

## Research Article

# Study on Strength Development Mechanism of Organic Soil in Dianchi Lake, China

Siyang Huang <sup>1</sup>, Jing Cao <sup>1</sup>, Cheng Kong,<sup>2</sup> Yue Gao,<sup>3</sup> Yunfei Song,<sup>1</sup> Fangyi Liu <sup>1</sup>,  
Huafeng Sun <sup>1</sup>, Zhengcong Lai,<sup>1</sup> Weiming Zhu,<sup>1</sup> and Hanhua Xu<sup>4</sup>

<sup>1</sup>Faculty of Civil Engineering and Mechanics, Kunming University of Science and Technology, Kunming 650500, China

<sup>2</sup>PowerChina Kunming Engineering Corporation Limited, Kunming 650000, China

<sup>3</sup>Shenzhen Geotechnical Investigation & Surveying Institute (Group) Ltd., Shenzhen 518028, China

<sup>4</sup>Kunming Prospecting Design Institute of China Nonferrous Metals Industry Co.,Ltd., Kunming 650093, China

Correspondence should be addressed to Jing Cao; 20040130@kust.edu.cn

Received 24 July 2022; Revised 24 September 2022; Accepted 27 October 2022; Published 2 November 2022

Academic Editor: Hossein Moayedi

Copyright © 2022 Siyang Huang et al. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

The organic soil is widely distributed around Dianchi Lake in Kunming, which is rich in the humic group (HG). In order to explore the effect of HG on the strength development of organic soil, this paper adopts the method of adding humic acid (HA) reagent into the undisturbed cohesive soil (blending method) and soaking it in fulvic acid (FA) solution (steeping method) to simulate the organic soil. Then, the effect of HG on soil is analyzed by the unconfined compressive strength (UCS) and the scanning electron microscope (SEM) tests. The UCS test shows that HA can significantly reduce the UCS of the samples, and it continues to decrease with the increase of the HA reagent content. FA can substantially enhance the UCS of the samples, which continues to increase with the concentration of FA solution (decreasing the pH value). Under each HG condition, the steeping of FA can significantly increase the UCS of the sample when the content of the HA reagent is less than 10%, and the growth rate of the UCS decreases when it is greater than 10%. With the increase of steeping age, the UCS of the 5% HA samples continued to increase and gradually became stable, and when the content of the HA reagent is more than 5%, the UCS curve first increases and then decreases. The SEM test shows that adding HA reagent can significantly increase the pore size, improve the connectivity between the pores, and weaken the connection of the soil structure. The steeping of FA can reduce the pore size, weaken the connectivity between the pores, and strengthen the connection of the sample structure.

## 1. Introduction

Since the 21st century, due to the rapid development of urbanization and the continuous increase of social demands, urban construction has continued to develop toward the city's edge. Many projects must be located in various areas, such as expansive soil, peat soil, and frozen soil [1, 2]. Peat soil is a kind of soft soil with unique properties [3], with high organic matter content, large void ratio, low bearing capacity, high water content, and low permeability [4, 5]. The unique properties of peat soil have brought many adverse effects to the actual engineering construction. How to build projects in these areas has become a widely concerned issue for many scholars and engineers.

The organic matter content in peat soil is high, and the humic group (HG) is the main component of organic matter [3]. The solubility difference of HG in acid and alkali solutions can be divided into three categories: humic acid (HA), which is only soluble in alkali solution but not in acid solution. Fulvic acid (FA) is soluble in acid and alkali, and humin is insoluble in any solution. HG contains a variety of active oxygen-containing functional groups, such as carboxyl, phenol hydroxyl, alcohol hydroxyl, methoxy, and ether [6], making HG's properties very complicated. It was found from research and practice that HG can interact with metal ions, oxides, and clay minerals, in peat soil, thereby changing its physical-chemical properties.

In 1987, Hobbs [7] pointed out that peat soil's organic matter content and the humification degree significantly impact the soil's structure and mechanical characteristics. In 1998, Lan et al. [8] studied the effects of HA on the decentralization of the soil. The results show that HG has a significant dispersal effect on the soil. After removing the hydrogen peroxide solution, the decentralization of the mucous particles decreases significantly. In 2004, Chirdchanin et al. [9] studied the engineering properties of organic soil through laboratory tests. The results show that HG can improve the compressibility of soil but reduce the water permeability and shear strength of soil. In 2007, Duraisamy et al. [10] proposed that the increase of HG in peat soil will cause the change in soil shear strength; Yan et al. [11] studied the physical and mechanical properties of peat soil through experiments. The results show that peat soil's physical and mechanical properties are affected by many factors, and organic matter is the most crucial factor. With the increase of organic matter content in peat soil, the compressibility increases, the consolidation coefficient decreases, and the permeability decrease. In 2019, Zou et al. [12] studied the effect of HG on soil-available cadmium (Cd) through adsorption experiments, scanning electron microscopy, infrared spectroscopy, and other experimental methods. The results show that HG has activation and passivation effects on Cd, and based on these effects, it can significantly change soil's physical and chemical properties. In 2021, Liu et al. [13] found that adding HG to montmorillonite would change montmorillonite's morphology. In 2021, Yue et al. [14] studied the effect of organic matter on the soil-water characteristics of peat soil by artificially preparing peat soil with different organic matter content. The results show that organic matter significantly affects peat soil's soil-water characteristic curve, and peat soil's water-holding capacity increases with increased organic matter content. In 2022, Cao et al. [15, 16] were used to simulate the peat soil environment (PES) by mixing HA reagent into cohesive soil and soaking it in an FA solution. The test result shows that the PES with different HA and FA contents can simulate by this method, but soaking samples in FA solution cannot reach the actual effect.

In summary, many scholars have conducted much research on the effect of HG on the engineering properties of peat soil. However, scholars mainly study HG as a whole, ignoring that HG is a complex mixture composed of HA, FA, and humin. Different components of HG may have different effects on the engineering properties of organic soil. On the other hand, fewer scholars have studied the effect of HG on the strength of organic soil. Therefore, this paper studies the effect of different components in HG on the strength of organic soil. The results have significant theoretical value and guiding significance for practical engineering.

## 2. Materials and Methods

**2.1. Simulation Basis of the Indoor Organic Soil Environment.** According to the content of organic matter in the soil, the "Standard for engineering classification of the soil" (GB/T 50145-2007) [17] divides it into inorganic soil (<5%), organic

soil (5%~10%), peat soil (10%~60%), and peat (>60%). The brackets indicate the content of organic matter in the soil. The American Society for Testing and Materials Standard Classification of peat samples by laboratory testing (ASTM D4427) [18] classifies peat soil into the following parts: (1) *Fibric*: peat with greater than 67% fibers. (2) *Hemic*: peat with between 33% and 67% fibers. (3) *Sapric*: peat with less than 33%. The soil with fibers greater than 75% is called peat.

In natural peat soil, humin, humic acid (HA), and cohesive soil particles together form the soil skeleton in the form of solid particles. The chemical structure and properties of humin are similar to those of HA, but humin is an inert humic group (HG) with relatively stable chemical properties [19, 20] and can exist in the soil environment for a long time. Compared with HA and humin, fulvic acid (FA) exhibits stronger reducing and complexing ability due to more acidic oxygen-containing functional groups such as carboxyl. To sum up, considering the chemical characteristics of different components in HG, HA reagent, and FA reagent selected as the test materials in this paper. This paper adopts the blending and steeping methods to conduct the simulation test according to the difference in the existing form and solubility of HA and FA in peat soil. In this method, HA reagent is mixed into cohesive soil with low organic matter content to prepare samples and then soaked in FA solution.

According to the previous research results, the total content of HG in the peat soil of Dianchi Lake is between 7.15% and 50.06%. Among them, the content of HA is between 2.36% and 28.13%, and the content of FA is between 0.79% and 8.34% [16]. The results provide the basis for incorporating HA and FA reagents in the samples.

