Influencing factors and mechanism analysis of strength development of geopolymer stabilized sludge

Heng-yu ZHOU
School of Civil Engineering and Architecture, Zhejiang Sci-Tec University, Hangzhou, Zhejiang 310018, China

Xiu-shan WANG
School of Civil Engineering and Architecture, Zhejiang Sci-Tec University, Hangzhou, Zhejiang 310018, China, wxs77777@163.com

Xing-xing HU
Zhejiang Titan Design & Engineering Co., Ltd., Hangzhou, Zhejiang 310012, China

Zhi-qi XIONG
China United Engineering Corporation Limited, Hangzhou, Zhejiang 310052, China

See next page for additional authors

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ZHOU Heng-yu[1], WANG Xiu-shan[1], HU Xing-xing[2], XIONG Zhi-qi[3], ZHANG Xiao-yuan[1]

1. School of Civil Engineering and Architecture, Zhejiang Sci-Tec University, Hangzhou, Zhejiang 310018, China

2. Zhejiang Titan Design & Engineering Co., Ltd., Hangzhou, Zhejiang 310012, China

3. China United Engineering Corporation Limited, Hangzhou, Zhejiang 310052, China

Abstract: To solve the problem of carbon emission and high energy consumption of traditional binder, the coal-bearing metakaolin (CMK) geopolymer was used to stabilize sludge. The unconfined compressive strength (UCS) test was conducted to determine the proportion of alkali activator firstly. On this basis, the effects of alkali-precursor ratio, precursor content, NaOH molarity, curing time, curing temperature and slag content on the mechanical properties of stabilized sludge were investigated. Finally, the SEM and XRD tests were conducted to analyse the microstructure of stabilized sludge. The results showed that the UCS of stabilized sludge first increased and then decreased with increasing Na_2SiO_3:NaOH ratio and the rational proportion of alkali activator of geopolymer was Na_2SiO_3:NaOH=75:25. The UCS increased as the alkali-precursor ratio, precursor content and NaOH molarity increased. As the curing time, curing temperature and slag content increased, the UCS of stabilized sludge improved more obviously. The microstructural analysis showed that no new minerals were formed in geopolymer stabilized sludge. With the increase of alkali-precursor ratio, precursor content, NaOH molarity, curing time, curing temperature and slag content, the amount of amorphous N–A–S–H and C–(A)–S–H gels increased, which made the soil structure denser through bonding and filling effects, thus increasing the strength of stabilized sludge.

Keywords: coal-bearing metakaolin; geopolymer; sludge; mechanical properties; microstructure

1 Introduction

Marine soft clay is widely distributed in the southeastern coastal areas of China. The clay foundation is characterized by high water content, low shear strength, and high compressibility, and it is commonly difficult to meet the engineering requirements[1]. Deep mixing method, an effective soft clay stabilization technology, mixes the native soil with Portland cement in the intended depth, and forms circular hardened columns through hydration reaction to stabilize soil[2–3]. However, the production of cement consumes a huge amount of energy, releases substantial level of dust and carbon dioxide, and generates environmental pollution. Thus, it is of great significance to seek environmentally friendly cementitious replacements for cement[4–5].

Geopolymer, which is also called "green cement", is an inorganic product of active aluminosilicates at alkaline environment. The raw materials of geopolymer are the by-products of industry such as fly ash (FA), slag (S), red mud (RM), and calcium carbide residue (CCR), the most commonly used alkaline activators are caustic alkali, silicate, carbonate, and sulphate. The massive researches indicated that the combination of sodium hydroxide and sodium silicate has the best excitation effect[6–8]. Compared with Portland cement, the CO_2 emissions of geopolymer production can be

reduced by 70%, and geopolymer has the advantages of light weight, excellent durability, low shrinkage and no alkali-aggregate reactions[9–10]. Recently, geopolymer has been widely used in the field of concrete, shallow foundation and road bases, but research in deep soil improvement[11–17] is limited. Yu et al.[18] used sodium silicate activated slag to prepare geopolymer on soft clay stabilization. They investigated the effects of alkaline activator modulus ratio and content on strength development of stabilized soil and established a prediction model of strength development. Wang et al.[19] used sodium hydroxide, sodium silicate, and sodium carbonate activated fly ash on sludge stabilization, respectively. They investigated the effect of different alkaline activators on strength of stabilized sludge and reported that sodium hydroxide and sodium silicate have excellent excitation effect while less effect of sodium carbonate. Yu et al.[20] evaluated the sulfate resistance of magnesium oxide activated slag stabilized clay and found the sulfate resistance of geopolymer stabilized clay is better than that of cement stabilized clay. Wu et al.[21] adopted "one-part" method to synthesize S–FA based geopolymer, which is used to stabilize muddy clay. The effects of the ratio of slag to fly ash in raw material, the ratio of activator to raw material, and the ratio of water to binder on the mechanical properties of stabilized clay were studied. Yi et al.[22] used sodium hydroxide, sodium

