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Influence of ultrafine cement on cement-soil in peat soil environment of Dianchi Lake

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Abstract: Treatment of peat soil foundation in Yunnan surrounding Dianchi and Erhai Lakes poses complex problems for engineering projects. It is insufficient to rely on ordinary cement to reinforce peat soil. In order to make the reinforcement reliable, this experiment mixed (ultrafine cement) UFC into ordinary cement to form a composite solidify agent. This study aimed to analyze the influence of UFC proportion on the strength of cement-soil in the peat soil environment. Unconfined compressive strength (UCS) and scanning electron microscope (SEM) tests were conducted on samples soaked for 28 and 90 days, respectively. The test results show that without considering the effects of Humic Acid (HA) and Fulvic Acid (FA), incorporating UFC can significantly improve the UCS of cement-soil. The rapid hydration of the fine particles generates a large number of cementitious products, improves the cohesion of the soil skeleton, and fills the pores. However, when the proportion of UFC increases, the aggregate structure formed by a larger quantity of fine particles reduces the hydration rate and degree of cement hydration, making the UCS growth rate of cement-soil insignificant. In the peat soil environment, HA significantly weakened the UCS of cement-soil in both physical and chemical aspects. However, UFC can mitigate the adverse effect of HA on cement-soil by its small particle size, high surface energy, and solid binding ability. In addition, FA has a positive effect on the UCS of cement-soil soaked for 28 days and 90 days. The UFC addition could promote the enhancement effect of FA on cement-soil UCS. SEM test results showed that cement hydration products increased significantly with the increase of UFC proportion, and cementation between hydration products and soil particles was enhanced. The size and connectivity of cement-soil pores were significantly reduced, thereby improving cement-soil structural integrity.

Keywords: peat soil environment; ultrafine cement (UFC); cement-soil; strength test; microstructure

超细水泥对泥炭土环境下水泥土影响分析

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摘　要:在云南环滇池、洱海地区,泥炭土地基的处理是实际工程项目的难题,仅依靠普通水泥加固泥炭土已不能满足要求。在有机质含量较低的冲洪积黏性土中掺入胡敏酸、水泥,并变化超细

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水泥(UFC)掺入占比,制备成水泥土试样。将试样浸泡在富里酸液中,以模拟泥炭土环境中的水泥土,通过对浸泡时间为28、90 d的水泥土试样进行无侧限抗压强度(UCS)试验和扫描电镜(SEM)试验,分析掺入UFC对泥炭土环境中水泥土强度的影响。结果表明:在不考虑胡敏酸和富里酸的影响时,掺入UFC可明显提高水泥土的UCS,其细颗粒快速水化,生成大量胶凝产物,提升了土体骨架的联结性并填充了孔隙;UFC掺入占比增加后,因细颗粒过多,形成的团聚体结构降低了水泥的水化速率和水化程度,进而使得水泥土的UCS增长率不明显;泥炭土环境下,胡敏酸在物理和化学方面都对水泥土的UCS产生了显著的削弱作用,而UFC凭借其粒径小、表面能高、结合能力强的特点,能适当削弱胡敏酸对水泥土造成的不利影响。此外,富里酸对浸泡时间为28、90 d的水泥土UCS具有一定的增强作用,而且添加UFC可适当促进富里酸对水泥土UCS的增强效果。扫描电镜(SEM)试验结果表明,随着UFC掺量的增加,水泥水化产物明显增多,水化产物和土颗粒间的胶结作用明显增强,水泥土孔隙的孔径显著减小,连通性显著降低,结构整体性增强。

关键词:泥炭土环境;超细水泥(UFC);水泥土;强度试验;微观结构

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1 Introduction

Peat soil is a particular soft soil with high organic matter content, low natural weight, high moisture content, large void ratio, low bearing capacity, and high compressibility which has many adverse effects on construction engineering[1-2]. It is often necessary to reinforce this kind of soft soil to meet the engineering requirements in construction. Cement materials are widely used in the reinforcement of this soft ground owing to its advantages of simple manufacture, low price, and easy handling. However, a large number of studies have shown that when only relying on ordinary cement to reinforce soft soil with high organic matter content, its solidification effect is not ideal. The main reason is that the humic group (HG) in peat soil participates in a series of reactions with the hydration products of ordinary cement [3-6]. Therefore, an additive is needed to partially replace ordinary cement and, to some extent, oppose the adverse effect of the HG on the strength of solidified soil. Some studies have pointed out that the smaller the cement particle size, the larger the specific surface area, the faster the hydration speed, and the faster the cement hardens[7]. For this reason, several scholars have studied ultrafine cement (UFC).

In 1974, Japan was the first to develop ultrafine cement (MC-500) as a grouting material[8]. Since then, there have been abundant studies on the application of UFC. Arteaga-Arcos et al. [9] showed that adding UFC can significantly improve the compressive strength of cement mortar compared with ordinary cement mortar. The improvement of mortar strength is most significant when the replacement rate of UFC to ordinary cement is 30% to 40%. Zheng et al. [10] studied the effect of UFC on the early mechanical properties of solidified soft soil. Their results show that the strength and elastic modulus of the cement-soil increase with the increase in UFC proportion, and its microstructure becomes dense. Li et al. [11] found that the increase of cement fineness can reduce the plastic viscosity of cement paste to a certain extent and reduces its porosity. Moreover, the early strength of the cement significantly improved, the hydration heat and peak temperature increased, and the induction period was shortened. Wang et al. [12] used ultrafine Portland cement (UPC) to reinforce sludge. The results showed that UPC-modified sludge could produce more hydration products, greater compressive strength, significant early strength, and stronger deformation resistance under the similar conditions. Compared with ordinary cement (OPC) modified sludge, the strength of UPC modified sludge after one day is about four times higher than that of ordinary cement (OPC) modified sludge. Guo et al. [13] concluded that a water-cement ratio of 1.4∶1 and a fineness of 1 250 mesh produce the optimal mechanical properties of ultrafine cement slurry. Kaufmann et al. [14] studied the effect of UFC proportion on the rheological properties and strength of Portland cement slurry. This study concluded that UFC can improve the rheological properties of the cement slurry, especially viscosity and yield value. Meanwhile, adding UFC can also improve the hardened cement mechanical properties, such as compressive strength, and flexural strength. Shi et al. [15] indicated that cement particle fineness significantly affects the early hydration process of cement; he found that the smaller the cement particle size, the higher the early compressive strength. The compressive strength of ultrafine cement mortar with a particle size of 6.8 μm can reach 55.94 MPa after solidifying for 24 hours, which is 118% higher than ordinary cement mortar.