**2.2. Materials.** In order to consider the influence of natural humic acid on the test results, the undisturbed soil used in the test is alluvial-proluvial cohesive soil with low humic acid content (0.32%). The classification method of alluvial-proluvial cohesive soil is based on the "Standard for engineering classification of the soil" (GB/T 50145-2007) [17]. The undisturbed soil is taken from Sanhe Village, Xinjie Town, Jinning County, Kunming City, which is brownish-yellow and brownish-red. According to the "Standards for Geotechnical Test Methods" (GB/T50123-2019) [21], the undisturbed soil is tested indoors. Its physical and mechanical properties are shown in Table 1. Its compressive modulus is 4.65 MPa.

Tianjin Guangfu Chemical Reagent Factory produces the HA reagent. The FA reagent is prepared by purifying young lignite in Yunnan through hydrogen peroxide degradation. The test water is distilled water. Each test material is shown in Figure 1.

**2.3. Sample Preparation.** The test is carried out according to the "Standards for Geotechnical Test Methods" (GB/T50123-2019) [21]. First, the undisturbed soil used in the test is crushed, air-dried, and then passed through a sieve with an aperture of 2.00 mm. Then, mix the test soil, humic acid reagent, and water evenly and put it into a three-part mold

TABLE 1: Physical and mechanical properties index of undisturbed soil for a test.

Undisturbed soil	Natural moisture content $\omega$ (%)	Liquid limit $w_L$ (%)	Plastic limit $w_P$ (%)	Natural density ( $\text{g}\cdot\text{cm}^{-3}$ )	Specific gravity of soil particle $G_s$	Compression modulus (MPa)	Natural humic acid content (%)
Cohesive soil	33.5	39.26	20.38	1.87	2.73	4.65	0.32

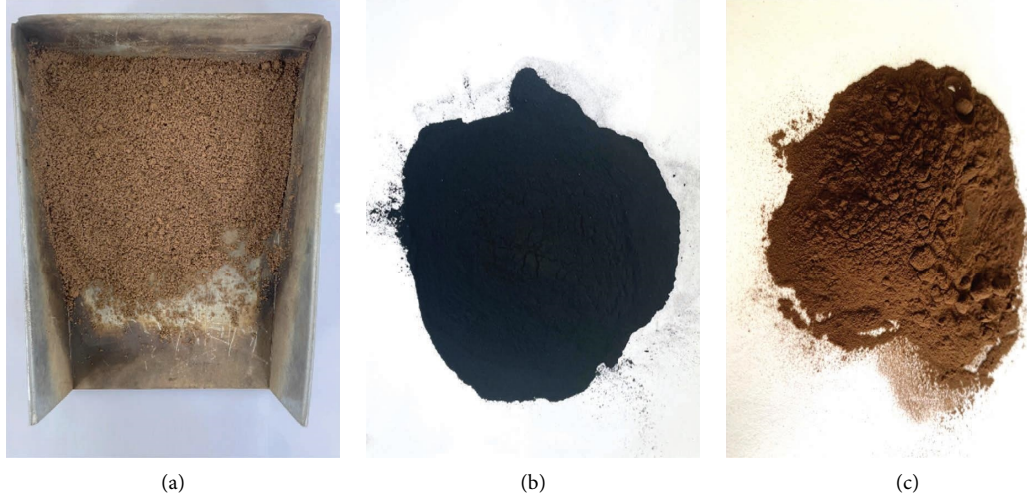


FIGURE 1: Test material: (a) undistributed soil; (b) humic acid reagent; (c) fulvic acid reagent.

(the inner diameter of the three-part mold is  $d = 39.10$  mm, and the height  $h = 80.00$  mm). Finally, the mixed material in the mold is compacted to make a sample, and after the mold is removed, it is wrapped with PVC for curing. The sample preparation process is shown in Figure 2. To ensure the accuracy of the test, the moisture content ( $\omega$ ) = 24%, and the void ratio ( $e$ ) = 0.8.

After the sample preparation is completed, soak the sample in FA solution. Since FA is acidic, the higher the concentration of the prepared solution, the lower the pH value. The test controls the concentration of FA by controlling the pH value of the solution. The pH value of the FA solution is measured with an electronic pH tester, and the pH value of the FA solution is kept constant by adding a FA reagent [22].

**2.4. Test Procedure.** Prepare samples with different contents of HA reagents, and soak the samples in FA solutions with different pH values at different times. The samples that have reached the design time of immersion are taken out from the immersion solution and air-dried naturally to the quality at the time of sample preparation.

Unconfined compressive strength (UCS) test and scanning electron microscope (SEM) test are carried out on the samples that completed the above steps. The YSH-2 electric lime-soil unconfined compressive instrument measures its UCS for the UCS test. During the test, the axial compression rate of the instrument is controlled to be 1.6 mm/min [21]. SEM test uses Czech TESCAN-VEGA3 automatic tungsten filament SEM and the test is divided into two test groups. Test group 1 (TS-1): prepare samples with

different contents of HA reagent and soak the samples in distilled water for 90 days. Test group 2 (TS-2): prepare samples with 15% HA reagent and soak the samples in FA solutions with different pH values for 90 days. The test conditions are shown in Table 2.

### 3. Test Results and Analysis

**3.1. Analysis of the Effect of Humic Acid on the Strength of Organic Soil.** To preliminarily analyze the effect of humic acid (HA) on the unconfined compressive strength (UCS) of organic soil, the samples soaked in distilled water (pH value: 7.0) for the same time are regarded as the same group of samples for comparative analysis. Figure 3 shows the relationship between the UCS of the sample soaked in distilled water simultaneously and the HA reagent's content. The UCS continuously decreased with the increased content of HA reagent added to the samples immersed in distilled water simultaneously. In addition, this study refers to some novel techniques to predict complex engineering problems [23–25]. Analysis of the mechanism: the surface of clay particles is usually negatively charged. Under the action of electrostatic attraction, clay particles will adsorb cations to their surface. The electric double layer of clay particles comprises the charged layer (adsorption layer) on the surface of clay particles and the ionic layer (diffusion layer) formed by cations on the surface of clay particles. The effect of HA on the sample's UCS is based on a series of physical-chemical interactions of clay particles, HA, cations, water, and other substances. HA has a significant molecular weight (compared with fulvic acid) and a complex molecular structure. A variety of oxygen-containing active functional

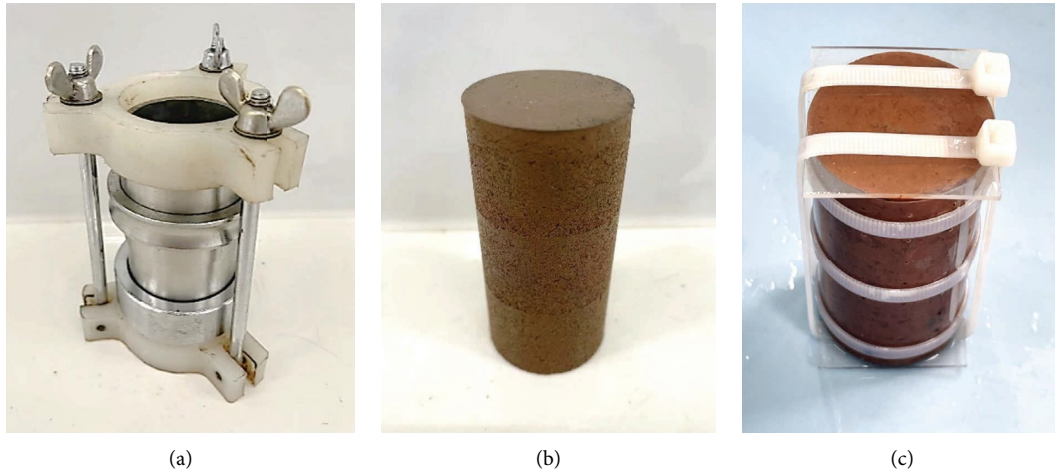


FIGURE 2: Sample preparation process: (a) three-part mold; (b) test sample; (c) PVC for curing.

TABLE 2: Test conditions.

