ISSN 2663-1563 Vol. 6, Issue 4: 62-69, DOI: 10.25236/AJAGE.2024.060410

# Experimental Study on Engineering Characteristics of Cement-metakaolin Composite Modified Expansive Soil

**Yuguo Zhang, Zhaobin Zhang*, Chunhao Zhao, Zilai Zhang, Jinshuai Kou, Zhan Jing**

*Institute of Civil Engineering and Architecture, Zhongyuan University of Technology, Zhengzhou, Henan, 450007, China*
**Corresponding author: 120862744@qq.com*

***Abstract:*** *In view of the unstable characteristics of expansive soil such as expansion and contraction, cement-metakaolin modified expansive soil samples were prepared. The mechanical properties and microscopic mechanism of modified expansive soil were studied by free expansion rate test, unconfined compression test, direct shear test and scanning electron microscopy (SEM). The test results show that the free expansion rate of the improved soil decreases slowly with the increase of the content of metakaolin in 7% cement improved expansive soil. The compressive strength and shear strength increased first and then decreased, and the improvement effect was the best when the content of metakaolin was 4%. The incorporation of metakaolin accelerates cement hydration, increases gel content, optimizes pore structure, and enhances mechanical properties. The effect of cement-metakaolin on expansive soil is remarkable. The test results show that the free expansion rate of the improved soil decreases slowly with the increase of the content of metakaolin in 7% cement improved expansive soil. The compressive strength and shear strength increased first and then decreased, and the improvement effect was the best when the content of metakaolin was 4%. The incorporation of metakaolin accelerates cement hydration, increases gel content, optimizes pore structure, and enhances mechanical properties. The effect of cement-metakaolin on expansive soil is remarkable.*

***Keywords:*** *Expansive soil, Cement, Metakaolin, Strength characteristics, Microscopic mechanism*

## 1. Introduction

Expansive soil is a kind of high plastic clay, which is mainly composed of hydrophilic minerals such as montmorillonite[1]. The main problem of uneven settlement deformation of pavement and foundation is caused by the unstable characteristics of expansive soil, such as expansion and contraction, fissure and so on. Therefore, it is necessary to improve the soil before engineering use, so as to meet the engineering use standard[2]. At present, the method of improving expansive soil is mainly to improve its characteristics through physical level, chemical reaction level and biological mechanism level. It is common to add fiber to improve expansive soil in physical improvement method, which is to form fiber-soil particle skeleton inside the soil to improve its shrinkage[3-4]. The biological improvement method is to add microorganisms, biological enzymes, etc., to improve the hydrophilic minerals with swelling and shrinkage characteristics in expansive soil, and reduce the water sensitivity of soil, so as to improve the swelling and shrinkage[5-7]. In the chemical improvement method, cement and lime modified expansive soil is more common, but it requires a lot of energy and resources in the use process, and will produce a large amount of waste gas and wastewater, which will cause certain pollution to the environment. Therefore, reducing the use of cement and lime is also a kind of environmental protection, so domestic and foreign scholars pay more attention to environmentally friendly new modifiers.