Although there have been many studies on the mechanical properties of UFC by domestic and foreign scholars, research on the effect of UFC on the strength of cement-soil in a peat soil environment is rare. In this study, UFC is used as an external admixture to simulate cement-soil in a peat soil environment by blending (Humic Acid (HA) is incorporated into soil specimens) and steeping (specimens are immersed in fulvic acid (FA) solution). Subsequently, UCS and SEM microscopic tests are conducted on the cement-soil samples. The strength development law and solidifying mechanism of cement-soil mixed with UFC in a peat soil environment are analyzed preliminarily to provide some theoretical support for subsequent experimental research and engineering practice.

2 Materials and methods

2.1 Indoor simulation of the organic soil environment

Due to the special geographical environment and plateau climate, the area around Dianchi Lake in Kunming belongs to a large ancient lake and swamp area with deep Quaternary sedimentary rocks and widely distributed peat soil[16-17]. Seven groups of representative peat soil samples of Dianchi lake facies were selected for experimental analysis to find out the distribution of peat soil in the area around Dianchi Lake. The test is based on *Determination of Forest Soil Humus Composition* (LY/T 1238—1999) to extract and determine the content and composition of HG in peat soil. The measurement results in Table 1 show that, although the samples were all taken from the area around Dianchi Lake in Kunming, the amounts of HG from different sites are quite different. The lowest amount of HG was only 7.15% (SS-4), and the highest 50.06% (SS-1). The content of each component of HG also varied significantly from site to site. The content of HA was the largest, ranging from 2.36% to 28.13%, and that of FA varied from 0.79% to 8.34%. Comparing the content and composition of HG in the peat soil samples shown in Table 1, it can be seen that the content of HA is high, and the content of FA in all soil samples does not exceed 10%[18]. Therefore, in our experiment, HA and FA were selected as the test acids, and the blending and steeping methods were designed to simulate a peat soil environment with different HG contents.

Table 1 Determination results of HG content in natural peat soil samples[18]

NO.	Site	Distance from the shore of Dianchi Lake/km	Total HG/%	HA content/%	FA content/%	Humin content/%
SS-1	Intersection of Huachen road and Yikang road	3.68	54.06	28.13	8.34	13.59
SS-2	Changhong road, Luoya community, Guandu District	3.50	34.38	14.56	5.11	14.71
SS-3	North of the intersection of Fubao road and Huanhu east road, Guandu district	0.80	15.18	6.61	2.45	6.12
SS-4	Intersection of Baiji road and Huanhu east road, Guandu district	0.52	7.15	2.36	0.79	4.00
SS-5	Intersection of Haidong road and Gudukou road, Guandu district	1.32	41.74	22.79	3.39	15.56
SS-6	Intersection of Yupu road and Gudian road, Chenggong district	1.10	40.26	22.22	2.67	15.37
SS-7	North of Haibao mountain, Chenggong district	1.36	9.07	4.06	2.92	2.09

2.2 Materials

The soil samples were natural samples collected from the alluvial north slope of the Jingyuan Student Residence on the Chenggong Campus of Kunming University of Science and Technology. The undisturbed soil sample was brownish yellow. The organic matter content of this soil sample was low, which has little influence on the test results. The basic physical properties of the soil used in the test are shown in Table 2, and its microstructure is shown in

Fig. 1. The cohesive soil aggregate has a sheet-like structure with significant cohesion.

Table 2 Basic physical indexes of the soil used in the test

Test soil	Natural water content /%	Liquid limit w_L/%	Plastic limit w_P/%	Natural density /(g/cm^3)	Grain specific gravity G_s
Cohesive soil	18.60	39.20	23.00	1.96	2.73

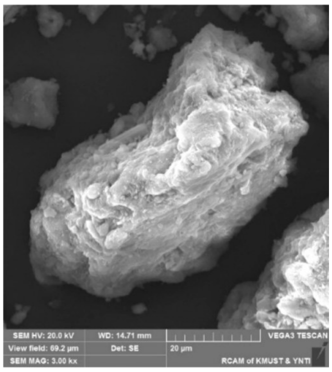


Fig. 1 Microstructure of cohesive soil aggregated

The humic acid reagent is humic acid produced by Tianjin Guangfu Chemical Reagent Factory, and its microstructure is shown in Fig. 2. It can be seen that the humic acid is loose and porous, and their structural cohesion is weak. The fulvic acid reagent is selected from the biochemical fulvic acid produced by Pingxiang Red Land Humic Group Co., Ltd. In the test, we used distilled water for mixing and for fulvic acid soaking. The cement was Shilin brand P·O 42.5 grade ordinary Portland cement produced by Huaxin Cement Co., Ltd. Kunming Branch. UFC is made of the cement mentioned above after physical processing and grinding, and its specific surface area is higher than 9 000 cm^2/g, with d_{90}<10 μm. The cumulative distribution curves of particle size gradation of both cements are shown in Fig. 3.