Test group (TG)	The content of HA reagent added $\lambda$ (%)	FA solution pH	Water content $\omega$ (%)	Void ratio ( $e$ )	Immersion age ( $d$ )
UCS TG	0, 5, 10, 15, 20, 25	4.5, 5.0, 5.5, 6.0, 7.0	24	0.8	28, 90, 180, 270, 365
SEM TG-1	0, 5, 10, 15, 20, 25	7.0			
SEM TG-2	15	6.0, 5.5, 5.0, 4.5	24	0.8	90

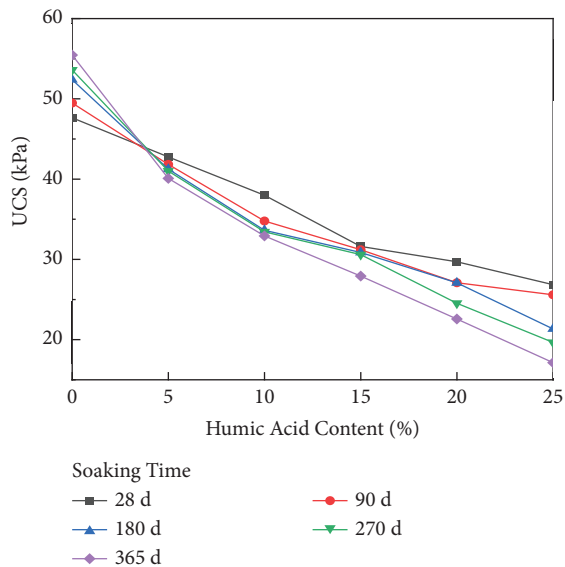


FIGURE 3: Relationship curve between sample UCS and the content of HA reagent.

groups, such as carboxyl, alcohol hydroxyl, and methoxy, are combined on the aromatic core structure of the HA monomer [7]. The presence of these functional groups makes HA show high surface reaction activity.

When the samples containing HA are immersed in distilled water, the molecular structure and functional groups of HA are wetted by water, showing higher surface reactivity. The above makes HA adsorb on the surface of clay particles by relying on its various oxygen-containing acidic

functional groups, react with high-valent cations on the surface of clay particles, reduce the valence of cations, and weaken the electrostatic attraction between cations and negative charges on the surface of soil particles. This phenomenon leads to an increase in the thickness of the diffusion layer of soil particles. The bond between soil particles is weakened [26]. On the other hand, HA particles are smaller than most clay mineral particles and have a more developed electric double layer than clay mineral particles. This structural feature determines the strong adsorption of HA particles. If there is a specific content of HA in the cohesive soil, the HA adsorbed on the clay particles' surface will enhance the cohesive soil's dispersibility [8]. It hinders the coagulation between clay particles and causes the deterioration of the physical properties and structure of the soil. Finally, HA can significantly reduce the UCS of the sample and will continue to decrease with the increased content of the HA reagent incorporated.

To preliminarily analyze the long-term effect of HA on the UCS of organic soil, Figures 4(a) and 4(b) show the relationship between the sample UCS soaked in distilled water and the soaking time. With the increase in soaking time, the UCS of the sample without HA gradually increased, and the sample containing HA decreased slightly. Analysis of the mechanism: the samples in this test are all remodeled soil samples. With the increase in soaking time, the recovery of the connection structure between soil particles makes the UCS of the samples gradually increase slightly. However, the HA adsorbs with the clay particles [27, 28], reducing the valence of high-valent cations on the surface.

Moreover, the electrostatic attraction between the cations and the negative charges on the surface of the clay

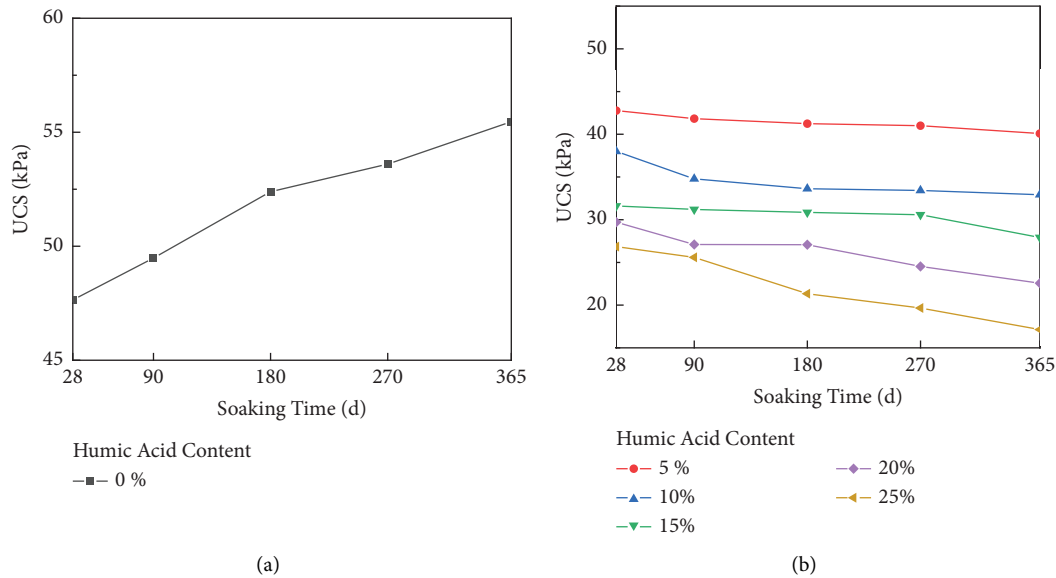


FIGURE 4: Relationship curve between sample UCS and soaking age.

particles gradually weakened. The thickness of the electric double layer of the clay particles increases, the coagulation between them is weakened, the dispersibility is enhanced [8], and the recovery of the interparticle connection structure is inhibited. The soil structure gradually deteriorated with the increase in soaking time, and finally, the UCS of the samples containing HA decreased slightly with the increase in soaking time.

**3.2. Analysis of the Effect of Fulvic Acid on the Strength of Organic Soil.** To preliminarily analyze the effect of fulvic acid (FA) on the UCS of organic soil, the samples without HA soaked for the same time are regarded as the same group of samples for comparative analysis. Figure 5 shows the relationship curve between the sample UCS without HA and the pH value of the FA soaking solution with different pH values simultaneously after soaking in the FA solution. When the sample without HA is soaked for the same time, the sample UCS continues to decrease with the increased pH value of the FA solution. Analysis of the mechanism: FA and HA are amorphous, polydisperse polymer organic mixtures. FA is an essential part of HG, and its molecular structure contains many oxygen-containing functional groups, such as carboxyl, phenolic hydroxyl, and methoxy [7]. Compared with HA, FA is soluble in both acidic and alkaline solutions and has a lower relative molecular weight (generally less than 2000). Moreover, the content of acidic functional groups such as the carboxyl group and phenolic hydroxyl group of FA is higher than that of HA [29–31], showing more apparent weak acidity and higher surface reactivity than HA.

When the sample is soaked in the FA solution, the FA will invade the pores of the cohesive soil with the soaking solution depending on its small molecular structure and low molecular weight. It has various effects, such as coordination exchange, ion exchange, cation bridge, and hydrogen bond with the surface of clay particles [27, 28]. The clay particles

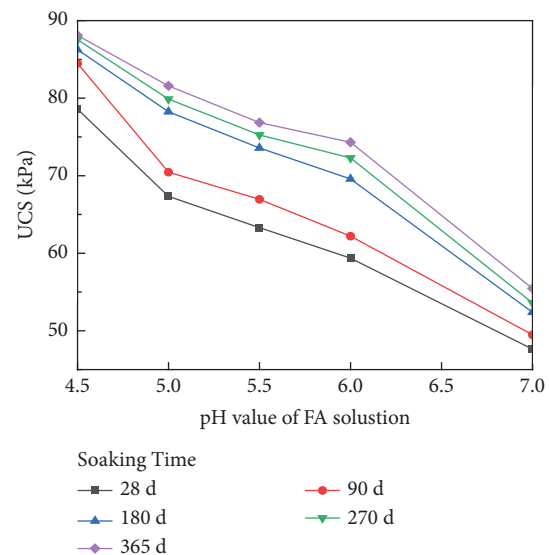


FIGURE 5: Relationship curve between sample UCS and pH value of FA solution.

can adsorb the free FA in the pore water through the above two or more reaction forms. FA is wrapped on the skeleton of the sample soil by adsorption, and changes from a free state to a bound state, forming a stable organic-inorganic composite together with the clay particles, and due to the colloidal properties of FA itself [32] the colloidal connection between clay particles [26].