carbonate, and sodium sulfate activated slag and calcium carbide residue on soft clay stabilization, respectively. The results indicated that the sodium carbonate had no stabilization efficacy, while the sodium sulfate had the best excitation effect. The strength of the sodium hydroxide stabilized sample decreased at later stage. Phetchuay et al.[23] used FA–CCR based geopolymer to stabilize marine clay and indicated that FA–CCR based geopolymer could enhance the strength of stabilized clay and decrease the emission of CO_2, which could replace cement on marine clay stabilization. Yaghoubi et al.[24–25] used FA-GGBS based geopolymer to stabilize marine clay, and suggested that the composite geopolymer could be applied in deep soil mixing projects with environmental benefits. Therefore, the deep soft clay with high moisture content is difficult to stabilize. Most researches focus on high-calcium geopolymer stabilized clay presently, while there are less researches on the low-calcium geopolymer stabilized clay and its influencing factors analysis of strength development.

In this study, coal-bearing metakaolin (CMK) was used as precursor to prepare geopolymer stabilized sludge. The unconfined compressive strength (UCS) test was conducted to determine the proportion of alkali activator firstly. On this basis, the effects of A/P, precursor content, NaOH molarity, curing ages, curing temperature and slag content on the mechanical properties of stabilized sludge were investigated. Finally, the micro–mechanisms of stabilization were analyzed by the SEM and XRD tests, which provided a theoretical

reference for the practical application of geopolymer on sludge stabilization.

2 Materials and methods

2.1 Materials

The sludge was collected from a construction site located in Gongshu District, Hangzhou. It was dark gray and flow plastic state in appearance. After ovendried, crushed, passed through a 2 mm sieve, the obtained sludge was stored in the sealed barrel. The physical properties and the chemical compositions of the sludge are summarized in Tables 1 and 2, respectively.

The metakaolin was produced by calcination of crushed coal gangue from Yuncheng, Shanxi province, which was classified as CMK. It is white powder. The ground-granulated blast furnace slag (GGBS), gray powder, was provided by a local plant in Henan province, China. The surface morpho- logies and the chemical compositions of the CMK and GGBS are shown in Fig. 1 and Table 2, respectively.

The alkaline activator consists of sodium hydroxide and sodium silicate solution. The sodium silicate solution was provided by Hengli Chemical Co., Ltd., in Tongxiang, China, which contains 28% SiO_2, 14% Na_2O and 58% H_2O by weight. The sodium hydroxide was 97% purity, which was provided by Aibi Chemical Reagents Co., Ltd., in Shanghai, China. Considering the fact that heat releases in the dissolution process of sodium hydroxide, the obtained solution needs to cool for 24 hours before use.

Table 1 Basic physical properties of sludge

Natural water content /%	Specific gravity G_s	Liquid limit /%	Plastic limit /%	Plastic index	Clay content /%	Silt content /%	Sand content /%
42.1	2.71	40.3	24.7	15.6	40.6	45.8	13.6

Table 2 Chemical composition of sludge, CMK and GGBS

Material	Chemical composition and content /%								
	SiO_2	Al_2O_3	CaO	MgO	Fe_2O_3	SO_3	Na_2O	K_2O	TiO_2
Sludge	72.33	17.16	1.32	1.21	4.49	—	0.52	1.29	1.30
CMK	51.35	46.83	0.21	0.17	0.42	—	0.16	0.17	0.48
GGBS	34.46	16.87	36.54	6.72	0.56	1.73	1.02	0.30	0.41

(a) CMK   (b) GGBS
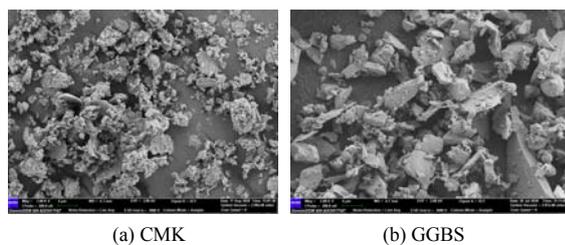
Fig. 1 Microstructure of CMK and GGBS

2.2 Testing program

Firstly, the effects of Na_2SiO_3: NaOH ratio on the strength development of geopolymer stabilized sludge were investigated under different alkaline precursor (A/P)

ratios, the rational proportion of alkaline activator was then determined. The detailed testing program was shown in Table 3.

Based on the rational alkaline activator proportion, the effects of A/P (by dry mass of precursor), precursor content (by dry mass of sludge), NaOH molarity, curing ages, curing temperature, and GGBS content (by dry mass of sludge) on the mechanical properties and microstructures of geopolymer stabilized sludge were analyzed. The specimens with 25% precursor content, 12mol/L NaOH, 28 d curing ages, 20 ℃ curing temperature, 20% GGBS content were defined as control trial, and the single influencing factor was changed on the basis of the control trial, as shown in Table 4.

