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Experimental Study on Cement-slag-titanium Gypsum-electrolithic Slag Compliant Curing of Dredged Silt

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Abstract: ***Soft soil curing has long been a scientifically and technically challenging subject. In order to solve the problems of insufficient early strength of cement-cured soft soils and the high resource, minimization and environmental costs associated with the use of cement, the development of cementitious curing agents with a "low carbon footprint" based on industrial solid waste instead of ordinary silicate cement is essential. This concept is also considered as a greener approach for the development of soft soil curing. In this study, slag and titanium gypsum were used as curing agents to partially replace cement in the treatment of dredged mud. The effects of curing agent dosage, slag-titanium gypsum ratio and alkaline exciter dosage on the strength of cured soil at different ages were mainly investigated. Unconfined compressive strength (UCS), scanning electron microscope (SEM) and X-ray energy spectrum analysis (EDS) tests were conducted. The results showed that the amount of curing agent mix, slag-gypsum ratio, and alkaline exciter content had a decisive effect on the UCS of cured silt. The optimum mixing ratio was 25% cement dosing, 55:10 slag-titanium gypsum ratio, and 10% alkaline exciter content. Scanning electron microscopy (SEM) demonstrated that the uniformly distributed gel-like products formed in the cured silt were tightly bound to the soil particles. In addition, EDS analysis confirmed that the gelatinous products were mainly composed of C-S-H gels and calcium-based aluminum silicates (C-A-S-H), and the needle-and-rod products were calcite.***

Keywords: Solid waste, Dredging sludge, Curing agent, Unconfined compressive strength, Microstructural characterization.

1. Introduction

China's dredging silt production is huge, according to statistics, in China's Yangtze River estuary deep-water basin channel dredging project, the amount of river bottom silt dredged out every year is as high as 2×10^7 m^3. And the amount of silt produced in the domestic river dredging project every year reaches at least 1,000m^3. 7×10^7 m^3, there are various other sources of dredging silt, the annual dredging volume of more than 1×10^9 m^3 [1-3] The annual dredging volume is more than m^3 [1-3], and China has become the first dredging country in the world. Dredged mud has the physical characteristics of high water content, high compressibility, low strength, and contains a certain amount of organic matter, which can easily cause foundation instability or uneven settlement, and it is generally difficult to meet the construction requirements [4,5]. The soil has low physical properties. This poses a serious challenge to the construction, operation and maintenance of infrastructure. Currently, there are several treatment methods for dredged mud: marine mud disposal, landfill, physical dewatering, incineration, and chemical curing. Comparison found that the effective use of marine mud throwing sludge is not enough and also has a certain degree of pollution to the sea, blowing landfill cycle is long and the subsequent foundation treatment cost is high, physical dewatering is only suitable for a small amount of sludge treatment, thermal treatment of sludge transportation difficulties, compared with each other, chemical curing method of curing costs are lower, suitable for curing large-scale sludge, there is a great prospect for development! [6-8]. There is a great prospect for development.

Chemical curing technology is a very widely used method of soft ground treatment, specifically refers to a series of chemical and physical interactions between the curing agent and the soft soil to form a cured soil with sufficient strength. [9-14]. The curing agent is a very widely used method of soft ground treatment. Currently, cement is the most commonly used curing agent in foundation treatment, and there are many studies on the mechanical properties and theoretical aspects of cement-cured soil [15-17]. Currently, silicate cement is the most commonly used curing agent in soft soil curing [18,19], and there have been many studies on the mechanical properties and theoretical aspects of cement-cured soils. In order to significantly improve the engineering properties of existing soils, the cement content used is often up to 15-20% of the soil mass [20-22]. However, the over-reliance on cement has caused many environmental problems, such as the production and release of carbon dioxide during cement production, which also leads to a significant increase in carbon emissions, as well as the consumption of various non-renewable resources. The production of cement leads to the emission of about 4 billion tons of carbon dioxide per year, which accounts for 8-10% of global carbon emissions [23-25]. In addition, each ton of CO_2 produced consumes about 5000 MJ of energy. Moreover, cement-cured soils often suffer from disadvantages such as insufficient early strength and poor durability during the construction period of the project. Therefore, it is necessary to develop environmentally friendly curing agents with excellent performance to replace cement [26,27].

In recent years, many studies have been conducted by scholars at home and abroad on the application of industrial wastes, such as slag and industrial waste gypsum, for sludge curing, which can effectively reduce cement consumption. In addition to the environmental advantages, the desirable properties of industrial solid waste, including mechanical, heat and corrosion resistance, as well as low shrinkage and the absence of alkali aggregate reaction, make it a suitable alternative to ordinary silicate cement [28-31].

For curing properties: Xiaofang Zhang et al. (2023) [32] found that the faster the hydration generation of cement-slag-fly ash cured silt and the faster the growth of bound water content, the higher the strength of cured soil silt accordingly; Huang Xuquan et al. (2018) [33] Using fluoro gypsum-based cementitious materials, quicklime and cement-cured silt, it was found that the unconfined compressive strength of fluoro gypsum-based cementitious materials-cured silt was much higher than that of quicklime and cement-cured silt at the same age; Ding Jianwen et al. (2010) [34] Using cement-phosphogypsum double mixing curing treatment for dredged silt, it was found that phosphogypsum was effective for the strength growth of dredged silt cured soil and the optimum mixing amount existed; Gui Yue et al. (2014) [1] Using fly ash, slag, phosphogypsum three kinds of industrial waste as the main components of curing agent, found that phosphogypsum composite curing agent curing effect is the best, cement and industrial waste composition of the composite curing agent curing effect is better than lime and industrial waste composition of the composite curing agent.

Microstructural aspects: Ruimin Chen et al. (2022) [22] found that the filling, cementing, skeletonizing, and reinforcing effects of hydration products increased the strength of the soil body and the soil structure became denser (Xueding Wu et al., 2018); Keyu Chen et al. (2021) [35] The introduction of quasi-water-cement ratio to predict the strength development of stabilized soils was investigated and the corresponding empirical formula (correlation coefficient of 0.98) was proposed. The changes in microstructure, mineral phase and molecular bonding were investigated using XRD, FTIR and FESEM, respectively. The results showed that the reduction of initial water content and the increase of geopolymer inclusions had various improvement effects on the cured strength. The geopolymer gel structure was gradually formed, and after curing, it bonded the soil particles together and formed new hydration products, and eventually the stabilized soil showed a denser and stronger microstructure; Gizem Aksu et al. (2022) [36] investigated the effect of nano-silica (NS) additives on improving the mechanical properties of clays, clay sands and sands. The engineering properties of the soils were investigated by Atterberg limit, compaction, unconfined compression, ultrasonic pulse velocity (UPV), freeze-thaw and straight shear tests. The results showed that the addition of NS also improved the shear strength parameters of the soil. Scanning electron microscope (SEM) images showed that cement and NS contributed to the improvement of the soil by producing a denser and more homogeneous structure. It is concluded that small amounts of NS addition may improve the geomechanical properties of the soil.