On the other hand, the FA in the soaking solution invades the sample's interior and can remain as a filler in some pores inside the sample. The pore size of some pores in the sample is reduced, and the structure's connection is strengthened. At the same time, as the pH value of the solution decreases, the concentration of FA in the solution increases, and the content of FA that penetrates the pores of the sample increases as the soaking solution increases

[27, 28]. Moreover, the decrease in pH value will weaken the protonation of acidic functional groups in the FA monomer [33], resulting in the enhancement of the hydrophobicity of some nonpolar components in the FA, weakening the water solubility and the electrostatic repulsion in the organic matter-mineral system will decrease accordingly. The results favor the adsorption of FA, and finally, FA can significantly enhance the sample UCS. Furthermore, it continued to increase with the increased concentration of FA (that is, the decrease of the pH value of the solution).

To preliminarily analyze FA's long-term effect on organic soil's UCS, Figure 6 shows the relationship between UCS and soaking time of samples without HA when soaked in FA solution with different pH values. It can be concluded from Figure 6 that (1) the sample UCS soaked in distilled water gradually increases slightly with the increase of soaking time. (2) When the samples are immersed in FA, the UCS increases with immersion time. The samples soaked in distilled water had a more significant UCS growth rate than those in FA. (3) For samples soaked in FA solution with a pH value of 4.5, the UCS increases rapidly within 28–90 d and increases slightly after 90 d; For samples soaked in FA solution with pH values of 5.0, 5.5, and 6.0, the UCS increased rapidly within 28–180 d and increased slightly after 180 d. Analysis of the mechanism: the samples in this test are all reconstituted soil samples. With the increase in soaking time, when the samples without HA are soaked in distilled water, the recovery of the connection structure between the cohesive soil particles gradually increases the UCS of the samples. When the samples are immersed in the FA solution, the soluble FA penetrates the sample's pores through the immersion solution and interacts with the clay particles through coordination and ion exchange [27, 28]. Therefore, it adsorbs on the surface of clay particles and relies on its colloidal properties to connect the clay particles [26]. Moreover, the FA remaining in the sample pores can reduce the pore size of some pores inside the sample and strengthen the connection of the sample structure.

On the other hand, the pH value of the solution is controlled to be constant in this experiment, and the FA reagent is continuously supplemented in the soaking solution. The interaction between the FA and the clay particles inside the sample continued with the increase in immersion time. However, due to the limited adsorption capacity of clay particles to HG, and the adsorption of FA preferentially occurring on the surface of clay particles at the edge of pores in the sample, FA can continuously invade the sample in the early stage of immersion and preferentially react with clay particles that are easy to bind at the edge of pores. However, with the increase in soaking time, the adsorption reaction between FA and the surface of the clay particles at the edge of the inner pores of the sample gradually tends to be saturated, and the number of binding sites on the surface of the clay particles that can produce adsorption decreases. Moreover, the clay particles far away from the pores are difficult to contact with FA and cause adsorption, making it difficult for the clay particles far away from the pores in the sample to

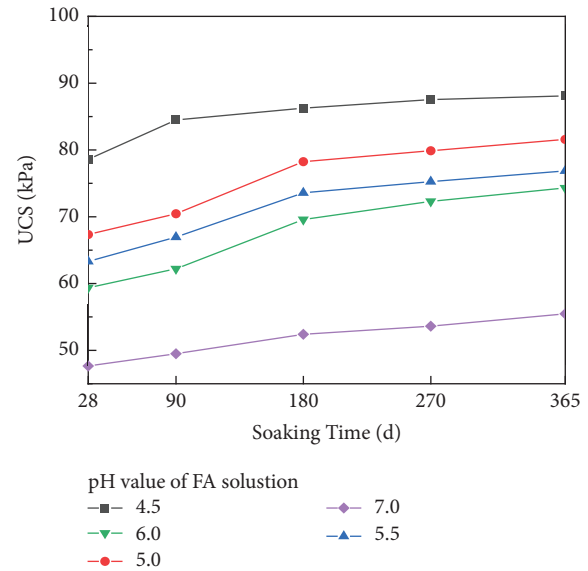


FIGURE 6: Relation curve between sample UCS and soaking age.

adsorb FA. FA gradually fills the internal pores of the sample, resulting in a decrease in the pore size of some pores inside the sample, which prevents the FA in the solution from invading the sample to a certain extent. Therefore, with the increase of soaking time, the sample UCS soaked in FA solution increases rapidly at first and then slightly.

**3.3. Analysis of the Effect of Humic Group on the Strength of Organic Soil.** To analyze the effect of HA on the sample UCS under various HA environments, Figures 7(a)–7(e) show the relationship curve between the sample UCS and the content of HA reagent added under different soaking times. From Figures 7(a)–7(e), it is found that (1) for the samples immersed in the FA solution with the same pH value for the same time, the UCS gradually decreases with the increase of the content of HA reagent added. Moreover, the sample UCS decreased rapidly with the addition of HA reagent from 0% to 10%. Moreover, the decrease rate of UCS decreased when it increased from 10% to 25%. (2) When the content of HA reagent is increased in the range of 0%–10%, the samples immersed in FA had a more significant UCS drop rate than those immersed in distilled water. When the HA reagent content increased from 10% to 25%, the samples immersed in FA solution had similar UCS decline rates to those immersed in distilled water. Analysis of the mechanism: when the sample is immersed in FA solution, the hydrophobicity of HA is enhanced in an acidic environment. Moreover, the electrostatic repulsion between HA and the clay particles in the sample is weakened. Compared with the samples soaked in distilled water, the HA in the samples soaked in FA has a higher surface reactivity. As a result, the adsorption capacity of the clay particles to HA increased. Moreover, the effect of HA on dispersibility is enhanced. Finally, the UCS of the sample decreases rapidly with the increased content of HA