Table 3 Proportion design of alkali activator

A/P	Na$_2$SiO$_3$: NaOH	Precursor content /%	NaOH /(mol·L^{-1})	Curing temperature /℃	GGBS content /%	Curing ages /d
0.5, 1.0, 1.5 and 2.0	0:100, 25:75, 50:50, 75:25 and 100:0	25	12	20	0	7 and 28

Table 4 Testing programs

Group	Factors	Value
1	A/P	0.5, 1.0, 1.5 and 2.0
2	Precursor content /%	10, 15, 20, 25 and 30
3	NaOH molarity /(mol·L^{-1})	3, 6, 9, 12 and 15
4	Curing ages /d	3, 7, 14, 28, 60, 90 and 180
5	Curing temperature /℃	20, 40 and 60
6	GGBS content /%	0, 10, 20, 30 and 40

2.3 Test procedure

2.3.1 Sample preparation and curing

According to the experimental programs, the dry clay and the CMK were weighed and mixed for 5 minutes with a mechanical mixer, after which the alkali activator and extra water (50% by dry mass of sludge) were added, and the mixing continued for an additional 10 min to homogenize the mixture. The prepared mixture was poured into PVC cylindrical mold with inner diameter of 50 mm and height of 100 mm in five layers, each layer was shaken for 2 minutes to eliminate air pockets. Then the prepared samples were wrapped by plastic film and placed in a controlled curing box. After 48 hours of curing, the samples were demolded and continue curing until designed time.

2.3.2 Unconfined compressive strength test

After the curing periods, UCS test was conducted with a 1 mm/min rate of displacement by an electronic universal testing machine (CMT4304, range: 30 kN). In each group of tests, the mean value of three samples were calculated. The sample was discarded as the standard deviation of its strength with the mean value exceeds 10%. The mean values of at least two samples represent the strength results.

2.3.3 SEM test

After conducting the UCS tests, the flaky fragments with 1×1 cm sectional area were selected as specimens. The specimens were frozen in liquid nitrogen for 20 min at −196°C and then air-dried at drying machine for 24 h to stop the hydration reaction. SEM tests were conducted by GeminiSEM500 field emission scanning electron microscope. Considering that samples lack conductivity and the surface charges are easy to accumulate, the specimens were coated with gold by JFC-1600 type carbon coater before SEM tests.

2.3.4 XRD test

Before XRD test, some unreactive samples were crushed into the powder by agate mortar, and sieved through 75 μm sieve. Then the XRD test was performed by using ARL XTRA X-ray diffractometer with a Cu Kα source. The scanning rate is 2°/min, and the scanning angle 2θ is 10°−70°.

3 Results and discussion

3.1 Mix proportion of alkaline activator

The relationships between Na$_2$SiO$_3$: NaOH ratio and strength of geopolymer stabilized sludge with different A/P after 7 and 28 days of curing are shown in Fig. 2. It can be seen that the strength of stabilized sludge first increases and then decreases with increasing Na$_2$SiO$_3$: NaOH ratio, and the maximum values are observed at optimum Na$_2$SiO$_3$: NaOH ratio. Because the amount of reactive [SiO$_4$]$^{4-}$ increases with Na$_2$SiO$_3$: NaOH ratio, more cementitious products could form at a certain alkaline environment, but an excessive Na$_2$SiO$_3$: NaOH ratio decreases the amount of OH$^-$, which is difficult to dissolve the CMK and reduce the soil strength. By analyzing the strength at 28 days , the optimum Na$_2$SiO$_3$: NaOH ratio is 50: 50, 50: 50, 75: 25, and 75: 25 for A/P of 0.5, 1.0, 1.5, and 2.0, respectively, which indicates that the optimum Na$_2$SiO$_3$: NaOH ratio increases with A/P, and similar trend can be found in the strength at 7 days . Because the concentration of OH$^-$ is low at low A/P condition, and excitation effect of alkali is insufficient in reaction, more NaOH is needed and the optimum Na$_2$SiO$_3$: NaOH ratio is relatively low. The strength of stabilized sludge is relatively high when the A/P is 1.5 and 2.0 and the Na$_2$SiO$_3$: NaOH ratio is

(a) Curing ages=7 d

(b) Curing ages=28 d
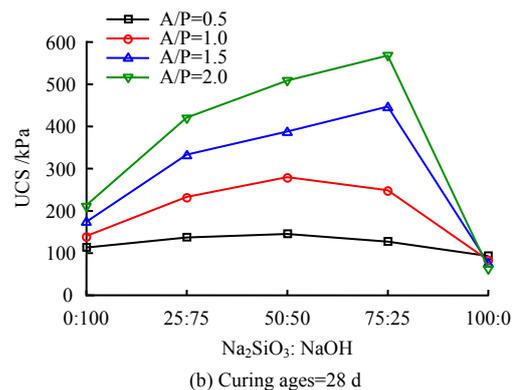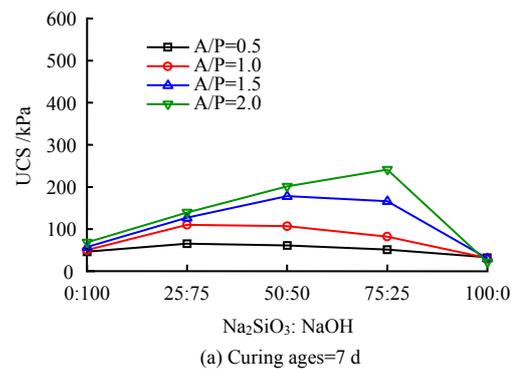
Fig. 2 Relationship between UCS and Na$_2$SiO$_3$: NaOH ratio