In curing materials: Xuehe Li et al. (2023) [37] The curing agent was jointly prepared by slag, steel slag, desulfurization gypsum and common silicate cement to improve the curing of Yellow River alluvial chalk, which solved the engineering problems such as low strength and poor water stability of Yellow River alluvial chalk while improving the resource utilization of industrial waste residues. Xiao J et al. (2023) [38] Preparation of CFB ash-steel slag micropowder multi-source solid waste synergistic grouting materials using circulating fluidized bed boiler desulfurization fly ash, steel slag micropowder, and desulfurization gypsum. Sun Renjuan et al. (2021) [39] Powdered soil curing agent was prepared based on fly ash, slag, desulfurization gypsum, ordinary silicate cement and solid waste-based thioaluminate cement, and the presence of hydrated calcium silicate gel and calomel crystals in the cured soil was found based on X-ray diffraction analysis and secondary electron imaging techniques. Seung-Hyuk Kim et al. (2023) [40] used Design Expert to determine the optimal ratio of slag, desulfurization gypsum, and calcium carbide slag cured clay, and to explore the effects of mechanical properties and micro-mechanisms of cured soils. Although the above studies are related to industrial waste slag curing sludge, there is no actual engineering background, especially dredging sludge as an example, to propose a specific proportioning scheme. In addition, there are fewer reports related to the strength and microstructural characteristics of slag titanium gypsum cured silt.

Based on the idea of curing waste with waste, this study selected slag and titanium gypsum to partially replace cement as the curing agent to reinforce the dredged mud, and carried out a curing test on the dredged mud of Bailin River. On the basis of the previous test, a "three-factor, three-level" orthogonal test was designed to investigate the effects of curing agent dosage, slag-gypsum ratio and cement dosage on the 7d unconfined compressive strength of the cured soil at different curing ages, and the optimal ratio was found. At the same time, in order to further study the curing mechanism of dredged silt with the optimal ratio of curing agent, two control groups were set up for the optimal ratio, one group of cement cured soil with the same dosage of curing agent, and the other group of ordinary silicate cement partially replaced by sulphoaluminate cement (15% silicate cement, 10% sulphoaluminate cement), in order to compare and explore the effect of adjusting the silica to aluminum ratio on the cured soil by increasing the proportion of fast-hardening sulphoaluminate cement (10%), and the effect of the silica to aluminum ratio on the cured soil at different curing ages was found. The effect of adjusting the silica-alumina ratio on the curing effect of silt was investigated. Unconfined compressive strength (UCS) test, scanning electron microscope (SEM) test, EDS analysis and other test methods were also carried out to observe and compare the evolution of the microscopic morphology of the cured silt, and reveal the curing mechanism of cement-slag-titanium gypsum on the dredged silt.

2. Test Materials and Methods

2.1 Test Materials

The test soil was obtained from the riverside of Linbai River basin, Yiling District, Yichang City, Hubei Province, China. The original soil samples were dried to constant weight in an oven at 105°C, passed through a 5㎜ sieve, and stored in a sealed bucket. The physical properties of the soil are shown in Table 1. The soil particle size distribution was determined by laser particle sizer as shown in Figure 1.

Table 1: Physical Properties of Dredged Silt

relative density	Initial moisture content/%	plastic limit /%	liquid limit /%	plasticity index /%	Optimum moisture content/%	Maximum dry density/(g · cm^{-3})
1.95	79.2	26.9	52.7	24.2	23.6	1.478

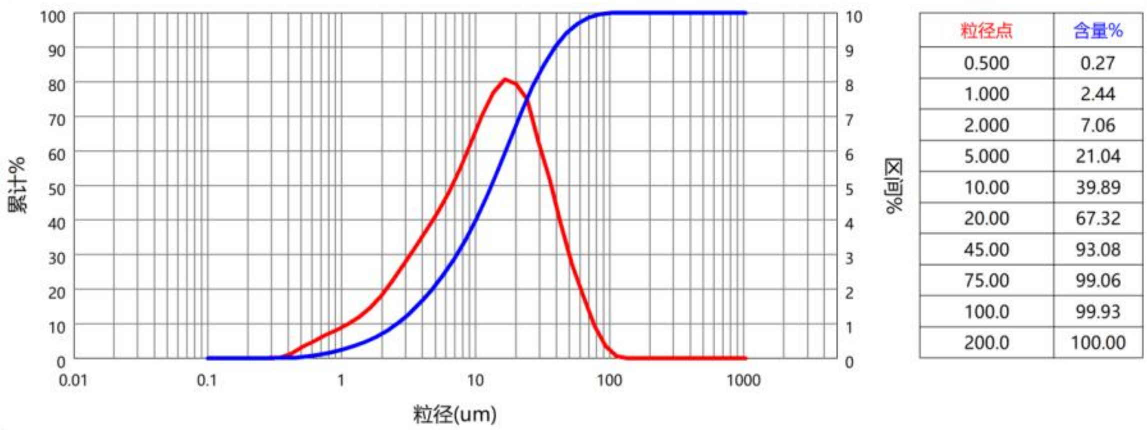


Figure 1: Particle size distribution of dredged silt

As can be seen from Figure 1, the silt particles are mainly concentrated between 2~50μm (0.002~0.05 ㎜), and the particles in this interval reach about 95%. The particle size distribution range of dredged silt is narrow, and the content of particles smaller than 0.02㎜ reaches 67.32%, the content of plastic particles from 0.02 to 0.05㎜ reaches about 30%, there are no filler particles from 0.05 to 1.2㎜, and there are no coarse particles from 1.2 to 2㎜, and it is calculated that $C_u = 4.32$, the uneven coefficient of silt is small and poor grading.

In this study, the curing agents used included P.O 42.5 cement (Zhucheng City Yangchun Cement Co., Ltd., Zhucheng, China) as well as slag, titanium gypsum, and calcium carbide slag. The industrial solid waste raw materials used were S95 grade slag (Longze Water Purification Materials Co., Ltd., Gongyi, Zhengzhou, China) and titanium gypsum (Guangxi Shiteng Science and Technology Co., Ltd.), which conformed to the Chinese standard GB/T 27690-2011. Figure 2 shows the appearance of the cement, slag, titanium gypsum, and calcium carbide slag.