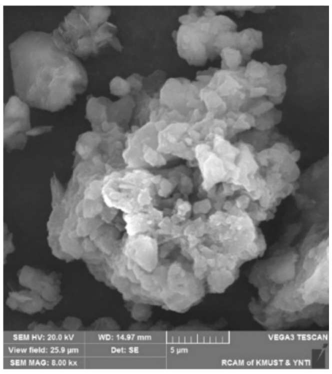


Fig. 2 Microstructure of humic acid aggregate

2.3 Preparation of cement-soil samples

The samples were prepared according to *Standards for Geotechnical Test Methods* (GB/T 50123−2019) [19]. The moisture content of the control sample was ω=24%, the void ratio e=0.8.

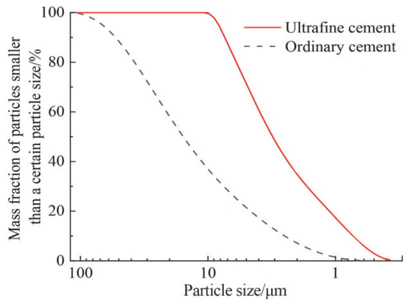


Fig. 3 Cumulative distribution curves of particle size gradation of UFC and ordinary cement

The materials were mixed evenly; a three-lobed mold (inner diameter d=39.10 mm, height h=80.00 mm) was used to prepare the cement-soil specimen. The dosage calculation method for each group of samples is as follows[20].

$$\lambda=\frac{m_{HA}}{m_{soil}+m_{HA}}\times 100\% \quad (1)$$

$$\beta=\frac{m_{cement}}{m_{soil}+m_{HA}}\times 100\% \quad (2)$$

Where λ is the amount of HA incorporated, %; m_{HA} is the mass of HA, g; m_{soil} is the mass of soil, g; β is the cement mixing ratio, %; m_{cement} is the mass of cement, g. The UFC proportion was set at 0%, 10%, 20%, 30%, 40% and 50% of the total cement content.

2.4 Immersion test, UCS test and SEM test

(1) The FA powder was dissolved in distilled water and two solutions with different concentrations (pH value: 5.0 and 6.0) were prepared. Distilled water (pH=7) was used for soaking. The pH of the FA soaking liquid was measured periodically to keep it constant, using a pH meter (accuracy 0.01) and adding FA powder when necessary[21].

(2) The test samples were cured for 28 days and 90 days. After the sample was naturally air-dried, the sample's unconfined compressive strength (UCS) was measured by YSH-2 electric lime soil unconfined compressive press (Nanjing Ningxi Soil Instrument Co., Ltd.). Sample preparation is shown in Table 3.

(3) To determine the microscopic morphology of the cement-soil a sample with 20% cement rate

Table 3　Sample preparation

Cement mixing ratio β/%	Humic acid content λ/%	UFC proportion/%	Soaking solution pH	Soaking time/days
20	0	0, 10, 20, 30, 40, 50	7.0	28, 90
	0, 15, 30	0, 10, 20, 30, 40, 50	6.0	28, 90
	15	0, 10, 20, 30, 40, 50	5.0, 6.0, 7.0	28, 90

and 15% HA content (pH=6.0) was cured for 90 d. The dried sample was prepared as a block with a length of 30 mm, a width of 20 mm, and a height of 15 mm for microscopic examination. A Czech VEGA3-TESCAN automatic tungsten filament scanning electron microscope was used to determine the microscopic morphology of the cement-soil.

3　Results and Mechanism Analysis

3.1　Effect and mechanism of UFC on the strength of solidified cohesive soil

To analyze the influence of UFC alone, the samples with different UFC proportions were immersed in distilled water without HA. As shown in Fig. 4, the UCS of the sample increases rapidly with the increase of the UFC from 0% to 10%, then gradually decreases, and when the UFC content is more than 30%, the UCS growth rate of the sample is not significant.

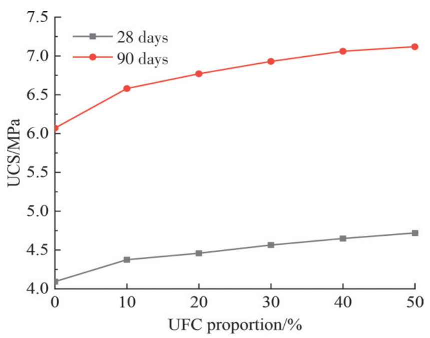


Fig. 4　Relationship between cement-soil UCS and UFC proportion

The pet-soil strengthening mechanism is analyzed as follows.

(1) Adding UFC increases the contact area between the particles and the solution, and the reaction is enhanced in comparison with ordinary cement. When the content of UFC increases, a large number of gelling substances such as calcium silicate hydrate (CSH), calcium aluminate hydrate (CAH), and calcium aluminosilicate hydrate (CASH) are generated by hydration. These cementitious particles produced by the hydration reaction have strong adsorption [22-24,10,15], resulting in a better cohesion of soil skeleton, which strengthens the soil structure[25]. At the same time, hydration products fill the inner pores so that the cement-soil forms a compact structure with increased strength.

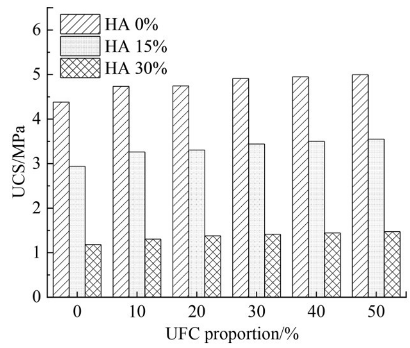
(2) However, when the UFC proportion is above 30%, the number of fine particles increases, the specific surface area further increases, the proportion of surface atoms or ions, the surface energy rises, and the ultrafine particles are in an unstable state. In addition, the distance between fine particles is very short, and the van der Waals force between particles is significantly larger than their gravity[26]. At the same time, under the influence of weak interaction forces, (such as electrostatic attraction and capillary force), some fine particles agglomerate to form aggregate structures. As a result, the specific surface area of the agglomerates is significantly reduced, the surface reactivity is reduced, and the hydration process is slowed down. Studies have shown[27-29] that the fineness of cement particles can be divided into four ranges: less than 3 μm, 3-30 μm, 30-60 μm, and greater than 60 μm. Due to the difference in cement hydration rate and hydration degree, the effect of cement particle fineness on cement-soil strength under different curing times is also different. Cement particles smaller than 3 μm hydrate quickly and contribute more to the early strength of the cement-soil (1-3 days). The hydration of cement particles with a particle size of 3-30 μm mainly affects the strength of cement-soil from 28 days to 90 days. The coarse cement particles of 30-60 μm are slightly hydrated at 28 days, mainly affecting the strength after 90 days. Cement particles larger than 60 μm have fewer hydration products and may only have a filling effect in cement-soil. The UFC particles d_{90}<10 μm in this test, and the agglomerate structure formed by fine particles after increasing the percentage of UFC, reduces the hydration rate and degree of hydration of cement. Therefore, the hydration of the aggregates is not