As a new type of environmentally friendly geopolymer, metakaolin has irregular molecular arrangement and presents a thermodynamic metastable state. It has good gelation characteristics after activation by alkaline or sulfate, and has obvious improvement on the macro and micro of cement. It can accelerate the hydration reaction of cement, improve the strength of cement, effectively reduce the emission of carbon dioxide in the process of using cement, and improve the pollution of cement to the environment. The filling effect and volcanic ash effect of metakaolin further optimize its structure[8-10]. Since the 1980 s, the new material of metakaolin has been studied abroad. In the middle and late 1990s, the main research results were used to improve the performance of cement and concrete, and there were also reports on the use of metakaolin as cementitious materials[11-12]. The use of metakaolin as a building material in China was relatively late, and it was not until 2000 that it entered the industry as a mineral admixture. Qian[13] found that high content of metakaolin can partially affect the fluidity of concrete by adding metakaolin to concrete, but it can be solved by water reducing agent. Metakaolin can improve the axial tensile strength and axial compressive strength of concrete, which proves the feasibility and effectiveness of metakaolin to improve concrete. Deng[14] studied the microstructure of modified soil with metakaolin to improve the performance of cement soil by scanning electron microscopy and mercury intrusion porosimetry. From the results, it can be seen that the addition of metakaolin to cement soil can effectively increase the content of gel material, improve the performance of cement hydration products, improve the pore structure of modified soil, optimize the pore ratio, and enhance the structural compactness. Aiming at the practical engineering problem of soluble salt erosion of cement-soil mixing piles, Chu[15] used metakaolin to inhibit soluble salt erosion, and found that metakaolin can effectively inhibit this engineering problem and significantly improve the mechanical strength of cement-soil.

According to the above research, the metakaolin is used to improve the expansive soil by cement. The mechanical strength is studied by laboratory test, and the accuracy of the macroscopic characteristics is verified by microstructure analysis, and the curing mechanism is further explained, which provides data support for the use of expansive soil in subgrade base.

## 2. Test Materials and Test Methods

### *2.1 1test materials*

The soil used in the test was taken from the open space next to a section of a county in Nanyang City, Henan Province. The depth of the soil was 1.5 m. The color of the soil sample was yellowish brown, which was a typical expansive soil with a large viscosity and a semi-hard state. The basic physical indicators are shown in Table 1. The cement (C) used in the test is ordinary Portland cement. The metakaolin (MK) used in the experiment was produced from a building material Co., Ltd.in Henan Province. It was pink white with a fineness of 1250 mesh and no obvious irritating odor. The main component contents of cement and metakaolin used in the test are shown in Table 2.

*Table 1: Basic physical indexes of expansive soil*

| Natural water content (%) | Specific gravity | Optimum moisture content (%) | Maximum dry density (g/cm$^3$) | Liquid limit (%) | Plastic limit (%) | Free swelling ratio (%) |
|---|---|---|---|---|---|---|
| 24 | 2.69 | 19 | 1.69 | 49.9 | 26.4 | 59 |

*Table 2: Main components and characteristic parameters of cement and metakaolin*

| Material | Content of chemical components(%) | | | | | | | | Activity index 28 days (%) | Ignition loss(%) |
|---|---|---|---|---|---|---|---|---|---|---|
| | CaO | $Al_2O_3$ | $SiO_2$ | MgO | $Fe_2O_3$ | $SO_3$ | $K_2O$ | $Na_2O$ | | |
| C | 57.42 | 6.26 | 21.99 | 3.71 | 3.93 | 2.51 | 0.72 | 0.19 | | 2.3 |
| MK | 1.72 | 44.37 | 46.13 | 0.09 | 2.5 | 0.01 | 0.75 | 0.11 | 107 | 0.26 |

### *2.2 Test scheme*

The soil samples were preliminarily screened, air-dried and crushed, and then dried by the oven at a temperature of 108°. Referring to the ' Technical Rules for Construction of Highway Pavement Base ' (JTG / TF20-2015), the cement mixing base value of 7% (defined as the ratio of cement mass to sample mass) was determined, and the five mixing amounts of MK (the ratio of MK mass to sample mass) were determined, which were 0%, 2%, 4%, 6% and 8%, respectively. After mixing evenly, it was placed in a sealed bag to squeeze the excess air stew material for 12h, and the prepared samples were placed in the curing box under standard curing conditions for 7,14 and 28d, respectively. Based on the " Technical Rules for Construction of Highway Pavement Base " (JTG / TF20-2015) and " Test Procedures for Stabilized Materials of Inorganic Binders for Highway Engineering " (JTGE51-2009), unconfined compressive test and direct shear test were carried out to determine the feasibility and improvement of C-MK to improve the mechanical properties of expansive soil. The unconfined compressive strength test requires the preparation of samples with a height of 50 mm and a diameter of 50 mm. The degree of compaction is 95% of the standard value of subgrade construction. The test equipment used is YYW-2 type unconfined compressive strength instrument; the ring knife sample with a height of 20 mm and a diameter of 61.8 mm was prepared for the direct shear test, and the compaction degree was 95% of the standard value of subgrade construction. The shear strength of the sample was measured by ZJ strain-controlled direct shear apparatus.