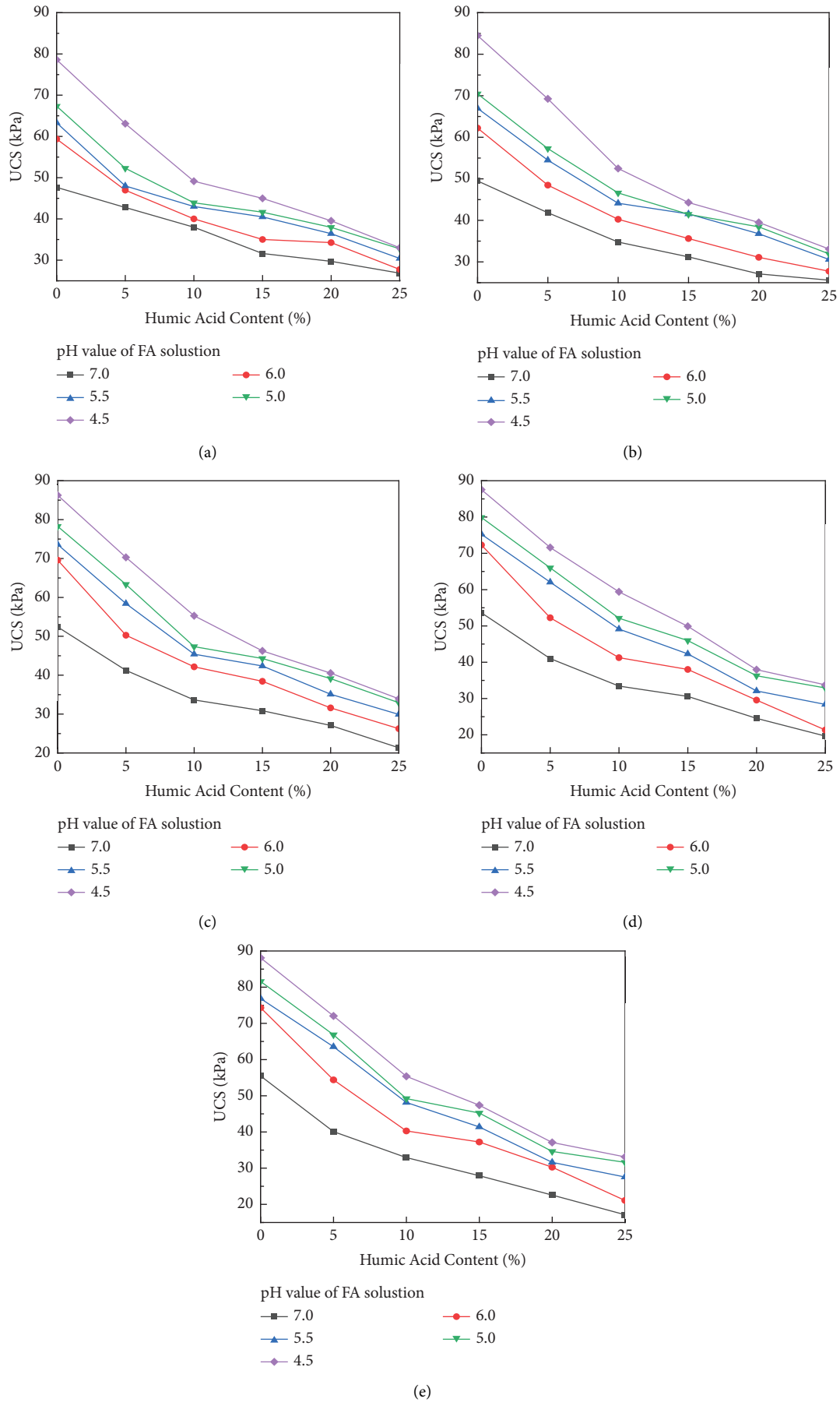


FIGURE 7: Relationship curve between sample UCS and the content of HA reagent. (a) 28 d, (b) 90 d, (c) 180 d, (d) 270 d, and (e) 365 d.

reagent from 0% to 10% and has a more effective UCS decrease rate than that of the sample immersed in distilled water.

However, the adsorption capacity of clay particles for HA is limited. When the HA reagent content increases from 10% to 25%, the bound HA gradually increases and tends to be saturated. In addition, the FA in the soaking solution will continue to invade the sample's interior and cause adsorption to the clay particles. The adsorption phenomenon between clay particles and HA gradually tends to be stable, and some HA that is difficult to combine with clay particles remains free and even precipitates from the sample. The adsorption phenomenon between clay particles and HA gradually tends to be stable, and some HA that is difficult to combine with clay particles remains free and even precipitates from the sample. As a result, the UCS decline rate decreased with the increase of the HA reagent from 10% to 25%. The UCS decline rate is similar to the samples immersed in distilled water.

To accurately analyze the long-term effect of HG on the UCS of organic soil, Figures 8–10 show the relationship curve between the sample UCS and the soaking time when the sample is immersed in the FA solution. Moreover, mark the soaking time when the sample UCS reaches the peak value in the figure. It can be concluded from Figures 8–10 that (1) with the increase in soaking time, the sample UCS with HA reagent content less than 5% continued to increase and gradually became stable. (2) When the pH value of the FA soaking solution is fixed, with the increased content of HA reagent added, the sample UCS begins to decrease at an earlier soaking time. When the content of the HA reagent is the same as the increased concentration of FA, the UCS curve of the sample showed a decreasing trend, and there was an apparent lag.

### 3.3.1. Analysis of the Mechanism

- (1) Since the effects of HA and FA are significantly different, the UCS change with the increase of soaking time results from the joint action of HA and FA. HA is the skeleton of the sample soil, can be adsorbed on the surface of the clay particles, and inhibit the recovery of the connection structure between the alluvial clay particles through a series of physical-chemical actions. Therefore, HA can make the sample UCS slightly decrease with the increase of soaking time. Soluble FA penetrates some of the pores inside the sample through the soaking liquid to connect the clay particles. Moreover, the FA remaining in the sample's pores can reduce the pore size of some pores inside the sample and enhance the structural connection of the sample. In this test, to control the soaking solution's pH value to be constant, the soaking solution is continuously supplemented with an FA reagent. The interaction between the FA and the clay particles inside the sample continued and gradually became stable

with the increase in soaking time. Therefore, with the increase in soaking time, the FA makes the sample UCS increase rapidly and then increase slightly.

- (2) The content of HA reagent in the sample is less than 5%, and the effect of HA on the recovery of the cohesive soil's interparticle bonding structure and the FA's electrostatic repulsion in the pore water is insignificant. In addition, less HA is adsorbed on the surface of the clay particles, and the FA in the soaking solution can continuously penetrate the sample's interior and combine with the clay particles. The FA gradually exerts the bonding effect between the clay particles. [34] Therefore, the sample UCS continues to increase with immersion time and gradually tends to be stable.
- (3) When the content of HA reagent in the sample is more than 5%, in the early stage of soaking (Stage 1), FA continuously invades the inside of the sample through the soaking liquid, causing colloidal bonding between the clay particles inside the sample. Compared with the effect of HA on the dispersion of clay particles, the bonding effect of FA on the clay particles inside the sample is more significant, and the effect of FA on the sample UCS is dominant. However, as the soaking time increases (Stage 2), the adsorption phenomenon between the FA in the pore water and the clay particles inside the sample gradually tends to be saturated. HA can continuously inhibit the recovery of the connection structure between soil particles, resulting in the enhancement of the dispersibility of the soil skeleton of the sample [35–37]. Finally, the UCS curve of the sample with the HA reagent content greater than 5% showed two stages of apparent increase first and then decrease.
- (4) By increasing the content of the HA reagent, the clay particles will be adsorbed and combined with more HA. On the one hand, it occupies a binding site where FA can bind to clay particles. On the other hand, the electrostatic repulsion between HA and FA is enhanced. As a result, the FA in the pore water is challenging to adsorb on the surface (containing HA particles). Moreover, the enhancement effect of the FA on the sample UCS is weakened. Ultimately, the samples with higher incorporation of HA reagent began to show a decreasing trend at earlier soaking age. By increasing the concentration of FA in the soaking solution, the content of FA in the pore water of the sample can be increased so that the clay particles inside the sample can adsorb more free FA. The bound FA encapsulated on the soil skeleton increases, and the colloidal bonding effect between clay particles (containing HA particles) produced by FA is enhanced [26]. Finally, with the increased concentration of FA (the decrease of the pH value of the soaking solution), the sample UCS's tendency to decrease caused by HA shows a significant hysteresis effect.



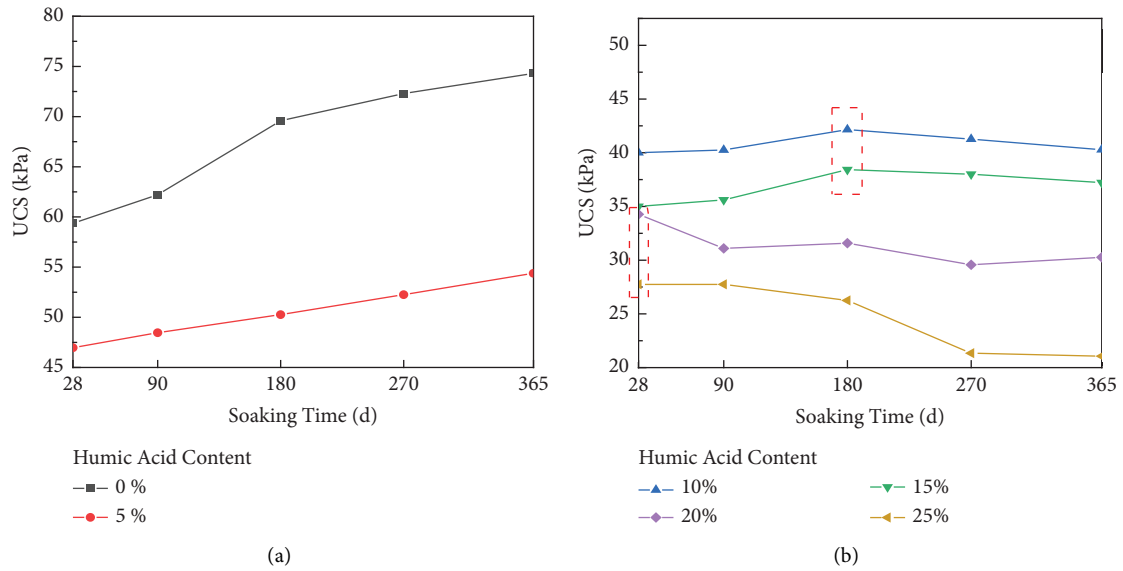


FIGURE 8: Relationship curve between sample UCS and soaking age (pH value of FA solution: 6.0).