complete before 90 days, and the strength growth rate of cement-soil with a UFC content greater than 30% is not noticeable.

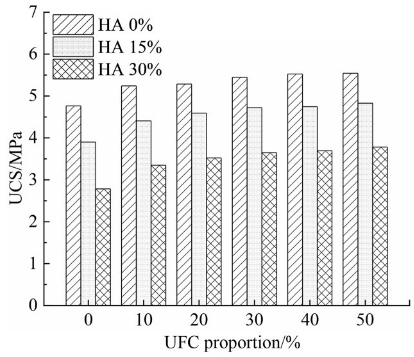
Our study results show that UFC can significantly improve the structure of soil cement, increasing its strength. In engineering practice, it is more economical and reasonable to use a UFC-cement ratio about 10%. When the content of UFC is greater than 10%, the reinforcement effect is not apparent.

3.2 Influence and mechanism of UFC on cement-soil strength in the peat soil environment

Fig. 5 shows the effects of HA and UFC on cement soil UCS under the FA soaking solution with a pH of 6.0. With the increase of HA content, the UCS of cement-soil decreases significantly, indicating that HA seriously affects the development of cement-soil UCS. The solidify effect will be significantly reduced when relying only on ordinary cement to reinforce peat soil with high HA content.



(a) 28 days



(b) 90 days

Fig. 5 Histogram of the relationship between UCS and UFC proportion of cement-soil (pH=6.0)

The adverse effect of HA on cement-soil UCS can be explained as follows. (1) The relative molecular weight of HA is considerable, its molecular structure is complex, and it is an aromatic organic compound with a benzene ring structure. This structure has a variety of oxygen-containing functional groups, and these benzene rings are chemically bonded to form a network of pores[30], making the HA molecule a loose sponge-like structure with a large amount of internal space[31]. Cohesive soil minerals are formed by unit cells composed of silicon-oxygen wafers and aluminum-hydroxide wafers. There are hydrogen bonds connecting oxygen atoms and hydroxyl groups between the unit cells, and the distance is not easy to change[32]. Therefore, the chemical structure of HA is worse than that of cohesive soil minerals, consistent with the microscopic results of cohesive soil aggregates and HA aggregates in Fig. 1 and Fig. 2. Therefore, with the increase in HA content, the overall pressure-bearing capacity of cement-soil decreases.

(2) The physical structure of HA determines its strong water holding capacity and adsorption. Humic acid particles can be adsorbed on the surface of cohesive soil particles and cement particles that have not been hydrated in time[4] and react with high-valent cations in the counterion layer on the surface of cohesive soil particles. This reaction reduces the valence of the cations and further weakens the electrostatic attraction between the cations in the counterion layer and the negative charges on the surface of the soil particles. Eventually, the thickness of the diffusion layer increases, the connection between soil particles is weakened[33], and the dispersion of cohesive soil is enhanced[34]. At the same time, the HA adsorbed on the surface of cement particles that have not been hydrated in time delays, to a certain extent, the formation of cement hydration products, thereby affecting the bonding between hydration products and cohesive soil particles. Therefore, a continuous lattice network structure cannot be formed between the cement hydration products and the cohesive soil particles, weakening the cement-soil structure, thereby reducing its UCS.

(3) Humic acid particles are slightly soluble in water, the carboxyl and phenolic hydroxyl groups on their surface are readily dissociated, and the amine group is easily protonated, which leads to HA readily reacting with metal ions in cement-soil. The reaction produces water-insoluble humic acid salt, which

reduces the concentration of OH^- and Ca^{2+} in the cement-soil pore water solution and hinders the formation of cement hydration and gelation products. At the same time, HA is not conducive to the dissolution of silicon-oxygen wafers and aluminum-oxygen wafers in the soil, thus significantly reducing the pozzolanic reaction in cement-soil[35]. The volcanic ash reaction has an outstanding contribution to the strength of cement-soil. The large amount of gel material produced by the pozzolanic reaction can cement the cohesive soil particles so that the dispersed particles are bound together, thereby strengthening the cement-soil structure. In summary, HA has weakened the development of cement-soil strength in both physical and chemical aspects.

The addition of UFC can significantly improve the development of cement-soil UCS in the peat soil environment, as it can be seen in Fig. 5. Moreover, the UCS of cement-soil increases gradually with the increase of UFC proportion, which indicates that the addition of UFC can appropriately weaken the side effects of HA on cement hydration. UFC particles are smaller and have higher surface energy, and their binding capacity is more potent than that of HA. On the one hand, UFC accelerates the hydration of cement to generate a large amount of highly alkaline hydration gel products and neutralizes part of the acidity generated by the dissolution of HA. On the other hand, the higher binding capacity of UFC inhibits the decomposition of HA to hydrated and cemented substances, which enhances the structure of cement-soil, increasing its UCS.

The above results show that the development of cement-soil UCS can be effectively improved when UFC is used as an admixture to reinforce peat soil containing HA. Fig. 6 is a schematic diagram of UFC promoting the strength of HA-containing cement soil.