Microscopic test SEM selected plain soil and three kinds of samples (plain soil, 7% cement, 7% cement + 4% metakaolin, 7% cement + 8% metakaolin) after direct shear test with a curing age of 28d. The test was carried out by German ZEISS Sigma 300 electron microscope scanning equipment to analyze the microscopic improvement mechanism of cement-metakaolin on expansive soil. The pore structure distribution and hydration products of improved expansive soil are analyzed by SEM scanning electron microscope. The improvement mechanism of cement-metakaolin on expansive soil is discussed from macro and micro aspects.

## 3. Test results and analysis

### *3.1 Free expansion rate test*

The free expansion rate of the improved expansive soil is shown in Figure 1. The free expansion rate of the expansive soil used in this experiment is 59%. After adding 7 % cement, the free expansion rate decreased significantly, with a decrease of 62%. After adding MK, the free expansion rate continued to decrease. After the MK content exceeded 4%, the decrease slowed down, and finally decreased to 14% at 8% MK. Compared with the free expansion rate of 7% cement-modified expansive soil, the decrease was 36%. The reason is that the cement dissociates $OH^-$and $Ca^+$ in the presence of water to form an alkaline environment, and $Ca^+$ replaces $K^+$ on the surface of the soil particles, thereby weakening the bound water film attached to the surface of the soil particles, so that the strong hydrophilic minerals in the expansive soil, such as montmorillonite, cannot enter the crystal layer, and cannot expand the crystal layer spacing, which inhibits the swelling and shrinkage of the expansive soil[16]. On the basis of cement, the addition of metakaolin aggravates the hydration reaction of cement, and also makes its own pozzolanic effect play a role, producing more gel materials, cementing soil particles, reducing large pores, optimizing small pores, and forming a stable and compact soil structure. The adsorption capacity of metakaolin alleviates the swelling characteristics of hydrophilic minerals in expansive soil, and enhances the ability to inhibit the swelling and shrinkage of expansive soil.

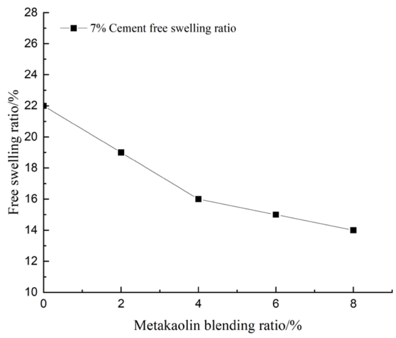



*Figure 1: Free expansion rate curve of cement-metakaolin modified expansive soi*

### *3.2 Unconfined compressive strength test*

Because the trend of compressive stress-strain curve of C-MK improved expansive soil under different curing ages is similar, only the compressive stress-strain curve under 7d is listed as shown in figure 2. It can be seen from Fig.2 that the stress-strain curve of C-MK improved expansive soil has obvious stress peak point, and it decreases significantly after the peak, and the curve is strain softening type. The stress increases with the increase of strain, and the increase rate also increases steadily. The increase rate decreases steadily before the peak value of the maximum stress, and a small crack parallel to the maximum principal stress appears on the surface of the sample. After reaching the peak stress, it enters the failure stage, and the crack penetrates. The stress decreases with the increase of strain, and the sample is completely destroyed, showing brittle axial compression failure.

