no variable can be introduced into the regression equation then the loop ends; Second, if a new variable is introduced into the regression equation, then recalculate the partial regression square sum of the variable already in regression equation in turn and consider whether the variable can be removed from the regression equation, if the variable can be removed then continue, if no variable can be removed then return to the first step; Carry on with the loop until no variables can be introduced into the regression equation and no variables can be removed from the regression equation.

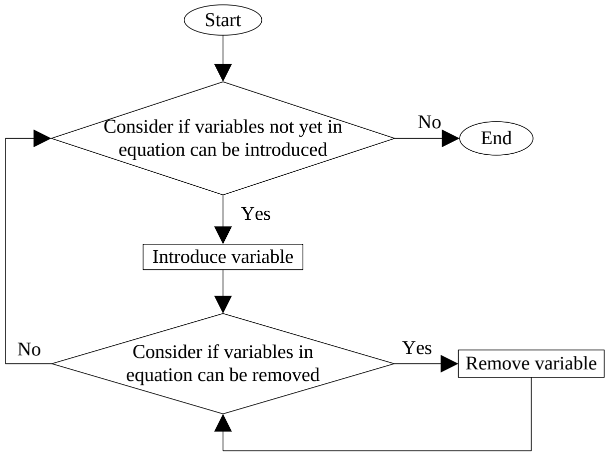


Figure 5. Basic steps of multiple stepwise regression analysis

By multiple stepwise regression analysis five variables are introduced into the regression equation: particle circularity (R_p), particle direction fractal dimension (D_{di}), particle equivalent diameter (Φ_p), pore area ratio (A_f), and particle size fractal dimension (D_{ps}). The regression equation between five main microstructure parameters and UCS is

$$q_u = 9.671 - 5.67 R_p + 1.505 D_{di} + 0.062 \Phi_p - 2.338 A_f + 0.38 D_{ps} \quad (3)$$

Wherein q_u refers to UCS (MPa), and the correlation coefficient of the regression equation is $R = 0.91$, indicating that the regression result is good. According to the intensity of effect on UCS, the order of the five microstructure parameters from primary to secondary is: particle circularity, particle direction fractal dimension, particle size fractal dimension, pore area ratio and particle equivalent diameter. From the five main microstructure parameters and the above ordering it can be seen that the microstructure parameters about particle have a more significant effect on UCS.

B. Relationship between Microstructure and Strength

1) Relationship between particle circularity and UCS

It can be seen from the regression equation that UCS is negatively correlated with particle circularity. The greater the particle circularity is, the lower the UCS is. This is because the greater the particle circularity is, the closer the particle shape is to a circle, and the circular particles are more liable to slip, leading to instability of microstructure and lower strength.

2) Relationship between particle direction fractal dimension and UCS

It can be seen from the regression equation that UCS is positively correlated with particle direction fractal dimension. The greater the particle direction fractal dimension is, the higher the UCS is. This is because the greater the particle direction fractal dimension is, the more chaotic the particle arrangement is. The particles with chaotic arrangement are more easily embedded with each other and need more energy to rotate, causing more stable microstructure and higher strength.

3) Relationship between particle size fractal dimension and UCS

Form the regression equation it can be seen that UCS is positively correlated with particle size fractal dimension. The greater the particle size fractal dimension is, the higher the UCS is. Large particle size fractal dimension means nonuniformity of particle size, that is, there are both large particles and small particles in soil. Large particles can form the soil skeleton structure and small particles can fill the pores in the skeleton structure, thus making the soil more dense and stable. This explains why UCS is positively correlated with particle size fractal dimension.

4) Relationship between pore area ratio and UCS

Form the regression equation it can also be seen that UCS is negatively correlated with pore area ratio. The larger the pore area ratio is, the lower the UCS is. Although pore area ratio herein is based on two-dimensional images and differs from the conventional porosity, it can also reflect the amount of pore in soil. The larger the pore area ratio is, the more the pore is and the less dense the soil is, and the strength is lower.

5) Relationship between particle equivalent diameter and UCS

Form the regression equation it can be seen that UCS is positively correlated with particle equivalent diameter. The larger the particle equivalent diameter is, the higher the UCS is. This is because larger particle equivalent diameter means more gel products. In the chemical reaction gel produces generate and wrap the particles or fill the pores between particles, which increase the equivalent diameter of particles, enhance the connection between particles and improve the integrity of soil. This explains the positive correlation between particle equivalent diameter and UCS.