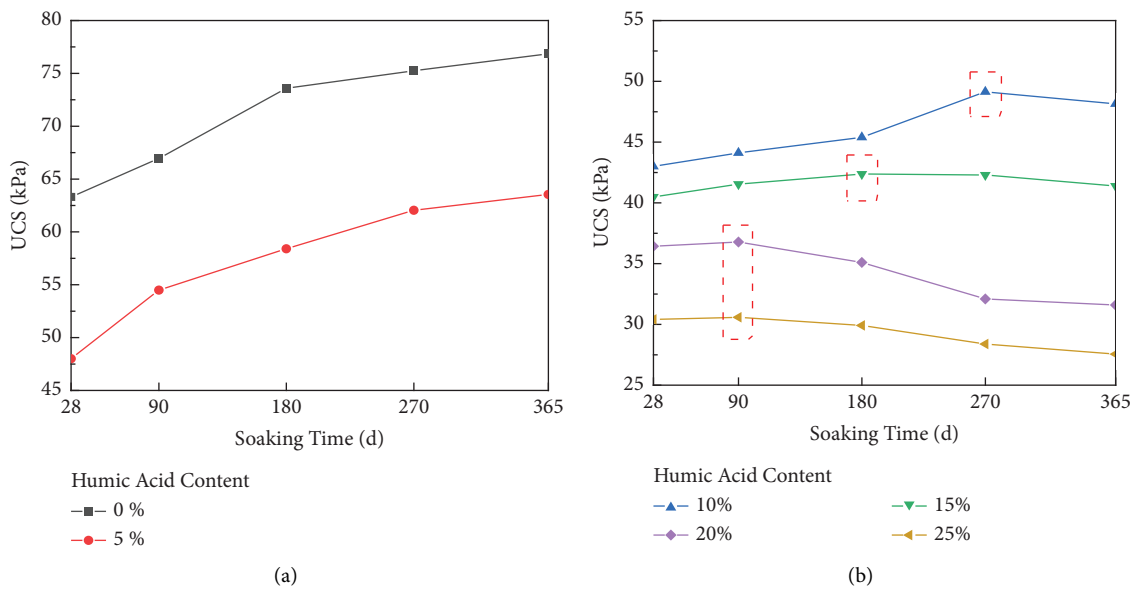


FIGURE 9: Relationship curve between sample UCS and soaking age (pH value of FA solution: 5.5).

3.4. Analysis of the Effect of Humic Acid on the Microstructure of Organic Soil. Figures 11(a)–11(f) show the scanning electron microscope (SEM) images of samples with different HA contents immersed in distilled water for 90 days at a magnification of 2000 times (test group 1). By observing Figure 11(a), it can be concluded that in this test, the internal structure of the alluvial cohesive soil sample is well connected, the pore size of the pores is small, and the connectivity between the pores is poor. Comparing Figures 11(a)–11(f), it can be found that when the content of HA reagent in the sample increases in the range of 5% to 25%, the internal pore size of the sample gradually increases. The pores are gradually connected, and the soil particles in the sample are gradually overhead, forming an apparent loose overhead skeleton, and the connection of the sample

structure is weakened. The reason is that HA can react with high-valent cations on the surface of clay particles, reducing the cation valence. The electrostatic attraction between the cations and the negative charges on the surface of the clay particles weakens, the thickness of the diffusion layer increases, and the connection between the soil particles weakens [26]. On the other hand, the HA particles will be adsorbed on the clay particles' surface, increasing the clay's dispersibility [8]. It hinders the coagulation between clay particles and causes the deterioration of the physical properties and structure of the soil.

Figures 12(a)–12(e) show the SEM images of the samples with 15% HA added in FA solutions with different pH values for 90 days at a magnification of 2000 times (test group 2). Comparing Figures 12(a)–12(e), it can be concluded that as

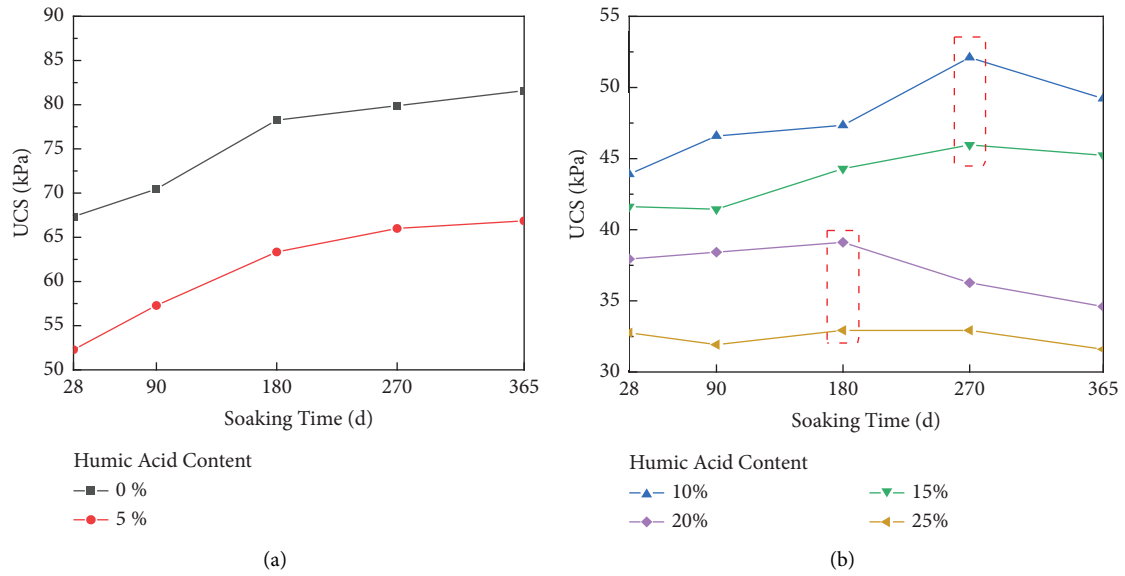


FIGURE 10: Relationship curve between sample UCS and soaking age (pH value of FA solution: 5.0).