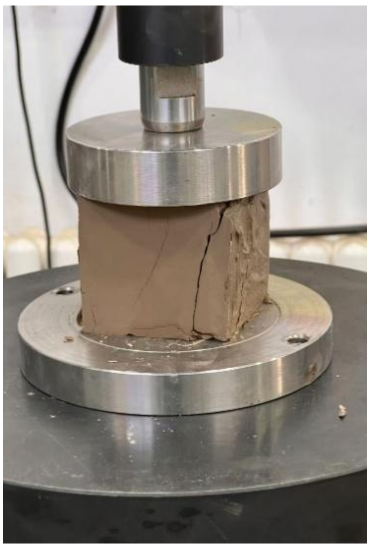


Figure 2: Unconfined compressive strength test

Table 2 shows the chemical composition of raw material cement (P.O42.5), sulfoaluminate cement (R.SAC42.5), slag and titanium gypsum. The test cement is ordinary silicate cement P.O42.5; the test slag is selected as grade S95, originated from Gongyi, Zhengzhou, and can be found in slag CaO、SiO_2 and Al_2O_3 The content of slag is as high as 86.5%; the origin of test sulfoaluminate cement is Weifang, Shandong Province, and the main composition is $CaO(45.30\%), Al_2O_3(18.60\%), SO_3(12.50\%)$ Titanium gypsum is the industrial gypsum by-produced by neutralizing a large amount of acidic wastewater during the production of titanium dioxide by sulfuric acid method. CaO The total amount of titanium gypsum reaches 72.70%. SO_3 The total amount of titanium gypsum reaches 72.70%, and the test titanium gypsum comes from Guangxi Shiteng Science and Technology Co.

Table 2: Chemical composition of raw materials

raw materials	Chemical composition and content						
	CaO	SiO_2	Al_2O_3	MgO	Fe_2O_3	SO_3	TiO_2
ooze R.SAC42.5	45.30	7.23	18.60	1.35	4.30	12.50	0.87
P.O42.5	51.42	24.99	8.26	3.71	4.03	2.51	
slag (mining)	35.3	34.5	16.7	5.01	1.50	1.24	
titanium plaster	36.60	4.40	1.50	0.70	17.30	36.10	3.40

2.2 Pilot Program

The aim of this part of the experiment was to elucidate whether slag titanium gypsum partially replaces cement as a curing agent for dredged silt is comparable or superior to cement in terms of reinforcement and to obtain the optimal proportioning scheme. In this study, remolded soil with an initial water content of 55.0% (ratio of water content to dry soil mass) was again prepared.

On the basis of the previous test, a "three-factor, six-level" orthogonal test was conducted. The dosage of curing agent (ratio of curing agent to remodeled soil) was 14%. In addition, in order to study the effects of cement dosage, slag-titanium gypsum ratio and alkaline stimulant dosage on the strength of cured soil, three cement dosages (20%, 25%, 30%), six slag-titanium gypsum ratios (45:10, 45:15, 50:10, 50:15, 55:10, 60:10), and three alkaline stimulant dosages (5%, 10%, 15%) were used. The specific mix ratios are shown in Table 4.

Table 3: Orthogonal tests

serial number	Amount of curing agent/ %	Cement Admixture/%	Slag-titanium-gypsum ratio	Alkaline exciter/%	water-cement ratio
C-1	8	100	-	-	0.55
C-2	14	100	-	-	0.55
C-3	18	100	-	-	0.55
I-1	8	25	50:10	15	0.55
I-2	8	25	55:10	10	0.55
I-3	8	25	60:10	5	0.55
I-4	8	25	50:15	10	0.55
I-5	8	25	45:15	15	0.55
I-6	8	20	55:10	15	0.55
I-7	8	30	55:10	5	0.55
II-1	14	25	50:10	15	0.55
II-2	14	25	55:10	10	0.55
II-3	14	25	60:10	5	0.55
II-4	14	25	50:15	10	0.55
II-5	14	25	45:15	15	0.55
II-6	14	20	55:10	15	0.55
II-7	14	30	55:10	5	0.55
III-1	18	25	50:10	15	0.55
III-2	18	25	55:10	10	0.55
III-3	18	25	60:10	5	0.55
III-4	18	25	50:15	10	0.55
III-5	18	25	45:15	15	0.55
III-6	18	20	55:10	15	0.55
III-7	18	30	55:10	5	0.55

2.3 Sample Preparation

Before the specimen preparation, the dredging silt was dried, ground and passed 2 mm sieve; and the cement, slag and titanium gypsum were dried at 60°C and passed 1 mm sieve. This test according to Table 3 preparation I ~ III type curing agent in 8%, 14%, 18% doping (curing agent accounted for the mass ratio of dry soil) of the standard maintenance age specimen, in accordance with the water-cement ratio of 1:0.55 preparation of slurry, to be sufficiently mixed with the water and curing agent to be static for 10min, in the mixing of the silt, placed in the blender until homogeneous, and made the specimen.

Table 4 shows the experimental test program involved in this paper, the unconfined compressive strength is measured by using a 70.7mm cube test mold, taking the internal fragments of the 7d and 28d age specimens with drying at 40°C, and SEM tests with fragments of about 5mm.

Considering the rapid exothermicity of calcium carbide slag in contact with water, the alkaline activator was prepared 1~2 h in advance, and then mixed into the uniformly mixed slag titanium gypsum dry powder to make the curing agent slurry. In order to obtain a homogeneous soil structure, cement/curing agent cured soil samples were prepared according to the following procedures: (1) formulate the curing agent (cement and curing agent) according to the above ratio; (2) mix the curing agent paste into the remolded soil continuously and uniformly and stir until the mixture reaches a homogeneous state; and (3) fill the soil mixtures into each of the above mentioned cube molds in accordance with the Chinese standard JGJ/T 233-2011, and Vibrate for 1~3 min to exclude air bubbles in the air samples; (4) Cover the surface of the soil samples with cling film to prevent water loss, and then put them into the curing box with a temperature of 20±2°C and humidity of 95±1% for 1 d; (5) After 1 d of curing, demold the soil samples and continue to seal them with cling film, and then put them into the curing box until the test time.

2.4 Test Methods

(1) Unconfined compressive strength (UCS)

As shown in Figure 3, according to the Chinese standard JGJ/T233-2011, the functional road material test platform RSM-UTM was used, the maximum load was 100kN, and the loading rate was set to 1mm/min. 3 parallel samples were measured for each group of specimens, and the average value was taken after the abnormal data were presented.
(2) Scanning electron microscope test (SEM)

First, the hydration process was terminated by placing the specimens in anhydrous ethanol at a set curing temperature environment. The drying process was then carried out in a freeze dryer, where frozen water molecules were sublimated directly into water vapor to minimize the effect of the drying process on the hydration products and the internal structure of the soil. The freeze-dried specimens were ground and passed through a 0.15 mm sieve. A small amount of soil was placed in a D8 advance XRD made by Bruker, Germany. Scans were performed between 5° and 90° in steps of 0.02° at a rate of 8(°)/min to determine the mineral phase composition of representative samples. The lyophilized specimens were cut into pieces less than 10 mm in length and width. Subsequently, the samples were fixed with adhesive tape and gold-sprayed, and the microstructure of the samples was observed using SEM (F30).