ISSN 2663-1563 Vol. 6, Issue 4: 62-69, DOI: 10.25236/AJAGE.2024.060410

The corresponding stress when the stress-strain curve of the sample reaches the peak is the unconfined compressive strength. From figure 2, it can be seen that metakaolin enhances the improvement effect of cement on expansive soil. With the increase of MK content from 0% to 4%, the compressive strength of C-MK improved expansive soil shows an increasing trend, and the improvement effect reaches the best when the MK content reaches 4%. When the MK content is less than 4%, the compressive strength of C-MK improved expansive soil increases rapidly, and the compressive strength decreases slightly with the continuous increase of MK content. The reason is that the incorporation of MK significantly improves the compressive strength. The cement hydration reaction product CH has a significant excitation effect on the active substances $SiO_2$ and $Al_2O_3$ in MK. The activation of MK 's pozzolanic activity makes MK join the hydration reaction. The secondary hydration reaction of MK increases the content of hydrates and increases the hydration rate of cement. The adsorption and cementation of metakaolin will also make the structure denser and optimize the pore structure. The improved expansive soil has a denser structure and more uniform pores, which makes the strength increase significantly. The sufficient active substance of the excessive metakaolin cannot be fully excited by the CH generated by cement hydration, the secondary reaction effect is weakened, the pore structure of the soil is not completely optimized, the porosity is increased, and the compressive strength is slightly reduced.

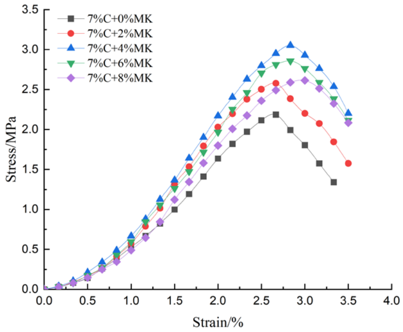



*Figure 2: Unconfined compressive stress-strain curve(7d)*

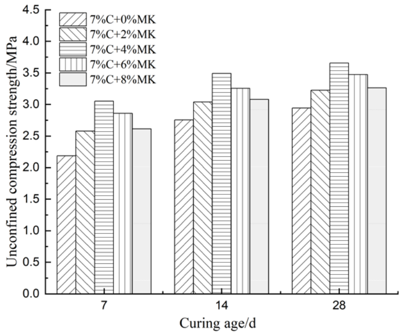



*Figure 3: Column diagram of unconfined compressive strength*

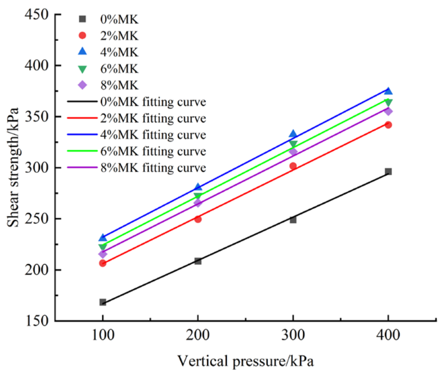
It can be seen from Fig.3 that at the curing age of 7d, 14d and 28d, the incorporation of MK greatly improves the compressive strength of cement-improved expansive soil under the same cement content. When the curing age is 7d, the compressive strength of C-MK improved expansive soil is 3.05 MPa when the MK content is 4%, which is 1.4 times that of cement improved expansive soil under the same curing age, while the compressive strength of plain soil is 0.586 MPa, which is 5.2 times that of plain soil. As shown in Fig.3, when the curing age is 14 d, the compressive strength of cement-improved expansive soil mixed with 4% MK is 3.491 MPa, which is 1.29 times that of cement-improved expansive soil alone. When the curing age is 28d, the compressive strength of cement-improved expansive soil mixed with 4% MK is 3.657 MPa, which is 1.25 times that of cement-improved expansive soil. Under the same cement-metakaolin content, the compressive strength increases significantly with the increase of curing age. This is because the increase of curing age promotes the hydration reaction of C-MK, generates more gel materials, cements the pores of filled soil particles, and improves the compressive strength of C-MK improved expansive soil. The compressive strength enhancement rate is large before the curing age of 28d, and the strength growth rate is small and the growth is slow after the curing age of 28d. Therefore, the strength of cement curing for 28d is used as the design strength of cement.