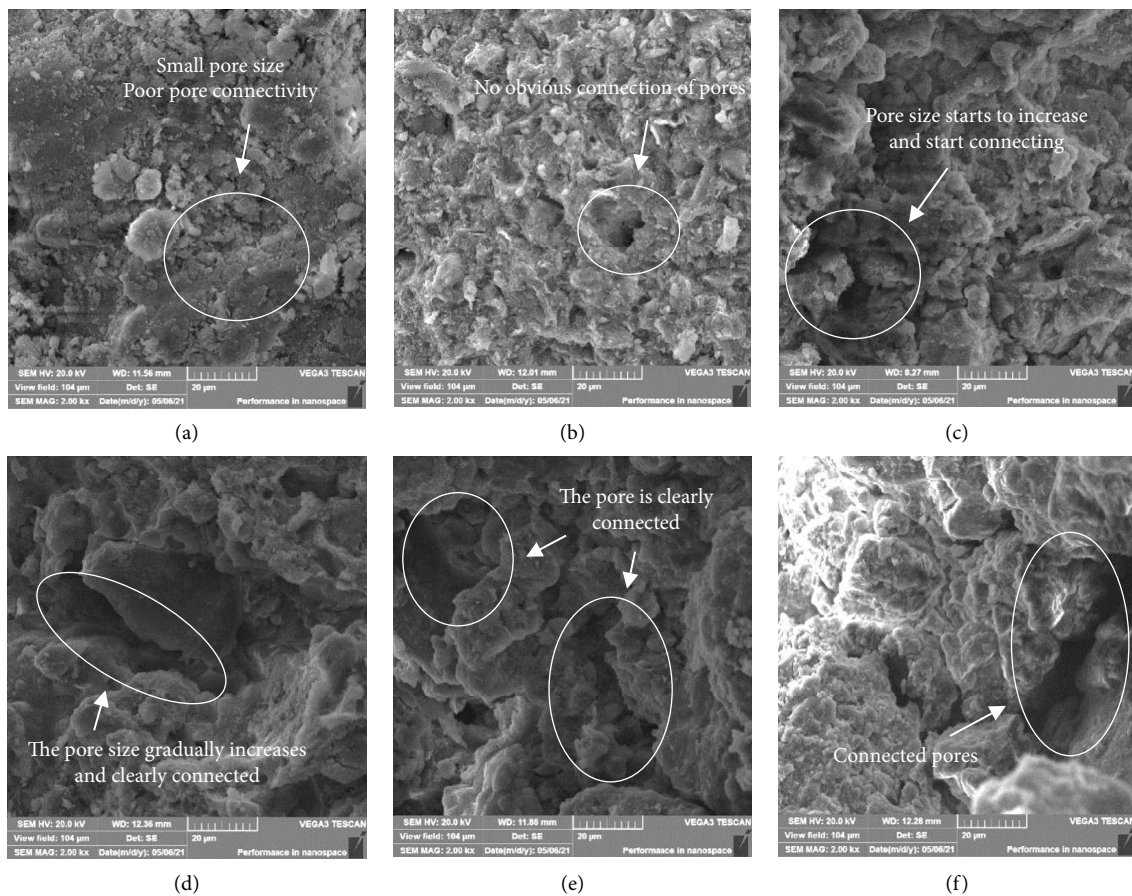


FIGURE 11: SEM images of samples with different contents of HA reagent ( $\times 2000$ ): (a) 0% HA reagent; (b) 5% HA reagent; (c) 10% HA reagent; (e) 15% HA reagent; (f) 20% HA reagent; (g) 25% HA reagent.

the pH value of the soaking solution decreases, the pore size of the pores inside the sample gradually decreases, and the connectivity of the pores gradually weakens. The coupling of

the specimen structure is strengthened. The reason is that FA can penetrate the sample's pores with the soaking liquid and gradually wrap on the soil skeleton through adsorption.

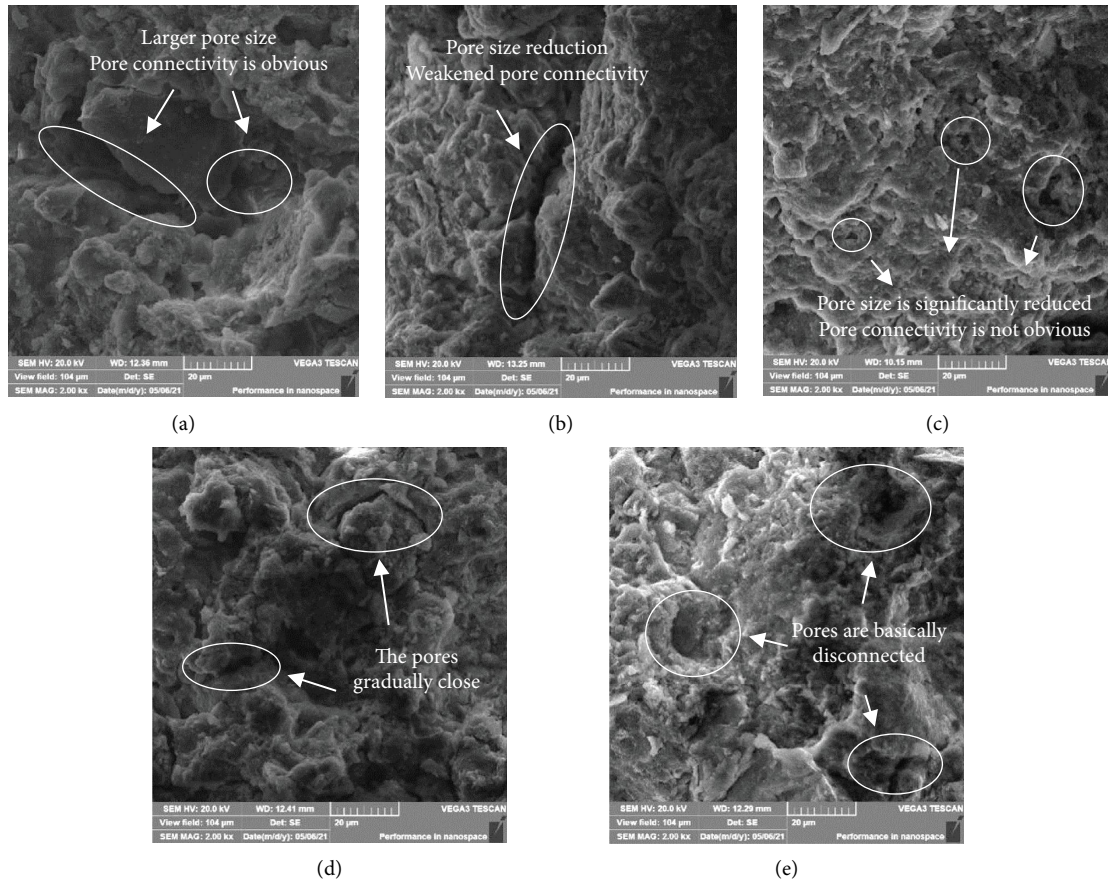


FIGURE 12: SEM images of samples soaked in FA solution with different pH values ( $\times 2000$ ): (a) distilled water, (b) 6.0 pH value, (c) 5.5 pH value, (d) 5.0 pH value, and (e) 4.5 pH value.

Moreover, due to its colloidal properties [32], colloidal connections are generated between clay particles (containing HA particles) [26]. On the other hand, the soluble FA particles will be filled into pores inside the sample, and the pore size inside the sample will be reduced.

#### 4. Conclusion

This paper uses mixing and infiltration methods to simulate the peat soil environment, and humic acid (HA)'s long-term influence trend on organic soil's strength is analyzed through the unconfined compressive strength (UCS) test. The effect of the humic group (HG) on the microstructure of organic soil is investigated by scanning electron microscopy (SEM) test. The influence mechanism of HG on the engineering properties of organic soil is preliminarily revealed, and the following conclusions are obtained:

- (1) HA can significantly reduce the UCS of the sample, it continues to decrease with the increase of the content of HA reagent added, and the UCS of the sample decreases slightly with the increase in soaking time. This test phenomenon is because the HA adsorbs with the clay particles, reducing the valence of high-valent cations on the surface. Moreover, the electrostatic attraction between the cations and the negative charges on the surface of the clay particles

gradually weakened. The thickness of the electric double layer of the clay particles increases, the coagulation between them is weakened, the dispersibility is enhanced, and the recovery of the interparticle connection structure is inhibited.

- (2) Fulvic acid (FA) can significantly enhance the UCS of the sample, it continues to increase with the concentration of FA, and the UCS of the sample increases rapidly at first and then slightly increases with the gradual increase of immersion time. This test phenomenon is because the FA in the soaking solution invades the sample's interior and can remain as a filler in some pores inside the sample. The pore size of the sample is reduced, and the structure's connection is strengthened. Moreover, the decrease in pH value will weaken the protonation of acidic functional groups in the FA monomer, resulting in the enhancement of the hydrophobicity of some nonpolar components in the FA, weakening the water solubility and the electrostatic repulsion in the organic matter-mineral system will decrease accordingly. The results favor the adsorption of FA.
- (3) Under each HG environment, the UCS of the sample decreased rapidly when the HA reagent increased from 0% to 10%. Moreover, the decrease rate of the UCS decreased when it increased from 10% to 25%.

When the content of the HA reagent is less than 10%, the infiltration of FA can significantly increase the UCS of the sample, and when it is more than 10%, the growth rate of the sample UCS decreases. With the increase in immersion time, the UCS of the sample with the HA reagent content of not more than 5% continued to increase and gradually became stable. The intensity curve of the samples with the HA reagent content of more than 5% showed two stages of first increase and then decreased.

- (4) The addition of HA can significantly increase the pore size of the sample, improve the connectivity between the pores, and weaken the connection of the sample structure. The infiltration of FA can reduce the pore size of the sample, weaken the connectivity between the pores, and strengthen the connection of the sample structure.

### Data Availability

The data used to support the finding of this study are included in the article.

### Conflicts of Interest

The authors declare that they have no conflicts of interest.

### Acknowledgments

This study was supported by the Natural Science Foundation of Yunnan Province (41967035), China.