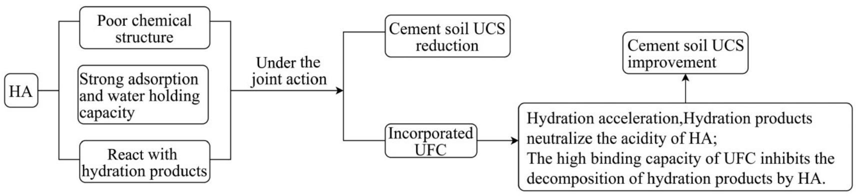


Fig. 6　Schematic diagram of the strength of UFC-promoted cement soil containing HA

Fig. 7 shows the effects of soaking solution pH and UFC on cement-soil UCS with a 15% HA content. When the pH of the soaking solution decreases (owing to the increase of FA concentration), the UCS of the cement-soil increases significantly, indicating that the FA has a certain enhancement effect on the samples before soaking for 90 days. Table 4 shows the cement-soil strength growth rate (δ_U) under different soaking times. The calculation method of $\delta_{U_{5-7}}$ is as follows, and the calculation method of $\delta_{U_{6-7}}$ refers to $\delta_{U_{5-7}}$.

$$\Delta_U = U_5 - U_7 \tag{3}$$

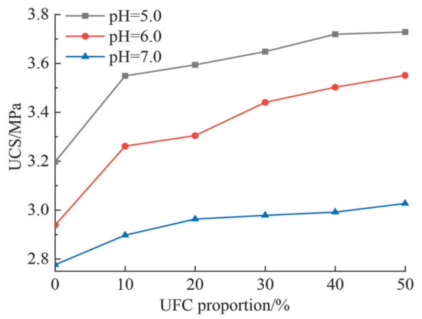
$$\delta_{U_{5-7}} = \frac{\Delta_U}{U_7} \times 100\% \tag{4}$$

where U_5 represents the UCS of cement-soil soaked in a fulvic acid solution with pH=5.0, U_7 represents the UCS of cement-soil soaked in a fulvic acid solution with pH=7.0, Δ_U represents the difference between the UCS of cement-soil in a pH=5.0 fulvic acid solution and the strength of cement-soil in distilled water.

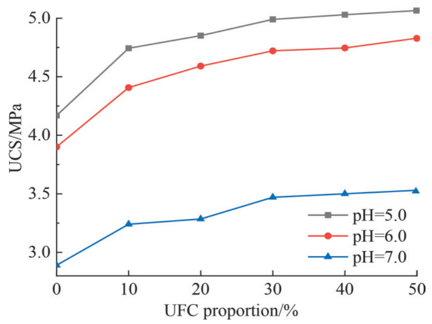
It can be seen from Table 4 that under the same UFC proportion, the δ_U of cement-soil showed a trend of first increasing and then decreasing. The δ_U of the samples in the FA solution with a lower pH value is more significant than in the FA solution with a higher pH value. It shows that adding UFC can properly promote the enhancement effect of FA on

Table 4　Strength growth rate δ_U of cement-soil in fulvic acid solution compared with distilled water

Soaking time/days	Intensity growth rate δ_U/%	Strength growth rate of cement soil under different UFC proportion/%					
		0%	10%	20%	30%	40%	50%
28	$\delta_{U_{5-7}}$	15.17	22.49	21.28	22.49	24.32	23.18
	$\delta_{U_{6-7}}$	5.84	12.58	11.52	15.53	17.08	17.32
90	$\delta_{U_{5-7}}$	44.24	46.38	47.66	43.80	43.70	43.48
	$\delta_{U_{6-7}}$	34.96	36.02	39.74	36.06	35.60	36.79



(a) 28 days



(b) 90 days

Fig. 7 The relationship curves between cement-soil UCS and UFC proportion (15% HA content)

cement-soil UCS. The enhancement effect of FA on cement-soil UCS can be explained as follows. FA configuration and adsorption behavior are like polyelectrolytes, which are affected by the solution's pH value and ionic strength[36]. The decrease in pH leads to the protonation of the acidic functional groups of FA, which are involved in hydrogen bonding, thereby linking the structural units of FA together within or between molecules to form polymers. As the hydration reaction of cement proceeds, many metal cations will be ionized in the solution, resulting in a higher cation concentration. Charge repulsion between adjacent carboxyl (-COOH) or hydroxyl (-OH) groups on FA molecules can be neutralized or complexed by cations.

Furthermore, electrostatic gravitational forces attract polymers together, resulting in smaller, denser, and more rigid molecules; this transforms FA molecules from linear colloids to rigid spherical colloids[37-39]. Cement-soil soaked in FA is a porous medium. Due to the small molecular structure and low molecular weight of FA, it can invade the inner part of the cement-soil and remain as a filler in part of the pores, which decreases sample porosity. Additionally, FA can also exert its colloidal properties to generate the colloidal connection between cohesive soil particles; this enhances the overall cohesion of the cement-soil structure and improves the UCS of the sample.

It can also be seen from Fig. 7 that the addition of UFC significantly improves the development of peat soil UCS under FA soaking solutions with different pH values, and the UCS of cement-soil gradually increases with the increase of UFC proportion. The above results show that incorporating UFC can promote FA enhancement on cement-soil's strength. The mechanism of UFC action can be explained by its small particle size, large specific surface area, and fast hydration rate. Compared to ordinary cement, the hydration of UFC generates more high-alkaline cement hydration products, and the alkaline environment of the pore water solution is enhanced. The solubility of HA in an alkaline environment is much greater than in an acidic environment, so the HA as the soil skeleton inside the cement-soil sample soaked in distilled water will be continuously dissolved. As a result, the internal pore size of the sample increases, the pores are interconnected[18], the cement-soil structure continues to deteriorate, and the compressive capacity of the cement-soil sample is weakened. When the cement-soil is immersed in the FA solution, the soluble FA invades part of the pores inside the specimen through the soaking solution. A part of the hydration products of FA and cement undergo a series of physical-chemical reactions, which reduce the highly alkaline environment of the pore water solution. This phenomenon reduces the solubility of HA, which is the framework of the soil, weakening the deterioration effect of the cement-soil structure. Another part of FA is gradually wrapped on the soil skeleton through adsorption, and due to the colloidal properties of FA itself[40], colloidal connections are formed between the originally dispersed cohesive soil particles[30]. Moreover, the rigid spherical colloid formed by FA and metal cations ionized by cement hydration can partially fill the internal pores of cement-soil, which enhances the overall connectivity of the sample, reduces the size of the pores, and makes the structure tighter. Therefore, the UCS of cement-soil increases with decreasing pH of the soaking solution.