In summary, 7% C-4% MK modified expansive soil is the best dosage, and each dosage of C-MK modified expansive soil meets the specified value of subbase of Chinese highway (1.5 MPa ~ 2.0 MPa).

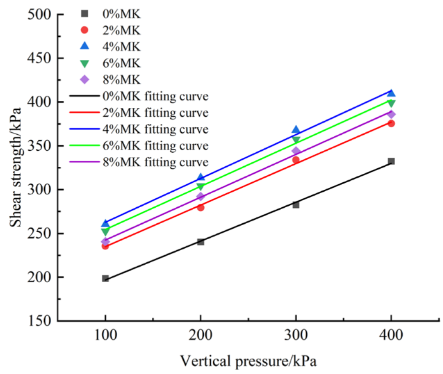
ISSN 2663-1563 Vol. 6, Issue 4: 62-69, DOI: 10.25236/AJAGE.2024.060410

### *3.3 Direct shear test*

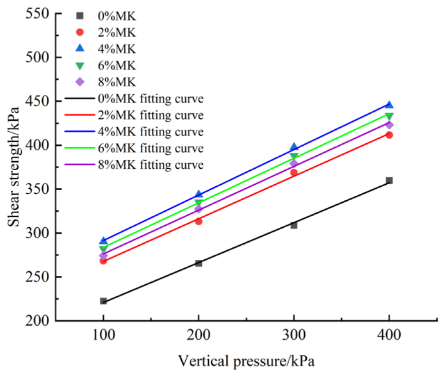
In order to study the shear strength analysis of cement-metakaolin composite improved expansive soil under lateral confinement, the direct shear test was carried out on the sample, and the shear strength $\tau_f$ under vertical pressure σ of 100 kPa, 200 kPa, 300 kPa and 400 kPa was obtained. The $\tau_f$-σ curve and fitting curve are shown in Fig.4.




*(a)Curing age 7d*

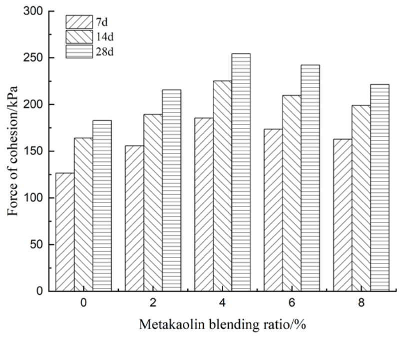



*(b)Curing age 14d*

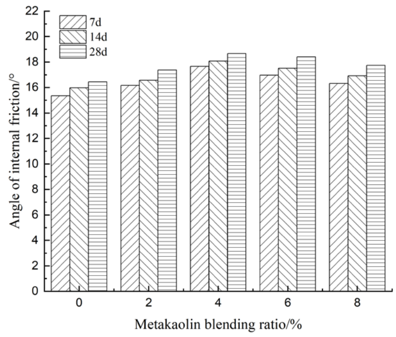



*(c)Curing age 28d*

*Figure 4: $\tau_f - \sigma$ curve of expansive soil improved by cement-metakaolin*




*(a)Force of cohesion*




*(b)Angle of internal friction*

*Figure 5: The relationship between Mohr-Coulomb strength index and dosage of C-MK modified expansive soil*