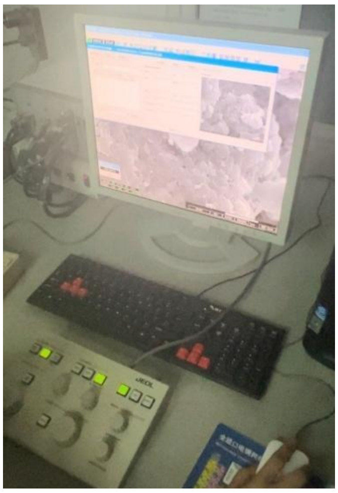


Figure 3: Scanning electron microscope test

3. Results and Discussion

3.1 Effect of Type and Dosage of Curing Agent on Compressive Strength of Cured Soil

Figure 4 shows the effect of different curing agent contents on the strength of cement/geopolymer cured soil. Taken together, increasing the curing agent dosage and prolonging the curing period can improve the unconfined compressive strength of cured soil. From Figure 4a, the 7 d unconfined compressive strength of cement-cured soil was found to be 0.78, 1.03, 1.73 MPa, and the 28 d unconfined compressive strength was found to be 1.19, 1.72, and 2.27 MPa when the curing agent content was 8%, 14%, and 18%, respectively. the optimum cement dosing was above 18%. It was also found that the 7-28 d strength ratio (ω) of hydraulic soil ranged from 45.1% to 77.5%.

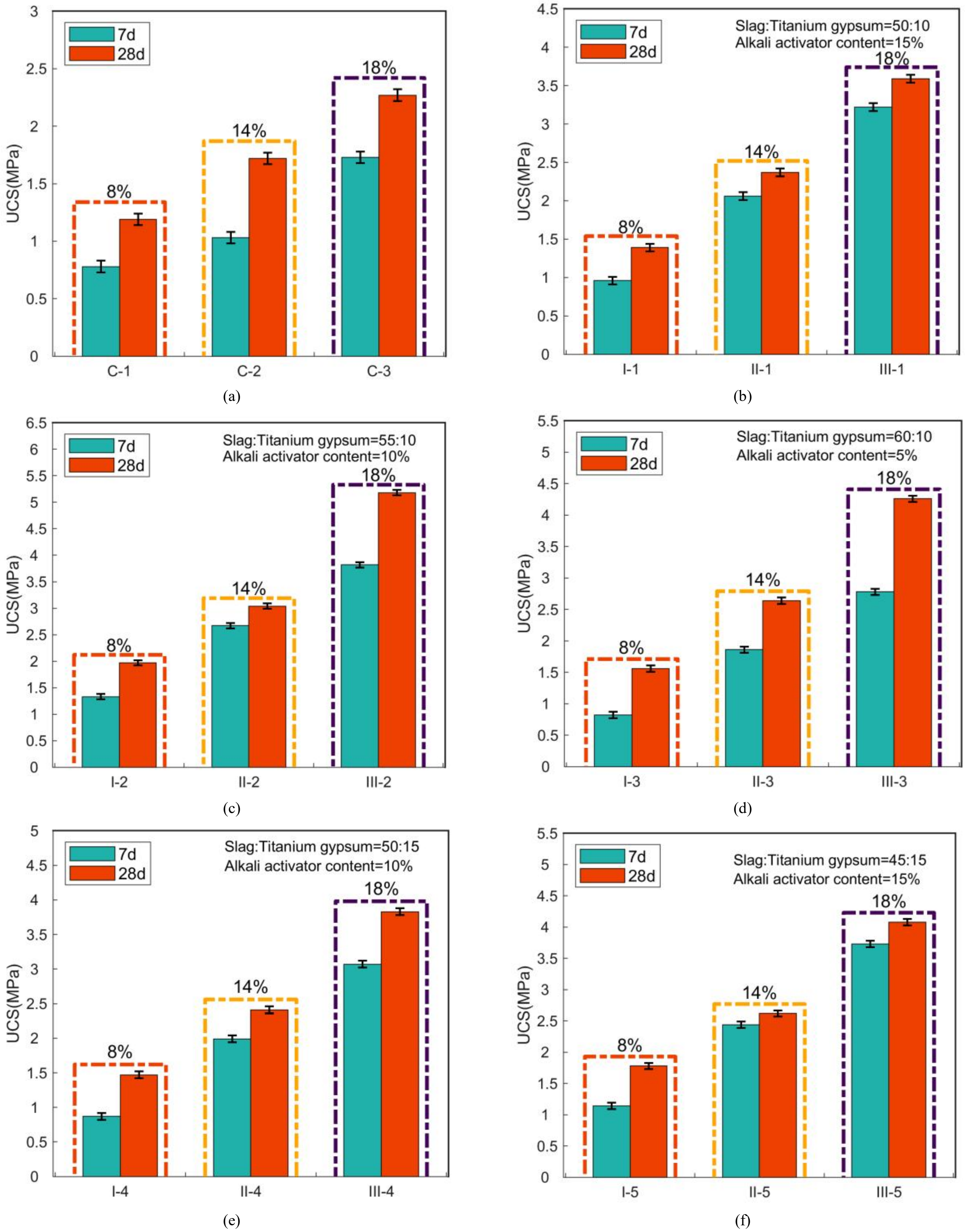


Figure 3: Unconfined compressive strength values of cement/curing agent cured soils with different curing agent contents (8%, 14% and 18%): (a) cement cured soil; (b-f) curing agent cured soil.

It can be seen from Figure 4b-f that for the curing agent-cured soil specimens, the unconfined compressive strength increases with increasing curing agent content, but the growth rate decreases gradually. For example, in the case of slag: titanium gypsum ratio of 50:10 and alkaline exciter content of 15%, when the content of curing agent was increased from 14% to 18% (I-1, II-1, and III-1), it can be seen that the 28 d unconfined compressive strengths of the cured soils were 1.39, 2.37, and 3.59 MPa, respectively. it can be seen that the 28 d unconfined compressive strengths of III-1 were 158.3% higher than that of I-1, but only 158.3% higher than that of I-1. 158.3% higher than I-1, but only 51.4% higher than II-1. This may be due to the presence of some unreacted slag and titanium gypsum particles in the cured soil, leading to the deterioration of the internal microstructure of the sample. This hindered further improvement in strength. Therefore, 14% is the optimum curing agent content in terms of strength test results and economics.