### References

- [1] J. Cao, S. Li, and H. Liu, "On the strength of cement soil affected and effected by the humic acid and its mechanism," *Journal of Safety and Environment*, vol. 21, no. 06, pp. 2571–2576, 2021.
- [2] S. Li, *Research on Engineering Behavior and Microstructure of Humic Acid on Cement Soil*, Kunming University of Science and Technology, Kunming, China, 2021.
- [3] R. Feng, L. Wu, and Y. Zhang, "Study on the consolidation properties of peaty soil," *Chinese Journal of Underground Space and Engineering*, vol. 15, no. 05, pp. 1384–1392, 2019.
- [4] F. Zhang, C. Huang, and T. Yao, "Experimental study on laws of compression and rebound deformation of peaty soil," *Chinese Journal of Geotechnical Engineering*, vol. 43, no. S2, pp. 259–262, 2021.
- [5] M. Du, M. Zhao, and Y. N. Wu, "Settlement analysis of underground comprehensive pipe gallery based on peat soil foundation," *Industrial Safety and Environmental Protection*, vol. 47, no. 10, pp. 66–70, 2021.
- [6] Q. Wang, *Interactions of Humin Acids with Fe<sup>3+</sup>, Al<sup>3+</sup>, Mn<sup>2+</sup> Ions and Their Oxid and the Mechanisms*, Southwest Agriculture University, Chongqing, China, 2005.
- [7] N. B. Hobbs, "A note on the classification of peat," *Géotechnique*, vol. 37, no. 3, pp. 405–407, 1987.
- [8] Y. Lan, HuQiongying, and J. Xue, "Humic acid effect on dispersion of soil and mineral clay," *Acta Pedologica Sinica*, vol. 35, no. 02, pp. 195–201, 1998.
- [9] M. Chirdchanin, J. Lu, and O. Katsutada, "Effects of humic acid and salt concentration on the microstructure of lime stabilized clay," *Chinese Journal of Geotechnical Engineering*, vol. 26, no. 2, pp. 281–286, 2004.
- [10] Y. Duraisamy, B. B. K. Huat, and A. A. Aziz, "Engineering properties and compressibility behavior of tropical peat soil," *American Journal of Applied Sciences*, vol. 4, no. 10, pp. 768–773, 2007.
- [11] L. Yan, L. Nie, and X. U. Yan, "The mechanism of organic matter effect on physical and mechanical properties of turfy soil," *Chinese Journal of Geotechnical Engineering*, vol. 33, no. 4, pp. 655–660, 2011.
- [12] C. Zou, B. Guo, and Y. Lin, "Effects of humic acid particles with different sizes on available cadmium in soil," *Acta Agriculturae Zhejiangensis*, vol. 31, no. 04, pp. 616–623, 2019.
- [13] B. Liu, M. Luo, and S. Yang, "Preparation of montmorillonite-humic acid complex and study on the adsorption properties for strontium," *China Environmental Science*, vol. 41, no. 09, pp. 4204–4210, 2021.
- [14] G. Yue, R. Liu, and Z. Zhao, "Study on soil water characteristic curve of peaty soil with high degree of decomposition," *Journal of Disaster Prevention and Mitigation Engineering*, vol. 41, no. 03, pp. 622–628, 2021.
- [15] J. Cao, S. Y. Huang, W. L. Liu, Y. Gao, Y. F. Song, and S. P. Li, "Study on strength development and microstructure of cement-solidified peat soil containing humic acid of Dianchi Lake," *Advances in Materials Science and Engineering*, vol. 2022, Article ID 8136852, 11 pages, 2022.
- [16] J. Cao, S. Y. Huang, W. L. Liu, C. Kong, Y. Gao, and F. Y. Liu, "Study on simulation test of peat soil environment in Dianchi Lake," *Advances in Civil Engineering*, vol. 2022, Article ID 1437733, 2022.
- [17] Ministry of Water Resources of the People's Republic of China, *Standard for Engineering Classification of Soil: GB/T 50145-2007*, China Planning Press, Beijing, China, 2007.
- [18] Astm, *Standard Classification of Peat Samples by Laboratory Testing (ASTM D4427)*, ASTM, Pennsylvania, PA, USA, 2017.
- [19] S. Zhang, Q. Wang, and J. Chen, "Tests for effect of soil humid acid components on strengte of cemented soft soils," *Journal of Engineering Geology*, vol. 17, no. 06, pp. 842–846, 2009.
- [20] M. Klavins and E. Apsite, "Sedimentary humic substances from lakes in Latvia," *Environment International*, vol. 23, no. 6, pp. 783–790, 1997.
- [21] Ministry of Water Resources of the People's Republic of China, *Standard for Geotechnical Testing Method: GB/T 50123-2019*, China Planning Press, Beijing, China, 2019.
- [22] J. Cao, Y. Hu, and H. Liu, "Experimental study on corrosivity of CFG pile material in fulvic acid," *Bulletin of the Chinese Ceramic Society*, vol. 38, no. 12, pp. 3990–3998, 2019.
- [23] Y. Zhao, H. Hu, C. Song, and Z. Y. Wang, "Predicting compressive strength of manufactured-sand concrete using conventional and metaheuristic-tuned artificial neural network," *Measurement*, vol. 194, Article ID 110993, 2022.
- [24] Y. Zhao, X. Zhong, and L. K. Foong, "Predicting the splitting tensile strength of concrete using an equilibrium optimization model," *International Journal*, vol. 39, no. 1, pp. 81–93, 2021.
- [25] Y. Zhao, H. Moayedi, M. Bahiraei, and L. K. Foong, "Employing TLBO and SCE for optimal prediction of the compressive strength of concrete," *Smart Structures and Systems*, vol. 26, no. 6, pp. 753–763, 2020.
- [26] J. Cao, K. Cheng, and S. Li, "Effect of humic acid on strength of peat soil and its mechanism analysis[J/OL]," *Journal of Safety and Environment*, vol. 1-8, 2021.

- [27] A. Li, W. Ran, and J. Dai, "Advances in the study of adsorption of natural organic material on minerals and its environmental effects," *Acta Petrologica et Mineralogica*, vol. 24, no. 06, pp. 671–680, 2005.
- [28] W. ShiYong, W. Tan, and L. Fan, "Advances on the study of mineral-humus interactions in soils," *Soil and Fertilizer Sciences in China*, vol. 1, no. 01, pp. 1–6, 2009.
- [29] Y. Hou, *Experiment Study on Engineering Properties of the Solidified Plateau Lacustrine Peaty Soil*, Kunming University of Science and Technology, Kunming, China, 2015.
- [30] L. Wang, *Study on Extraction and Separation of Fulvic Acid from Sewage Sludge Compost*, Tianjin University, Tianjin, China, 2018.
- [31] H. Xiaodi, P. Zhou, and Y. Cao, "Origins and evolution processes of humic substances in wastewater treatment," *Chinese Journal of Environmental Engineering*, vol. 11, no. 01, pp. 1–11, 2017.
- [32] J. Cao, Z. Yu, H. Liu, and Z. Song, "Experimental study on erosion of fulvic acid on red clay cement soil composites," *Journal of Kunming University of Science and Technology*, vol. 40, no. 01, pp. 35–38+83, 2015.
- [33] K. Johannsen, M. Assenmacher, M. Kleiser, G. Abbt-Braun, and F. H. Frimmel, "Effect of molecular size on the adsorbability of humic substances," *Vom Wasser*, vol. 8, pp. 185–196, 1993.
- [34] E. M. Murphy, J. M. Zachara, S. C. Smith, J. L. Phillips, and T. W. Wietsma, "Interaction of hydrophobic organic compounds with mineral-bound humic substances," *Environmental Science & Technology*, vol. 28, no. 7, pp. 1291–1299, 1994.
- [35] C. L. Lee, L. J. Kuo, H. L. Wang, and P. C. Hsieh, "Effects of ionic strength on the binding of phenanthrene and pyrene to humic substances: three-stage variation model," *Water Research*, vol. 37, no. 17, pp. 4250–4258, 2003.
- [36] N. E. Palmer and R. von Wandruszka, "Dynamic light scattering measurements of particle size development in aqueous humic materials," *Fresenius' Journal of Analytical Chemistry*, vol. 371, no. 7, pp. 951–954, 2001.
- [37] J. M. Oades, "An introduction to organic matter in mineral soils," *Minerals in Soil Environments*, vol. 1, pp. 89–159, 1989.