VI. Conclusion

With the increase of admixture content UCS of lime stabilized silt almost remains unchanged; UCS of cement + lime stabilized silt increases, and cement is better than lime on stabilizing effects; UCS of SEU-2 stabilized silt increases significantly. The stabilizing effect of SEU-2 is better than that of the other two admixtures.

Through multiple stepwise regression analysis five main microstructure parameters with relatively stronger influence on UCS were selected, and according to the intensity of effect on UCS, the order of the five microstructure parameters from primary to secondary is: Particle circularity, particle direction fractal dimension, particle size fractal dimension, pore area ratio and particle equivalent diameter.

The regression equation between UCS and five main microstructure parameters of stabilized silt was established. In the five main microstructure parameters, particle direction fractal dimension, particle size fractal dimension and particle equivalent diameter have positive correlation with UCS, while particle circularity and pore area ratio have negative correlation with UCS.

References

[1] G. H. Cai, Y. J. Du, S.Y. Liu, and D.N. Singh, “Physical properties, electrical resistivity, and strength characteristics of carbonated silty soil admixed with reactive magnesia,” *Canadian Geotechnical Journal*, vol. 52, pp. 1699-1713, April 2015.

[2] M. Oualmakran, B. Mercatoris, and B. François, “Pore-size distribution of a compacted silty soil after compaction, saturation, and loading,” *Canadian Geotechnical Journal*, vol. 53, pp. 1-8, June 2016.

[3] N. K. Tovey, “A digital-computer technique for orientation analysis of micrographs of soil fabric,” *Journal of Microscopy-oxford*, vol. 120, pp. 303-315, December 1980.

[4] B. Shi, Y. Murakami, and Z. S. Wu, “Orientation of aggregates of fine-grained soil: Quantification and application,” *Engineering Geology*, vol. 50, pp. 59-70, September 1998.

[5] A. Martínez-Nistal, F. Veniale, M. Setti, and F. Cotecchia, “A scanning electron microscopy image processing method for quantifying fabric orientation of clay geomaterials,” *Applied Clay Science*, vol. 14, pp. 235-243, April 1999.

[6] A. H. Mahfouz, L. Han-Long, G. Yufeng, P. Jie, and L. Tongchun, “Microstructure study of soft clayey soil under consolidation by vacuum preloading method,” *Geomechanics and Geoengineering: An International Journal*, vol. 2, pp. 97-108, June 2007.

[7] E. Phillips, J. J. M. van der Meer, and A. Ferguson, “A new 'microstructural mapping' methodology for the identification, analysis and interpretation of polyphase deformation within subglacial sediments,” *Quaternary Science Reviews*, vol. 30, pp. 2570-2596, September 2011.

[8] Y. Tang, J. Zhou, J. Hong, P. Yang, and J. Wang, “Quantitative analysis of the microstructure of Shanghai muddy clay before and after freezing,” *Bulletin of Engineering Geology and the Environment*, vol. 71, pp. 309-316, May 2012.

[9] C. D. Ruan, and C. R. Ward, “Quantitative X-ray powder diffraction analysis of clay minerals in Australian coals using

Rietveld methods," *Applied Clay Science*, vol. 21, pp. 227-240, August 2002.

[10] E. S. Kikkinides, and M. G. Politis, "Linking pore diffusivity with macropore structure of zeolite adsorbents. Part I: three dimensional structural representation combining scanning electron microscopy with stochastic reconstruction methods," *Adsorption-Journal of the International Adsorption Society*, vol. 20, pp. 5-20, January 2014.

[11] A. Sridharan, A. G. Altschaeffl, and S. Diamond, "Pore size distribution studies," *Journal of Soil Mechanics & Foundations Div*, vol. 97, pp. 771-787, June 1971.

[12] T. S. Nagaraj, N. S. Pandian, and P. Raju, "Stress state permeability relationships for fine-grained soils," *Geotechnique*, vol. 43, pp. 333-336, June 1993.

[13] A. A. Kilfeather, and J.J.M. van der Meer, "Pore size, shape and connectivity in tills and their relationship to deformation processes," *Quaternary Science Reviews*, vol. 27, pp. 250-266, February 2008.

[14] A. Anandarajah, and N. Kuganenthira, "Some aspects of fabric anisotropy of soil," *Geotechnique*, vol. 45, pp. 69-81, March 1995.

[15] P. Y. Hicher, H. Wahyudi, and D. Tessier, "Microstructural analysis of inherent and induced anisotropy in clay," *Mechanics of Cohesive-Frictional Materials*, vol. 5, pp. 341-371, June 2000.

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