Compared to cement-cured soils, curing agent-cured soils have higher ω values for the same curing agent. Unlike cement where early hydration is incomplete, slag and titanium gypsum react rapidly in the presence of alkaline exciters. It was also found that the strength of cured soil was consistently higher than that of hydraulic soil at the same maintenance age. When the content of curing agent was 14%, the 28-d unconfined compressive strengths of hydraulic soil (C-2) and cured soil (II-1) were 1.03 and 2.06 MPa, which were 34.3 and 68.7 times (0.03 MPa) higher than that of the in-situ soil, respectively. In addition, the strength of II-1 was 2.01 times that of C-2. The results showed that the use of cement and curing agent as curing agents to curing soft soil significantly improved the mechanical properties of the soil [23]. It is noteworthy that industrial waste has a better curing effect on soft soil, which may be attributed to the volcanic ash reaction in industrial waste [41]. The incorporation of slag and titanium gypsum increased the silica and calcium phases in the cured soil, and the alkaline activator dissolved the amorphous silica, aluminum, and calcium in the slag and titanium gypsum to form a large number of monomers. As a result, a condensed gel network was constructed, which could encapsulate the soft soil particles and fill the gaps between the particles, thus increasing the overall strength of the cured soil [25]. In addition, some silica and amorphous phases are present in the soft soil, which may also contribute to the formation of geopolymer network structure in the presence of alkaline activators [42].

3.2 Effect of Slag-titanium-gypsum Ratio on Unconfined Compressive Strength of Geopolymer-cured Soils

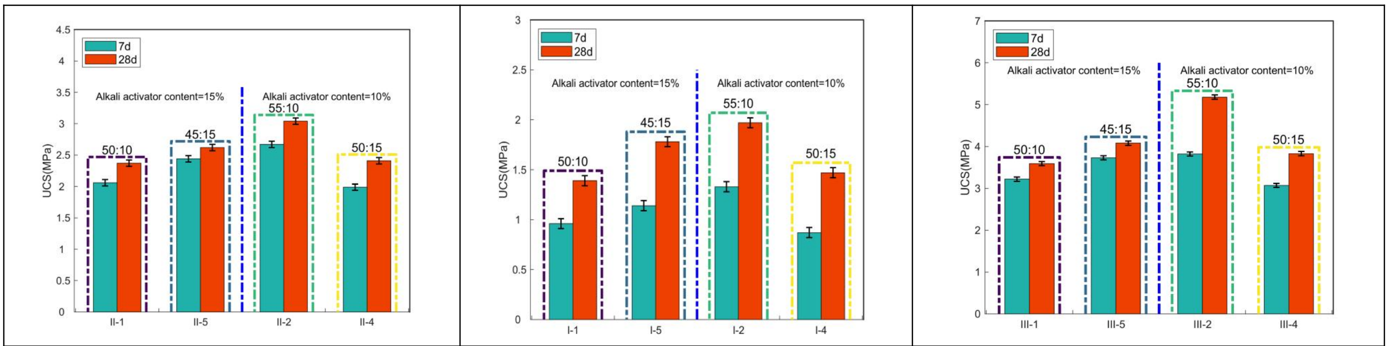
Figure 5 shows the evolution of the unconfined compressive strength of the curing agent-cured soils with respect to the slag-titanium-gypsum ratio and the age of maintenance. As shown in Figure 5 b, the 28 d unconfined compressive strengths of II-1 and II-2 were 2.37 and 3.04 MPa, respectively, under the condition of 14% curing agent content and 15% alkaline exciter content. their ω values were 69.1% and 87.8%, respectively. Meanwhile, the 28 d compressive strengths of II-4 and II-5 were 2.41 and 2.62 MPa, respectively, under the condition that the alkaline exciter content was reduced to 10%. their ω values were 82.5% and 93.1%, respectively. A similar evolutionary pattern is observed in Figure 4a, c.

From the results of the unconfined compressive strength tests in Figure 4, it can be seen that the strength of the cured soil with a slag-titanium-gypsum ratio of 55:10 develops more rapidly, and a higher 28d unconfined compressive strength is obtained. For the cured soil specimens with a slag-titanium gypsum ratio of 55:10, silicate and aluminate ions were rapidly generated in the presence of an alkaline exciter. They then polymerized with Ca^{2+} ions to form a large number of overlapping gel products, which facilitated the strength development of the cured soil.

Meanwhile, it is shown that the active components of slag can be effectively excited by titanium gypsum in an alkaline environment, which breaks the Si-O and Al-O bonds and thus promotes the generation of a large number of gel-like products, such as hydrated calcium silica-aluminate (C-A-S-H), which keeps the strength of the cured soil soil roughly solidified.

It can also be seen that the unconfined compressive strength of the mineral-polymer clays decreases significantly as the slag-titanium gypsum ratio changes from 55:10 to 50:15. This is mainly due to the higher amount of titanium gypsum incorporated, which inhibits the hydration process of the cement and the formation of cementitious hydrates.

When the dosage of alkaline exciter was increased to 15%, the curing effect of the curing agent on the soft soil was significantly weakened. The main reason for this may be that under a more alkaline environment, the Si-O and Al-O bonds were first broken, and then a three-dimensional silica-aluminate network structure containing SiO4 and AlO4 tetrahedra was formed by condensation reaction (C-A-S-H gel). Such a structure is very solidified, which hinders its secondary reaction with the slag hydrate, thus weakening the adhesion of the geopolymer to the soft soil particles.



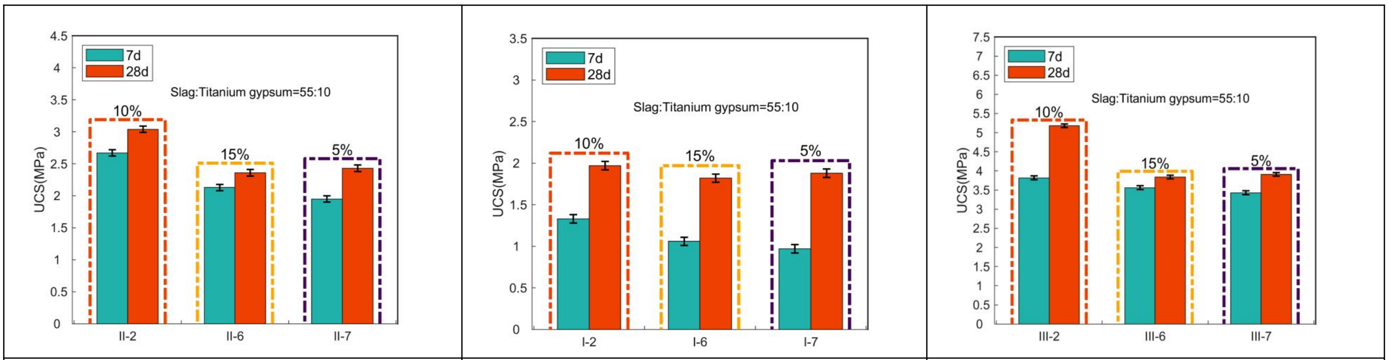
(a) (b) (c)

Figure 5: Unconfined compressive strength values of geopolymer-cured soils with different slag-titanium-gypsum ratios (55:10, 50:10, 45:15, and 50:15): (a) curing agent admixture = 8%; (b) curing agent admixture = 14%; and (c) curing agent admixture = 18%.