75: 25. As a result, it is recommended that the A/P should be greater than 1.0 and the rational Na_2SiO_3: NaOH ratio is 75: 25.

3.2 The effect of A/P on the strength of stabilized sludge

Alkali precursor ratio (A/P) represents the mass ratio of the alkaline activator to the precursor, which is similar to the water cement ratio. The relationship between A/P and strength of the geopolymer stabilized sludge is shown in Fig. 3. It can be found that the strength of geopolymer stabilized sludge increases with A/P. The strength of stabilized sludge at 3, 7, 14, and 28 days increases by 33.3%, 45.2%, 28.1%, and 27.1%，respectively, and the 28-days UCS increases from 447 kPa to 568 kPa.

The amount of OH^- and $[SiO_4]^{4-}$ increases with A/P, the former promotes the dissolution of aluminosilicate precursor and the latter provides the active raw material, then more N–A–S–H gels are formed. Several researches reported that the strength of the geopolymer stabilized sludge first increases and then decreases with the increase of A/P. The reasons for strength reduction are that excessive alkaline activator accelerates the early reaction and the unreactive precursors are wrapped by quickly generated gels, which leads to insufficient reaction. However, this phenomenon is not found in this study[23–27]. Because the sludge has high water content, which dilutes the concentration of alkaline activator. Therefore, more alkaline activator is needed to excite CMK effectively.
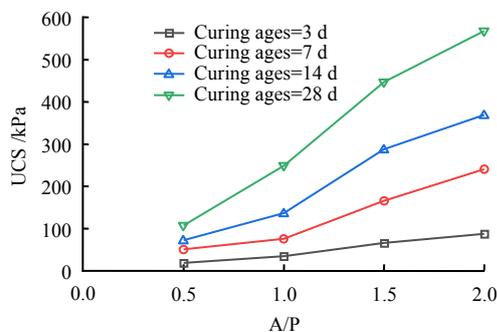
Fig. 3　Relationship between UCS and alkali precursor ratio

3.3 The effect of precursor content on the strength of stabilized sludge

The relationships between the strength of the geopolymer stabilized sludge and the precursor content are shown in Fig. 4. It can be seen that the strength of the stabilized sludge increases with precursor content. The strength of the stabilized clay at 3, 7, 14, and 28 days increases by75.8%, 95.8%, 74.7%, and 69.8% as the precursor content increases from 25% to 30%, and the strength of the stabilized sludge at 28 days increases from 447 kPa to 759 kPa. Furthermore, the strength development of geopolymer stabilized sludge could be divided into two zones, especially for long curing ages.

The strength of the stabilized sludge improves slowly within the range of 10% to 15%(inert zone). When the precursor content exceeds 20%, the strength of the stabilized sludge increases significantly(active zone). Consequently, the precursor content should be higher than 20% in practical application in order to ensure the validity of geopolymer on sludge stabilization.

Because alkalinity and reactivity are weak at constant A/P and low precursor content. The undissolved CMK particles only play a filling role rather than gelling. As the amount of amorphous silicon-aluminum oxides in the matrix increases, more N–A–S–H gels are formed through alkali activation. The free water content decreases while the alkali concentration increases, thus the CMK particles are effectively dissolved and the strength of the stabilized sludge improves significantly. Further- more, Ghadir et al.[9] reported that higher precursor content is unfavorable for the strength development of geopolymer stabilized sludge with low moisture content because of the lack of medium for vitreum dissolution and ions transfer.
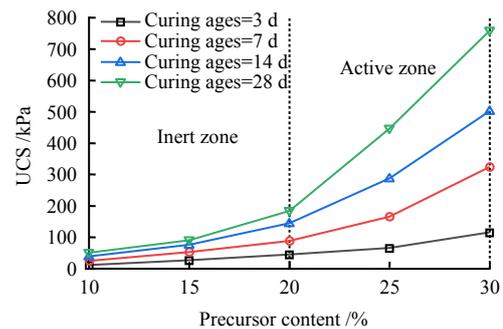
Fig. 4　Relationship between UCS and precursor content

3.4 The effect of NaOH molarity on the strength of stabilized sludge

Figure 5 shows the relationship between NaOH molarity and strength of the geopolymer stabilized sludge. As shown in Fig. 5, the strength of stabilized sludge increases with the increasing of NaOH molarity. When the NaOH molarity increases from 12 to 15 mol/L, the strength of the stabilized sludge at 3, 7, 14, and 28 days increases by 37.9%, 36.7%, 30.2%, and 24.4%, respectively. The 28-days strength of stabilized sludge increases from 447 kPa to 596 kPa.