The above results show that when the soaking time of cement-soil samples is 28 days and 90 days, FA has a certain strengthening effect, and the incorporation of UFC can appropriately promote the strengthening effect of FA on cement-soil. Fig. 8 is a schematic diagram of the effect of UFC-promoted FA on the strength enhancement of cement soil.

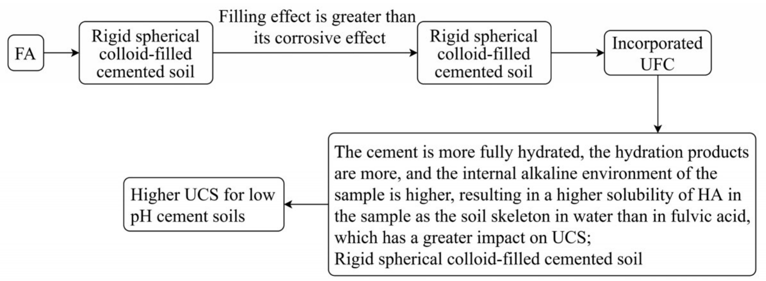
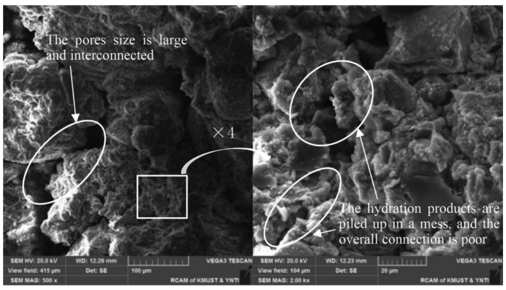


Fig. 8　Schematic diagram of the effect of UFC promoted FA on the strength enhancement of cement soil

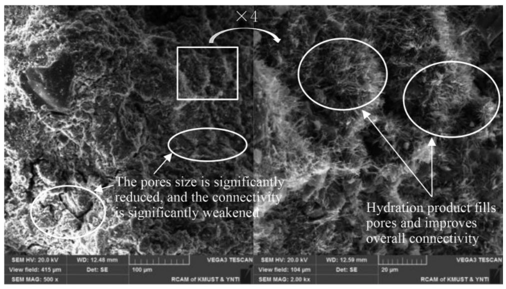
3.3　SEM test and microstructure analysis

To further analyze the strength change mechanism of UFC cement-soil in a peat soil environment, SEM experiments were conducted on cement-soil with different UFC proportions. Fig. 9 shows typical SEM images of cement-soil samples at 500× and 2 000× magnification (90 days soaking time, 15% HA content, pH=6.0 solution, 0%, 10%, 20%, 30%, 50% UFC proportions).

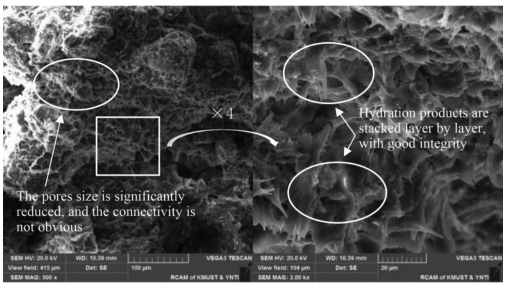
Fig. 9(a) shows the microscopic image of the sample with 0% UFC proportion. It can be seen from the image that cement hydration products wrap the soil particles of the sample to form larger aggregates, but the degree of cementation between aggre-



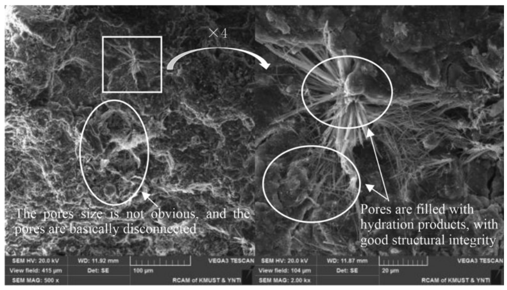
(a) UFC 0%



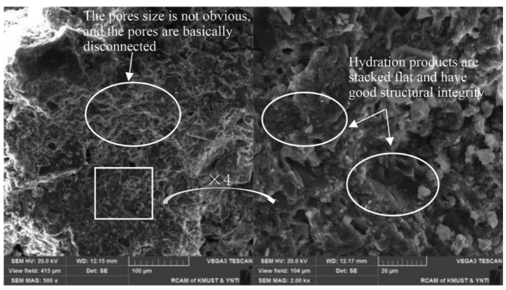
(b) UFC 10%



(c) UFC 20%



(d) UFC 30%



(e) UFC 50%

Fig.9　Microstructure images of cement-soil with different UFC proportion

gates is poor. The fibrous, rod- or flake-like gel products that function as cementation in the sample are either scarce or not visible, and the skeleton is relatively loose. The pores in the samples have large sizes and are interconnected, the hydration products are piled up disorderly, and the overall structural cohesion is not robust. Finally, the sample's microstructure showed the form of "large aggregates-larger pores-scattered accumulation of soil particles."

The microscopic image of the 10% UFC content sample in Fig. 9(b) shows that the structural connectivity of the sample is significantly enhanced, and the dense fibrous or massive hydration products spread over the agglomerates and between the pores are clearly visible. The hydration products in the pores and on the surface of the agglomerates interlaced to form a dense structure. The pores are significantly filled, connectivity is significantly reduced, and the overall structure is like a spatial lattice-like structure, although the structural integrity is still poor.