In conclusion, whether the ratio of slag to titanium gypsum in the curing clay is 45:15 or 50:10, their strengths are almost equal. However, the cured soil with a slag to titanium gypsum ratio of 55:10 develops strength faster and also has better flowability. Moreover, the market price of slag is higher than that of titanium gypsum. Therefore, a 55:10 slag-titanium gypsum ratio is recommended for geopolymer soils.

3.3 Effect of Alkaline Activator Content on Unconfined Compressive Strength of Cured Soil

Figure 6a-c show the variation of unconfined compressive strength of cured soil with alkaline activator content. It can be found that the unconfined compressive strength of cured soil increases and then decreases with increasing alkaline activator content. It decreases with increase in alkaline activator content. The addition of alkaline activator The addition of alkaline activator increased the OH- and SiO^{3-} in the geopolymer soil leading to rapid dissociation of cement and formation of cementitious hydrates. The 7d and 28d unconfined compressive strengths of II-7 were 1.95 and 2.43 MPa, respectively, at the slag to titanium gypsum ratio of 55:10 under the following conditions as shown in Figure 6b. It can be inferred that the alkaline activator of the alkaline activator of the low content (5%) was unable to fully stimulate the alumino-silicate in the slag, thus limiting the developmental potential of the consolidated soil, which limits the development potential of the strength of the cured soil. When the alkaline activator content was increased to 10%, the 7d and 28d unconfined compressive strengths of II-2 were 2.67 and 3.04 MPa, respectively. where the 28d unconfined compressive strength was 101.3 times higher than that of undisturbed soil and 1.77 times higher than that of C-2. However, when the alkaline activator content was increased from 10% to 15%, it would not further improve the mechanical properties of the cured soil and even had a slight deteriorating effect on the unconfined compressive strength. Compared with II-2, the 7d and 28d unconfined compressive strengths of II-6 decreased by 20.2% and 22.4%, respectively. The higher alkaline activator content resulted in rapid release of Al, Si and Ca ions from the geopolymer slurry, which shortened its initial setting time. During sample preparation, it was found that the geopolymer slurry would solidify when mixed. The slurry will solidify when mixed with remolded soil. This has an adverse effect on this on the formation of cured soil structure. Therefore, the optimum alkaline activator content of the geopolymer soil is 10% at a slag to fly ash ratio of 55:10.



(a) (b) (c)

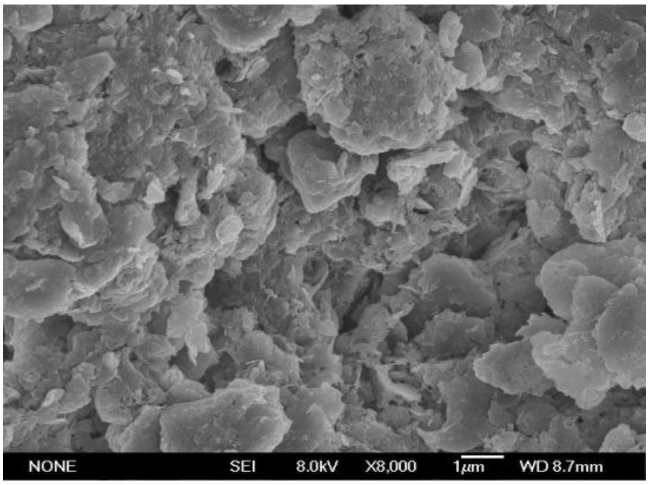
Figure 6: Unconfined compressive strength values of geopolymer-cured soils with different alkaline activator contents (15%, 10% and 5%) (a) Curing agent dosage = 8%; (b) Curing agent dosage = 14%; (c) Curing agent dosage = 18%.

3.4 Characterization of Soft Soil Microstructure

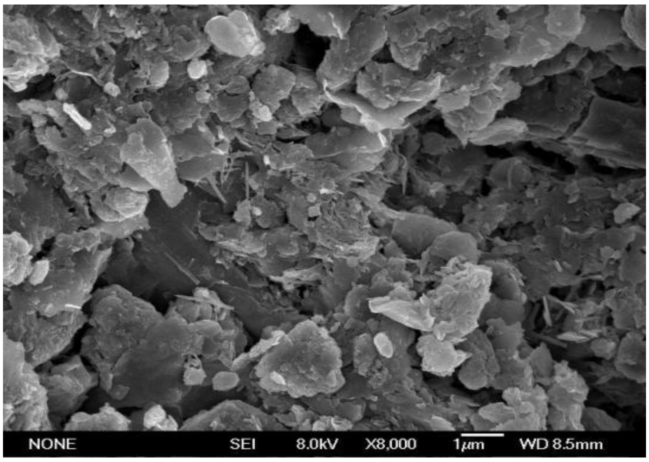
In order to investigate the micromorphology of cured soils at different curing ages, this section details the SEM analysis of geopolymer cured soil samples (II-2 and II-4 with slag-titanium gypsum ratios of 55:10 and 50:15, respectively), with the addition of a cement-cured soil control (C-2) for comparison. In addition, based on the SEM images, elemental analyses of the characterized products were carried out by X-ray spectrometry.Elemental analyses of the characterized products were carried out by X-ray spectrometry (EDS) to obtain the chemical compositions. The highlighted areas of EDS spectral analysis have been marked with white circles and the relative intensity values of the elements obtained are listed in the table.

For the 7d age cured soil (Figure 7), the micro-morphology are visible soil voids, less unhydrated soil particles, less hydration products C-S-H, II-3 has the smallest particle pores, C-2 has the most unhydrated soil particles and the largest pores, and II-2 has the most flocculated C-S-H, which indicates that 7d age is the age of the hydration products are not sufficiently gelatinous inter-particle pore space. As can be seen from Figure a, the surface of the soil particles of the gel-like hydration products produced by cement hydration in C-2 was wrapped, and the voids between the soil particles were not effectively filled, resulting in a relatively large dispersion of the soil particles. As can be seen from Figure 6b, a small amount of three-dimensional network products C-S-H and voids were observed in the SEM images of II-5 compared to C-2, and unhydrated titanium gypsum particles and a small amount of needle-and-rod calcium alumina could also be seen sandwiched between the soil particles. As can be seen in Figure c, the slag and titanium gypsum hydrated rapidly under alkaline conditions, generating a large number of uniformly distributed colloids that bonded the soil particles together. Compared to C-2, II-3 formed a denser microstructure, which manifested itself from a macroscopic point of view as an increase in UCS as described in Section 3.3.