The reactivity of CMK is low at weak alkalinity condition. The increase of NaOH molarity promotes the dissolution of aluminosilicate precursors, releases plenty of silicon and aluminum oxygen tetrahedron to polymerize, and consequently forms more N–A–S–H gels. Therefore, the increase of NaOH molarity is beneficial for the strength of stabilized sludge improvement. This result is consistent with findings from previous studies by using geopolymer on road bases[15–16], silty soft clay[28], and marine clay stabilization[23]. However, Pourabbas et al.[29] reported that excessive NaOH could

react with the cations in clay, which destroy the clay structure and inhibit the formation of cementitious products. In practical application, considering strength, economic, safety, and practicability, the recommended NaOH molarity is 12 mol/L. A relatively low NaOH molarity results in poor stabilization effect, while relatively high NaOH molarity decreases the fluidity of geopolymer binder and leads to early setting, which is not conducive to the on-site construction of deep soil mixing projects.
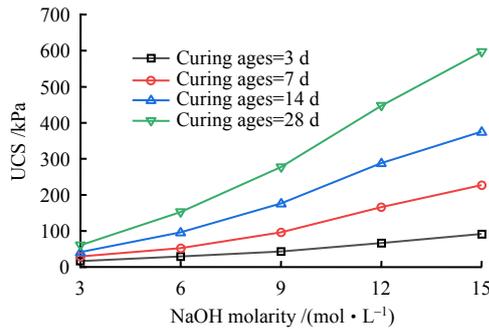
Fig. 5　Relationship between UCS and NaOH molarity

3.5 The effect of curing ages on the strength of stabilized sludge

Figure 6 shows the relationships between curing ages and strength development for cement stabilized sludge and geopolymer stabilized sludge, respectively. The cement is P.O.42.5 ordinary Portland cement, and the water cement ratio is 0.5. The strength of geopolymer stabilized sludge increases linearly with curing ages, it has low growth rate but long time duration, which agrees with the results of Phetchuay that FA based geopolymer was used on marine soft soil stabilization[23]. Compared with the samples at 28 days, the strength of stabilized sludge at 60, 90, and 180 days increases from 447 to 736, 968, and 1 579 kPa, which increases by 64.7%, 116.6%, and 253.2%, respectively. Furthermore, the strength development of geopolymer stabilized sludge is different from that of cement stabilized sludge. The strength of the cement stabilized sludge increases logarithmically, the early age strength increases fast but the later age strength increases slowly. Cristelo et al.[30–31] reported that the strength development of cement stabilized soil was slow after 30 curing ages, while the strength development of FA based geopolymer stabilized soil still increases after one year of curing, indicating that the geopolymer has the advantage of improving the later age strength of stabilized sludge.

This difference is due to that the hydration products of cement is mainly C–S–H gels and ettringite (AFt), which react faster at early stage and form network structure to provide strength, but the hydration reaction slows down as the cement is completely consumed. The N–A–S–H gels are the main hydration products of geopolymer. The reaction process is slow but lasts for

a long time at ambient temperature, thus the reaction process is relatively stable and the formed gel system is more homogenous. Furthermore, the N–A–S–H gels with highly polymerized three-dimensional network structure have more excellent performance than the chain-shaped C–S–H gels[33].
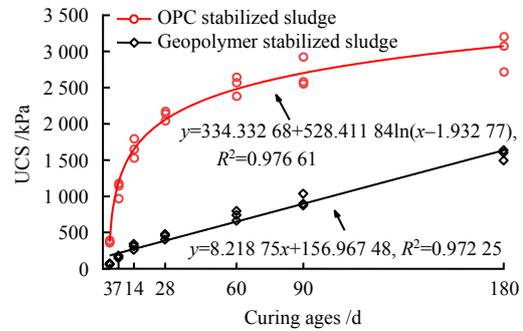
Fig. 6　Relationship between UCS and curing ages

3.6 The effect of curing temperature on the strength of stabilized sludge

The relationship between curing temperature and strength of geopolymer stabilized sludge is presented in Fig. 7. The increase of the curing temperature can significantly enhance the strength of stabilized sludge. Compared with the samples at 20 ℃ curing temperature, the samples with 40 ℃ curing temperature at 3, 7, 14, and 28 days increases by 184.8%, 180.1%, 158%, and 147.4%, respectively. The 28-days strength of stabilized sludge increases from 447 to 1 934 kPa. Furthermore, when the curing temperature was 20 ℃, the 28-days strength is 447 kPa, when the curing temperature is 40 ℃, the 7-days strength is 465 kPa, when the curing temperature is 60 ℃, the 3-days strength is 476 kPa, indicating that the increase of curing temperature can shorten the curing ages and improve the early strength of stabilized sludge.
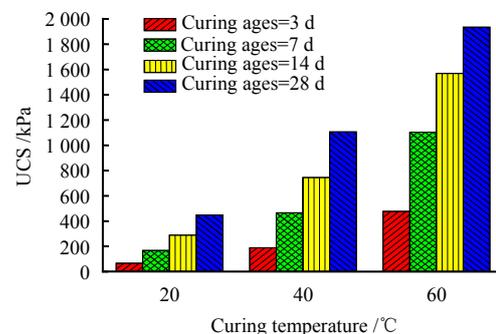
Fig. 7　Relationship between UCS and curing temperature