The relationship curve between the molar-Coulomb strength index of cement-metakaolin modified expansive soil and the content of metakaolin is shown in figure 5. The addition of MK can effectively improve the cohesion and internal friction angle of cement-modified expansive soil, and the improvement effect is the best when the MK content is 4%. When the curing age is 7d, the cohesion and internal friction angle of cement-modified expansive soil with 4% MK are 183.875 kPa and 25.77°, respectively, which are 47% and 2.81° higher than those of cement-modified expansive soil alone. When the curing age is 14d, the cohesion and internal friction angle of cement-modified expansive soil with 4% MK are 212.69 kPa and 26.58°, respectively, which are 39% and 2.66° higher than those of cement-modified expansive soil alone. When the curing age is 28d, the cohesion and internal friction angle of cement-improved expansive soil with 4% MK are 234.61 kPa and 27.39°, respectively, which are 34% and 2.93° higher

ISSN 2663-1563 Vol. 6, Issue 4: 62-69, DOI: 10.25236/AJAGE.2024.060410

than those of cement-improved expansive soil. From the growth rate of cohesion under the condition of age increase, it can be seen that MK has the effect of accelerating the hydration rate of cement modified expansive soil and improving the early strength of cement. The cohesion and internal friction angle of C-MK improved expansive soil increase steadily with the increase of curing age.

### *3.4 SEM test and analysis*

The damaged soil samples of the direct shear test were scanned by SEM electron microscope, and the microstructure characteristics were analyzed by taking the microstructure at 500 times and 5000 times. The microstructure morphology of each sample is shown in figure 6.

As shown in Fig.6 (a) and (b), the microstructure of expansive soil is mainly a face-to-face connected polymer. The surface is relatively smooth, and the interlayer has the characteristics of water absorption expansion and water loss shrinkage. After adding cement, the content of hydrophilic minerals is reduced and the expansion and shrinkage characteristics of expansive soil are inhibited. The cement stone-soil particle skeleton is formed to improve the mechanical strength and microstructure of expansive soil.

The cement itself does not have cementation, and the hydration reaction will produce a cemented gel material; the main components of cement are CaO, $SiO_2$, $Al_2O_3$ and $Fe_2O_3$. The hydration of cement is mainly the hydration reaction of cement clinker tricalcium silicate $C_3S$, dicalcium silicate $C_2S$, tricalcium aluminate $C_3A$ and tetracalcium alumino-ferrite $C_4AF$, resulting in a large amount of hydrated calcium silicate C-S-H and calcium hydroxide $Ca(OH)_2$ and a small amount of hydrated calcium aluminate C-A-H, hydrated calcium ferrite C-F-H, hydrated calcium sulphoaluminate C-A-S-H and other substances[17]. As a strong alkali substance, $Ca(OH)_2$ has low strength and poor stability. Therefore, by adding MK, volcanic ash reaction occurs and a large amount of C-S-H, C-A-H and other substances are produced to improve the mechanical properties and microstructure of expansive soil.