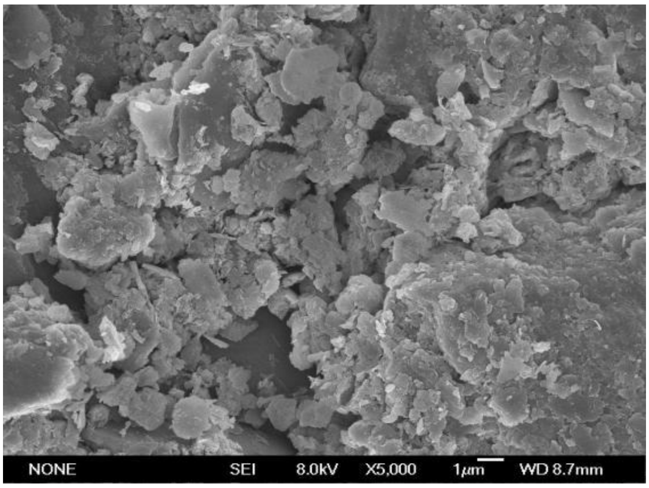
According to the results of EDS analysis (Figure 7d), elements Ca and Si accounted for 15.3% and 9.2% of the total amount of the observed needle-and-rod products, respectively, suggesting that this type of hydration product is a calcium aluminate, calcareous alumina (Aft).



(a)



(b)

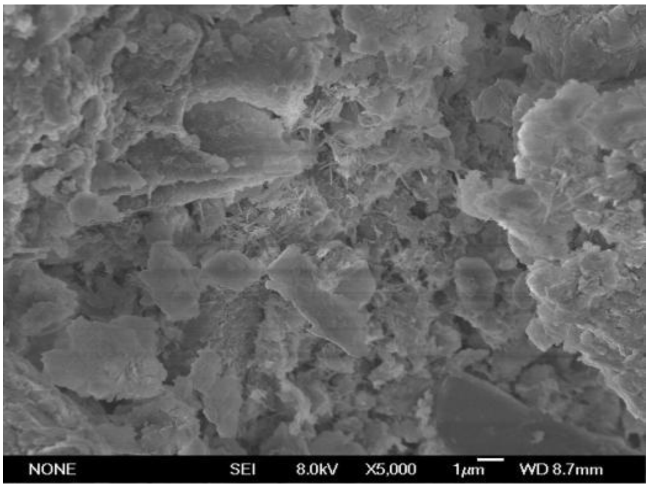


(c)

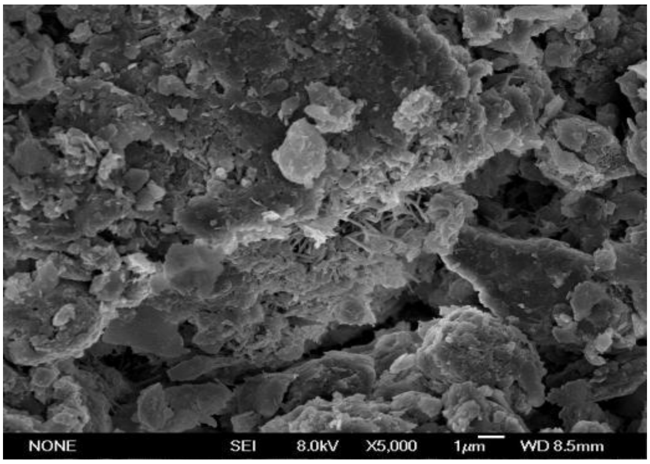
elemental	Relative strength (%)
Ca	15.3
Al	9.2
Si	8.4
O	57.4

(d)

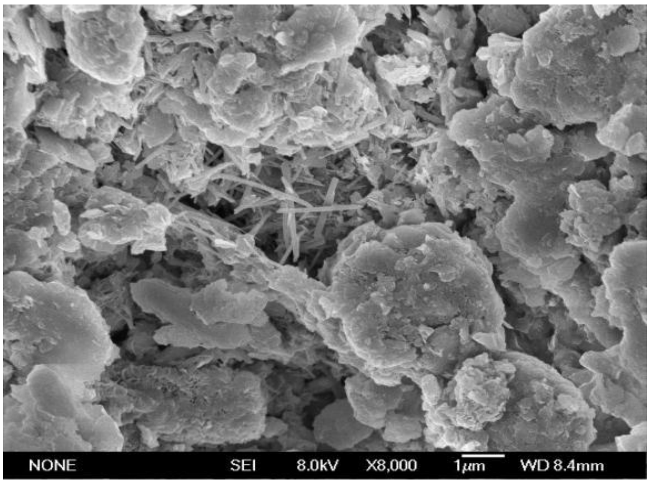
Figure 7: SEM images of curing age of 7 days (a) Cement cured soil (b) II-2 (c) II-4



(a)



(b)



(c)

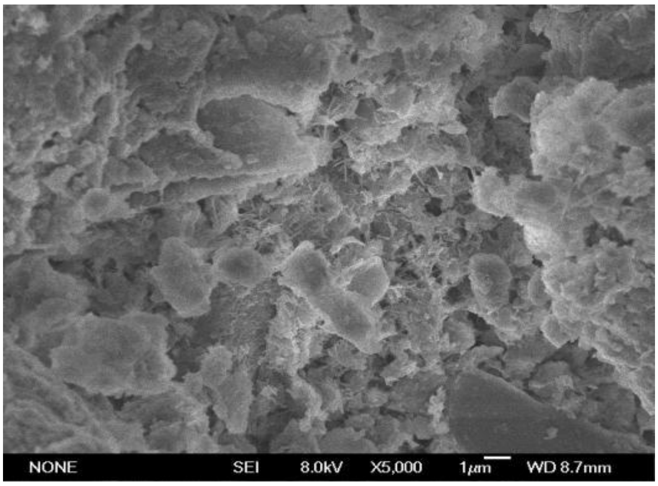
elemental	Relative strength (%)
Ca	11.9
Al	6.9
Si	9.0
o	67.0

(d)