Because high temperature curing condition promotes the dissolution of aluminosilicate precursors and accelerates the polycondensation of silicon aluminum oxide monomer, which leads to more gel products formation and improves the strength of the samples. Furthermore, Rong et al.[34] reported that Brownian movement of

colloids accelerate with temperature and the collision among colloids is enhanced, thus the potential energy of repulsion is overcome and the gels formation is accelerated. Although high curing temperature has a positive effect on the strength development of stabilized sludge, there are environmental, economic and construction restrictions to increase curing temperature. Therefore, the use of ambient temperature is more practical in field engineering, and the geopolymer is more suitable for the soft soil stabilization in high temperature areas.

3.7 The effect of GGBS content on the strength of stabilized sludge

Figure 8 shows the relationship between GGBS content and strength of geopolymer stabilized sludge, indicating that the use of GGBS to replace CMK can significantly improve the strength of stabilized sludge. Compared with the samples without GGBS, the strength of samples with 40% content at 3, 7, 14, and 28 days increases 497%, 338.6%, 268.1%, and 219.2%, respectively, and the 28-days strength of stabilized sludge increases from 447 to 1 427 kPa.

Compared with CMK, GGBS has more amorphous phase and higher activity. The glass phase in GGBS is dissolved by alkaline activation, and the Ca-O bond is easier to break than Si-O and Al-O bonds, thus the Ca^{2+} is released faster and provides additional nucleation sites for $[Si(OH)_4]$ and $[AlO_4]^-$ to form C–(A)–S– H gels, which coexists with N–A–S–H gels and improves the early strength of stabilized sludge. Furthermore, the Na^+ and K^+ are rich in the surface of clay particles, and they are easy to be replaced by Ca^{2+}, then the thickness of the diffusion layer in the clay particles decreases remarkably, the cohesion between them is enhanced, the internal friction angle increases, and the stability of stabilized sludge is improved.
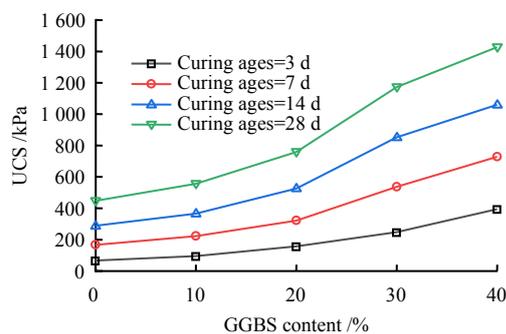
Fig. 8　Relationship between UCS and GGBS content

4　Micro-mechanism analysis

4.1　SEM

SEM micrographs for the untreated sludge and control trial samples at a magnification of ×3 000 are shown in Figs. 9(a) and 9(b). It is evident that layer structure and irregular blocky particles appear in the untreated sludge. The soil particles arrange randomly and exhibit loose and porous structure. After stabiliza-

tion, the cementitious products are observed on the surface of soil particles, the soil particles are bonded together, and the pore spaces are filled thoroughly, resulting in a denser microstructure and strength increase of stabilized sludge.
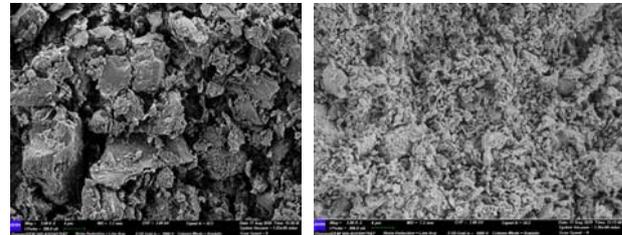
(a) Untreated sludge sample　　　(b) Control trial sample

Fig. 9　SEM images of geopolymer stabilized sludge (×3 000)