Fig. 9(c) shows the microscopic image of the specimen with a 20% UFC proportion. It can be seen from the image that the structural cohesion of the sample is further enhanced, and the dispersed aggregate units are are tightly cemented together. The massive hydration products overlap, filling the entire pores between the large aggregates, and forming a dense honeycomb-like lattice with considerable structural integrity.

The microstructure of the samples with UFC proportions of 30% and 50% is very dense, as shown in Fig. 9 (d)-(e). The hydration products have entirely wrapped the soil agglomerates to form a whole, the pores are basically invisible, the hydration products are piled up flat, and the structure is very tightly linked, consistent with the strength results.

The above results indicate that the development of cement-soil UCS in the peat soil environment depends on the number of hydration products, the compactness of the microstructure, and the degree of cementation of soil particles. With the increase of the UFC proportion, the number of cement hydration products increases, the pore size g decreases, and connectivity is not apparent. The degree of cementation between hydration products and soil particles is enhanced, and the structural integrity of cement-soil is excellent.

4 Conclusion

This study aims to explain the effect of UFC on cement-soil strength in the peat soil environment. Different proportions of UFC are added to ordinary cement to form a composite cement curing agent. Microscopic analysis was used to observe the microstructure of cement-soil with different UFC content and to reveal the solidification mechanism. The following conclusions are obtained:

(1) Without considering the effects of HA and FA, UFC can significantly improve the strength of cement-soil. Moreover, the UCS of cement-soil increases rapidly with the increase of UFC proportion from 0% to 10%. When the UFC proportion increases from 10% to 30%, UCS gradually levels off, and for UFC proportion above 30%, the UCS rate of cement-soil is not significant. This can be explained by the rapid hydration of fine cement particles at low UFC proportion, resulting in a large number of cementitious products, which promotes the improvement of soil skeleton cohesion and fills part of the pores, thereby increasing the UCS of cement-soil. However, the agglomerate structure formed by fine particles at high UFC proportion reduces the hydration rate and degree of cement, so the UCS growth rate of cement-soil becomes negligible. Therefore, when we use UFC to reinforce the cement-soil, it is recommended to use a UFC proportion about 10% of total cement addition.

(2) In the peat soil environment, HA will undergo a series of physical and chemical reactions with the hydration products of cement that can significantly reduce the UCS of cement-soil. However, the addition of UFC can weaken the negative impact of HA on the structure of cement-soil to a certain extent, which explains why, with the increase of UFC proportion, the UCS of cement-soil increases gradually.

(3) In the peat soil environment, FA has a certain enhancement effect on the UCS of cement-soil soaked for 28 days and 90 days, and UFC can promote the enhancement effect of FA on the cement-soil UCS. The addition of UFC accelerates

the hydration of cement, and the hydration process is enhanced. The hydration reaction produces more highly alkaline hydration products, increasing cement-soil's internal alkalinity. Therefore, UFC addition may promote the dissolution and desorption of HA, weakening the cement-soil structure. However, the dissolution and desorption of HA are low for the samples immersed in the FA solution, and its weakening effect on the cement-soil structure is insignificant. Consequently, under the same amount of UFC, the UCS of cement-soil shows an increasing trend with the decrease of the pH value of the soaking solution.

(4) SEM test results showed that cement hydration products increased significantly with the increase of UFC proportion. The pore size of cement-soil pores and the connectivity of pores are significantly reduced, the cementation between hydration products and soil particles is significantly enhanced, and structural integrity is enhanced. The macroscopic effect of the above changes is an increase in UCS of cement-soil.

References

[1] ZHANG F G. HUANG C F, YAO T J, et al. Experimental study on laws of compression and rebound deformation of peaty soil [J]. Chinese Journal of Geotechnical Engineering, 2021, 43(Sup2): 259-262. (in Chinese)

[2] DU M X, ZHAO M, WU Y N, et al. Settlement analysis of underground comprehensive pipe gallery based on peat soil foundation [J]. Industrial Safety and Environmental Protection, 2021, 47(10): 66-70. (in Chinese)

[3] YOUNG J F. A review of the mechanisms of set-retardation in Portland cement pastes containing organic admixtures [J]. Cement and Concrete Research, 1972, 2 (4): 415-433.

[4] ZENG W D, TANG X Y, HE M Z. Application of cement deep-mixing method in treatment of peat soil [J]. Journal of Geological Hazards and Environment Preservation, 2002, 13(2): 67-69, 79. (in Chinese)

[5] THOMPSON M R. Lime reactivity of Illinois soils [J]. Journal of the Soil Mechanics and Foundations Division, 1966, 92(5): 67-92.

[6] CHEN H E. A study on the behavior of organic matter in the progress of solidifying soft soil by cement [D]. Changchun: Jilin University, 2006. (in Chinese)

[7] WEI R T, ZENG Y J. Relationship between fineness and strength of different kinds of cement [J]. Cement Engineering, 1998(4): 14-15.

[8] HE Z M, LONG G C, XIE Y J, et al. Surface layer degradation effect of steam-cured concrete [J]. Journal of Build Materials, 2014, 17: 994-1008.

[9] ARTEAGA-ARCOS J C, CHIMAL-VALENCIA O A, YEE-MADEIRA H T, et al. The usage of ultra-fine cement as an admixture to increase the compressive strength of Portland cement mortars [J]. Construction and Building Materials, 2013, 42: 152-160.

[10] ZHENG X Y, LIU X X, WU J, et al. Impact of ultra-fine cement on early compressive strength of cement stabilized soft soil [J]. Journal of Engineering Geology, 2020, 28(4): 685-696.

[11] LI H J, YANG L, XIE Y J. Effect of fineness on the properties of cement paste[J]. Key Engineering Materials, 2014, 629/630: 366-370.