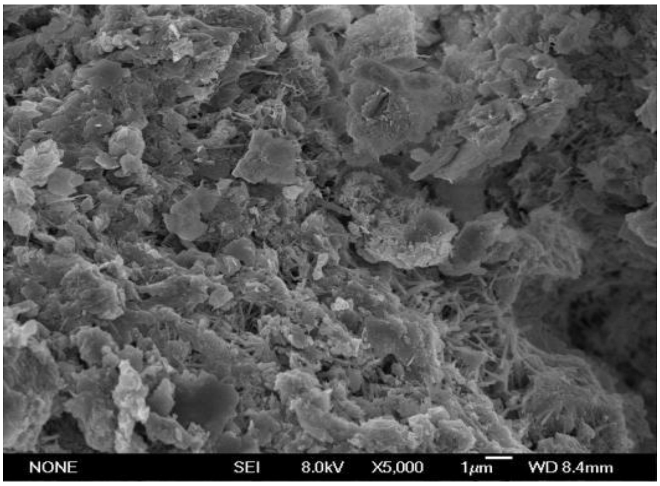
Figure 8: SEM images of curing age of 14 days (a) cement cured soil (b) II-2 (c) II-4 (d) eds of II-2

For the cured soil at the age of 14d, it can be seen from Figure 8 that the hydration of the cured soil increased compared with that at 7d, the unhydrated soil particles decreased, and the flocculation of the cemented C-S-H became more obvious.A small amount of pore space is visible in the cured soil of II-4, and the pore throwing of C-2 is the most in the cured soil of the 3, with the least amount of hydration, but the pore space is smaller than that at 7d, and the cellular C-A-S-H is visible in II-2, and the slag particles gradually hydrated and supported the soil skeleton; it shows that the hydration reaction was accelerated at 14d, and the C-S-H cemented the soil particles and filled the pores between the soil particles, which made the pores decrease dramatically in both number and volume. The above analysis can effectively explain the substantial increase in the unconfined compressive strength of the II-2 curing diagram in 3.3 compared with that at 7d.

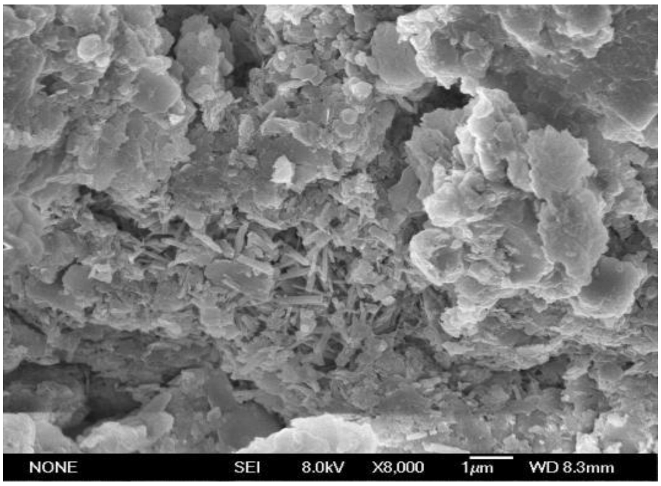
The EDS analysis of Figure 8 shows that the flocculent at this point (point c) consists of hydrated calcium silicate and C-A-S-H. Calcium alumina is mainly a crystalline material produced by the combination of cement hydration product C-A-H (hydrated calcium aluminate) and sulfate ions.



(a)



(b)



(c)

elemental	Relative strength (%)
Ca	12.2
Al	5.0
Si	9.0
o	58.0

(d)

Figure 9: SEM images of curing age of 28 days (a) Cement cured soil (b) II-2 (c) II-4

Analysis of Figure 9 shows that the hydrates of each cured soil at 28d have been sufficiently wrapped and gelled soil particles to form a dense spatial structure, and the structural compactness of C-2 has been basically comparable to that of II-2 and II-4, and the soil particles and pores have been wrapped and filled by hydrates, which indicates that the hydration rate of the cement cured soil increases rapidly in the later stages of maintenance. Comparing Figure 7 and 8, it can be found that the flocculated hydrates generated in large quantities from 7 to 14 d gradually formed a spatial reticulation during 14 to 28 d. Combined with the subsequent EDS analysis, the gelatinous products can be characterized. The EDS results in Figure 8d show that the gel is coexisted by C-A-S-H and C-S-H. and the gelatinization and reinforcement of the soil particles by the mesh structure is stronger than that at 14d, which makes the pore structure denseness increase dramatically. The above analysis can explain that the growth of the unconfined compressive strength of 3.3 has a hysteresis, attributed to the fact that the gradually increasing reticulated C-S-H can support the soil skeleton from 14 to 28 d, which enhances the friction between the soil particles, indicating that the growth of the macromechanical strength is not only related to the hydrate increment, but also related to the denseness of the soil particle structure, and the integrality and strength of the skeleton structure.

4. Conclusion

In this study, a comparative study of the unconfined compressive strength (unconfined compressive strength) and microstructural characteristics of cement-cured and curing agent-cured soils was carried out using unconfined compressive strength tests, scanning electron microscopy (SEM) and X-ray energy spectral analysis (EDS). The unconfined compressive strength (unconfined compressive strength) and microstructural characteristics of slag and titanium gypsum co-cured soils. The optimum proportioning scheme for the curing agent-cured soil was proposed according to the actual engineering background.

The following conclusions can be drawn:

(1) Increasing the content of curing agent and prolonging the curing age can improve the unconfined compressive strength of cured soil. When the content of curing agent is increased from 8% to 18%, the unconfined compressive strength of cement-cured soil increases almost linearly, while the growth rate of unconfined compressive strength of curing agent-cured soil decreases gradually. The growth rate of unconfined compressive strength gradually decreased.

(2) The geopolymer soils with a larger ratio of slag to titanium gypsum showed a faster increase in strength and obtained a higher 28 d unconfined compressive strength. Under the same conditions, when the ratio of slag to titanium gypsum was changed from 55:10 to 45:15, there was a slight decrease in the unconfined compressive strength of the curing agent-cured soils, whereas when the ratio of slag to titanium gypsum was changed from 55:10 to 50:15, the unconfined compressive strength decreased significantly.

(3) As the alkaline activator content increases, the unconfined compressive strength increases and then decreases, with the maximum value occurring at 10% alkaline activator content.

(4) Unlike cement-cured soil, curing agent-cured soil rapidly produces a large number of uniformly distributed gel-like products under the action of alkaline activator. Unlike cement-cured soils, curing agent-cured soils rapidly generate a large number of uniformly distributed gel-like products under the action of an alkaline activator which bind the soil particles tightly. The EDS results showed that the gel-like products consisted of C-S-H gel and C-A-S-H gel. It was also found that the increase in the amount of C-A-S-H gel was positively correlated with the increase in titanium gypsum content.

In conclusion, a hybrid proportioning scheme with 15% geopolymer, 25% cement, 55:10 slag to titanium gypsum, and 10% alkaline stimulant is recommended, i.e., II-2. The 7 d and 28 d unconfined compressive strengths of II-2 were 2.67 and 3.04 MPa, respectively. Its 28 d unconfined compressive strength was 101 times higher than that of in-situ soil and 1.76 times higher than that of cement-cured soil with the same curing agent content.

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