To further investigate the effect of various factors on the microstructure of hydration products, the samples under various conditions are magnified 10 000 times by SEM, as shown in Fig.10. The control trial sample is shown in Fig. 10(a), a small number of white N–A–S–H gels and undissolved CMK particles appear on the surface of the clay, confirming that the CMK are not activated and the gel products are limited at ambient temperature. When the A/P and NaOH molarity increase, the N–A–S–H gels increase and exhibit areal distribution [Figs. 10(b) and 10(d)], indicating that the increase of the alkalinity can promote the CMK dissolving and increase the extension of hydration. Fig. 10(c) shows the stabilized sludge sample with 30% precursor content, it can be seen that the N–A–S–H gels and undissolved CMK particles on the surface of soil increase and the pores around particles decrease, and the soil structure becomes denser. Fig. 10(e) shows the stabilized sludge sample at 180 days, it can be seen that a large amount of N–A–S–H gels appear on the surface of the soil, and the undissolving CMK particles decrease obviously, indicating that the geopolymerization is ongoing and the hydration degree becomes more sufficient with curing ages. Fig. 10(f) shows the stabilized sludge at 60 ℃, it can be seen that the soil surface is covered by N–A–S–H gels completely and there is no undissolved CMK particles, indicating that the increase of the curing temperature can significantly accelerate the CMK dissolution and condensation polymerization, thus plenty of gel products are generated in short time. Fig. 10(g) presents the stabilized sludge sample with 40% GGBS content, amounts of reticular C–(A)–S–H gels and white N–A–S–H gels appear in soil. The two types of gels coexist and cross-distribution in soil, which improves the compactness and structure of soil, where the C–(A)–S–H gels play the leading role on the strength increase.

The above analysis shows that the increase of A/P, precursor content and NaOH molarity can improve the

extent of hydration of stabilized sludge, while the increase of the curing ages, curing temperature, and GGBS content have more obvious efficacy. The

hydration products N–A–S–H and C–(A)–S–H gels increase the strength of stabilized sludge through bonding and filling effects.

(a) Control trial sample

(b) A/P=2.0

(c) Precursor content=30%

(d) NaOH molarity=15 mol/L

(e) Curing ages=180 d

(f) Curing temperature=60 ℃

(g) GGBS content=40%
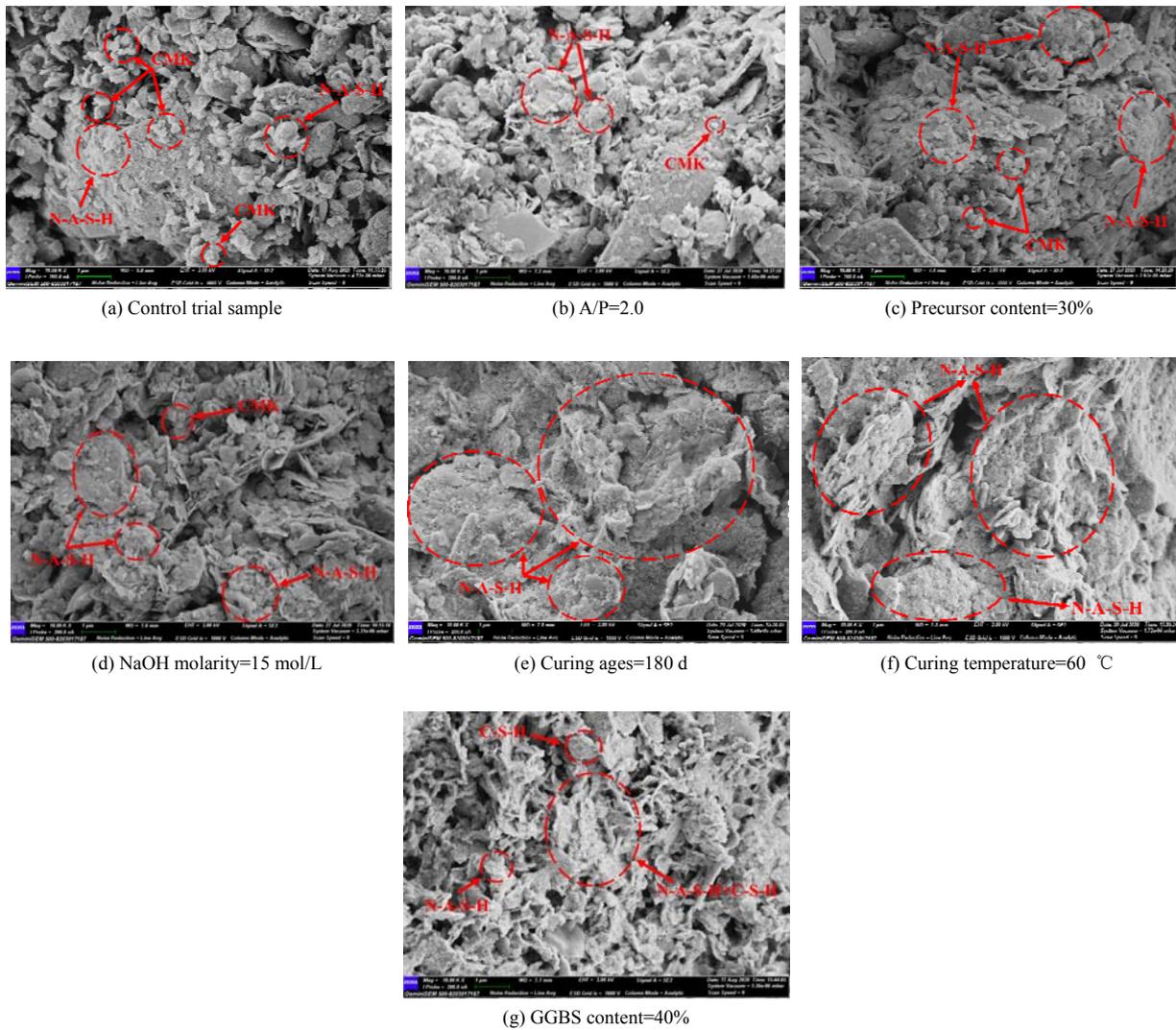
Fig. 10   SEM images of geopolymer stabilized sludge (×10 000)