[12] WANG S R. Experimental study on mechanical properties and structural characteristics of modified sludge in foundation pit [J]. Converter, 2021: 11-21.

[13] GUO D M, TAN J S, XIAO Z X, et al. Study on the optimum proportion and grouting effect of superfine cement slurry [J]. Journal of Henan Polytechnic University (Natural Science), 2017, 36(5): 1-8. (in Chinese)

[14] KAUFMANN J, WINNEFELD F. Influence of addition of ultrafine cement on the rheological properties and strength of Portland cement paste [C]//Innovations and Developments in Concrete Materials and Construction: Proceedings of the International Conference held at the University of Dundee, Scotland, UK, 9-11 September 2002. Thomas Telford Publishing, 2002: 827-836.

[15] SHI Y, WANG T, LI H Y, et al. Exploring the influence factors of early hydration of ultrafine cement[J]. Materials, 2021, 14(19): 5677.

[16] JIANG Z X. Dianchi peat soil [M]. Chengdu: Southwest Jiaotong University Press, 1994. (in Chinese)

[17] LI D. Study on microstructure characteristics and engineering mechanics model of peat soil in Dianchi Lake [D]. Kunming: Kunming University of Science and Technology, 2015. (in Chinese)

[18] CAO J, HUANG S Y, LIU W L, et al. Study on simulation test of peat soil environment in Dianchi Lake [J]. Advances in Civil Engineering, 2022, 2022: 1-12.

[19] Standard for Geotechnical Testing Method: GB/T 50123—2019 [S]. Beijing: China Planning Press, 2019. (in Chinese)

[20] CAO J, LI S P, LIU H M, et al. On the strength of cement soil affected and effected by the humic acid and its mechanism [J]. Journal of Safety and Environment, 2021, 21(6): 2571-2576. (in Chinese)

[21] CAO J, HU Y C, LIU H M. Experimental study on corrosivity of CFG pile material in fulvic acid [J]. Bulletin of the Chinese Ceramic Society, 2019, 38(12): 3972-3979. (in Chinese)

[22] CAO J, SUN C J, GAO Y, et al. Corrosion test of fly ash cement soil with fulvic acid [J]. Bulletin of the Chinese Ceramic Society, 2018, 37(6): 2019-2024. (in Chinese)

[23] CHEN X D, ZHOU J K, YAN Y Y. Hydration of ultrafine and ordinary Portland cement at early ages [J]. KSCE Journal of Civil Engineering, 2014, 18(6): 1720-1725.

[24] WANG A Q, ZHANG C Z, ZHANG N S. The theoretic analysis of the influence of the particle size distribution of cement system on the property of cement [J]. Cement and Concrete Research, 1999, 29(11): 1721-1726.

[25] FENG Z C, ZHU W, ZHANG C L, et al. Influence of clay content on mechanical properties of solidified silt [J]. Chinese Journal of Rock Mechanics and Engineering, 2007, 26(Sup1): 3052-3057. (in Chinese)

[26] LI F S. Ultrafine Powder Technology [M]. Beijing: National Defense Industry Press, 2000. (in Chinese)

[27] QINGYUN D. The effect and analyzing method of particle characteristic to cement performance [EB/OLJ]. http://www. bettersize. com/english/E_technology. E_technology3. htm.

[28] ŠKVÁRA F, KOLÁŘ K, NOVOTNÝ J, et al. The effect of cement particle size distribution upon properties of pastes and mortars with low water-to-cement ratio [J]. Cement and Concrete Research, 1981, 11(2): 247-255.

[29] CELIK I B. The effects of particle size distribution and surface area upon cement strength development [J]. Powder Technology, 2009, 188(3): 272-276.

[30] ZHANG S B. The infection on the humic acid in the progress of solidifying soft soil by cement soil [D]. Changchun: Jilin University, 2007. (in Chinese)

[31] KHAN S U. Distribution and characteristics of organic matter extracted from the black solonetzic and black chernozemic soils of Alberta: The humic acid fraction [J]. Soil Science, 1971, 112(6): 401-409.

[32] GONG X N. Soil Mechanics [M]. Beijing: China Architecture & Building Press, 2002.

[33] CAO J, KONG C, LI S P. Effect of humic acid on strength of peat soil and its mechanism analysis [J]. Journal of Safety and Environment, 2022, 22(5): 2493-2499. (in Chinese)

[34] LAN Y Q, HU Q Y, XUE J H. Humic acid effect on dispersion of soil and mineral clay [J]. Acta Pedologica Sinica, 1998, 35(2): 195-201. (in Chinese)

[35] PAN C G, XIE X Y, GEN J, et al. Effect of stabilization/solidification on mechanical and phase characteristics of organic river silt by a stabilizer [J]. Construction and Building Materials, 2020, 236: 117538.

[36] MURPHY E M, ZACHARA J M, SMITH S C, et al. Interaction of hydrophobic organic compounds with mineral-bound humic substances [J]. Environmental Science & Technology, 1994, 28(7): 1291-1299.

[37] LEE C L, KUO L J, WANG H L, et al. Effects of ionic strength on the binding of phenanthrene and pyrene to humic substances: Three-stage variation model [J]. Water Research, 2003, 37(17): 4250-4258.

[38] PALMER N E, VON WANDRUSZKA R. Dynamic light scattering measurements of particle size development in aqueous humic materials [J]. Fresenius' Journal of Analytical Chemistry, 2001, 371(7): 951-954.

[39] OADES J M. An introduction to organic matter in mineral soils[M]//SSSA Book Series. Madison, WI, USA: Soil Science Society of America, 2018: 89-159.

[40] CAO J, YU Z X, LIU H M, et al. Experimental study on corrosion of red clay-cemented soil composite mass under fulvic acid [J]. Journal of Kunming University of Science and Technology (Natural Science Edition), 2015, 40(1): 35-38, 83. (in Chinese)

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