4.2 XRD

Figure 11 shows the XRD diffractograms of the samples under various conditions. Quartz, muscovite, kaolinite, albite, K-feldspar, and chlorite are detected in the untreated sludge. Compared with the spectra of the untreated clay, there is no new change in the pattern, indicating that no new minerals form. It is noted that the intensity of the peaks relating to quartz, muscovite, and kaolinite decreases, which is caused by the increase of cohesion of clay particles, and partial minerals in the clay are consumed by pozzolanic reaction[6]. Furthermore, the products of N–A–S–H and C–(A)–S–H gels are amorphous, thus no obvious peaks are indexed. However, the corresponding diffuse diffraction peaks appear in the patterns when 2θ angles are within the ranges 28 to 30° and 34 to 35°. Zhang et al.[12] reported that the broad hump can mask other crystal peaks. Compared with untreated sludge and control trial sample, the intensities

of peaks related to quartz, kaolinite and feldspar decrease with the increase of A/P, precursor content, and NaOH molarity. The increase of curing ages, curing temperature, and GGBS content have more obvious results, indicating that the increase of the A/P, precursor content, and NaOH
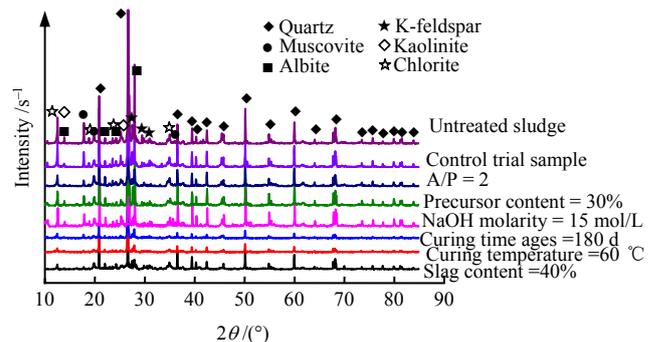
Fig. 11   X-ray diffractograms of geopolymer stabilized sludge

molarity can promote the hydration process of stabilized sludge, while the effect of improvement of increasing the curing ages, curing temperature, and GGBS content is more significant. The results are in accord with the results of UCS and SEM tests.

5　Conclusions

This paper determined the proportion of alkali activator and investigated the effect of A/P, precursor content, NaOH molarity, ages, curing temperature and slag content on the strength of stabilized sludge by UCS test. Besides, the micro-mechanisms of stabilization were analyzed by the SEM and XRD tests, The conclusions are as follows:

(1) The strength of the geopolymer stabilized sludge first increases and then decreases with the increase of Na_2SiO_3: NaOH ratio. The optimum Na_2SiO_3: NaOH ratio increases with A/P, and the recommended optimum alkali activator proportion is Na_2SiO_3: NaOH=75:25.

(2) The increase of A/P, precursor content, and NaOH molarity can enhance the strength of geopolymer stabilized sludge. The strength development of geopolymer stabilized sludge can be classified into two zones with increasing precursor content. The zone of 10% to 20% is regarded as inert zone, and the active zone is within the range of 20% to 30%. The recommended optimum A/P is 1, the precursor content should over 20%, and the NaOH molarity is 12 mol/L.

(3) Increasing the curing ages, curing temperature, and GGBS content can significantly increase the strength of the geopolymer stabilized sludge. The strength of the OPC stabilized sludge increases logarithmically with the increase of curing ages, while the strength of the geopolymer stabilized sludge increases linearly with the increase of curing ages, which is beneficial to the later age strength of stabilized sludge. The increase of the curing temperature and GGBS content can significantly shorten the curing ages and increase the early age strength of stabilized sludge.

(4) Microscopic tests results indicate that new mineral are not formed in stabilized sludge with the increase of A/P, precursor content, NaOH molarity, curing ages, curing temperature, and GGBS content, while the amorphous products N–A–S–H and C–(A)–S–H gels increase, which make the soil structure denser and decrease the pores around particles through binding and filling effect.

(5) The properties of geopolymer are different with composition, origin, and production process. Further research is needed to clarify the effects of type, fineness, calcination temperature, calcination time of metakaolin on the strength of stabilized sludge.

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