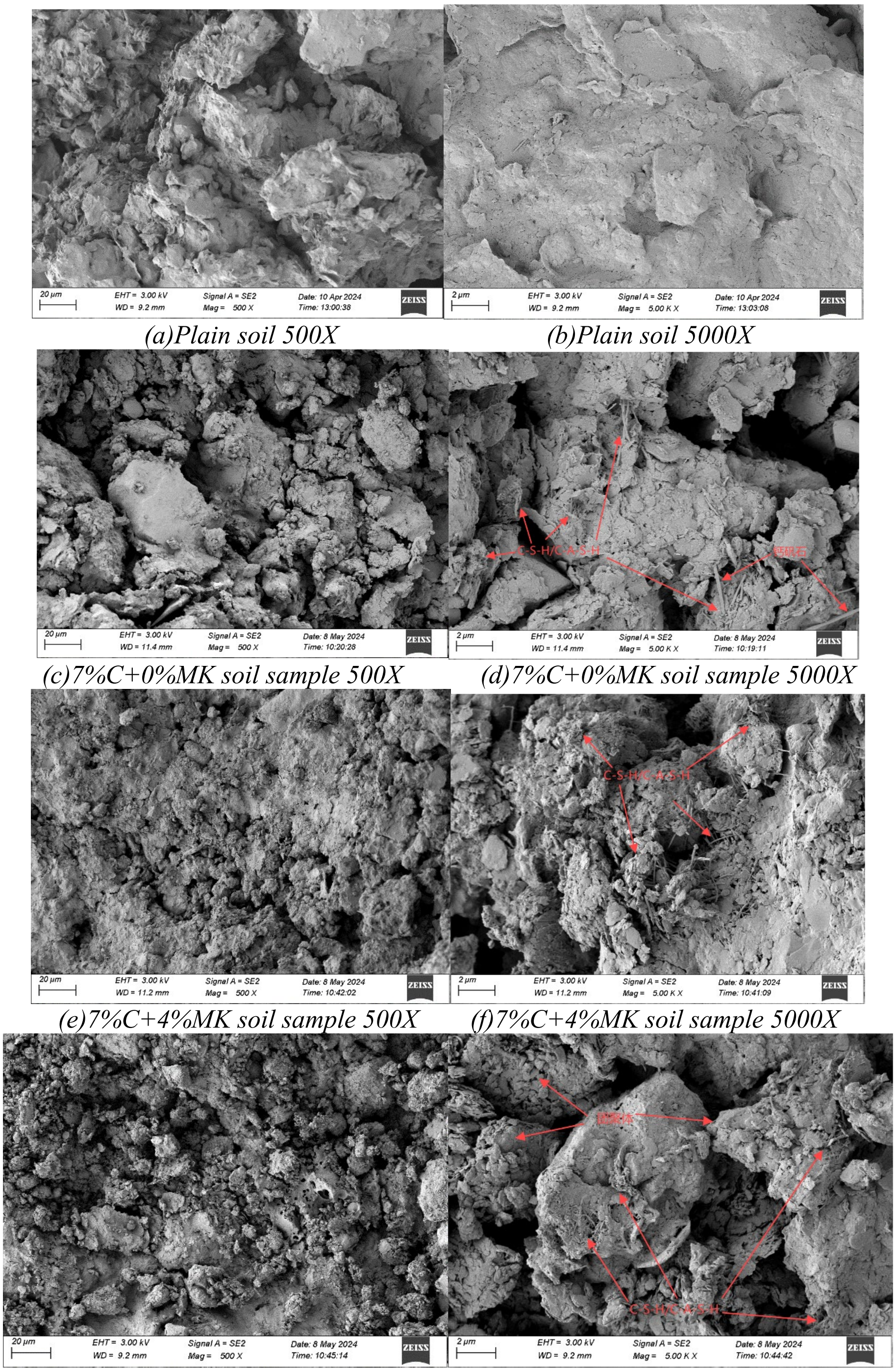
7C improved expansive soil and plain soil microstructure comparison, the addition of cement to improve the surface of the expansive soil-surface polymer, the resulting cementing material C-S-H, C-A-S-H and other connected soil particles, aggregates increased, small particles are not evenly adsorbed on the large particles, each unit is connected by the cement to form a cement-soil particle skeleton, improve the mechanical strength of expansive soil ; from the diagram, it can be clearly seen that there are amorphous C-S-H and needle-like C-A-S-H between the pores, and the large pores between the soil are obviously improved by the gel material, but the porosity still needs to be reduced ; there are also many hexagonal flaky crystal CH layers on the surface of the clay particles. This part of CH has low strength and poor stability, which affects the structural integrity[18]. Therefore, by adding MK to improve its performance.

The cement-improved expansive soil mixed with 4% MK, the flocculent and massive gel substances C-A-H and C-S-H produced on the surface of the soil particles increased, CH decreased significantly, and gel substances with higher strength and better stability were generated. The gel substances play a role in filling the cementation, filling the pores of the soil, connecting the soil aggregates, and the soil particles are more closely contacted and the structure is more uniform. Compared with the microstructure of the cement-improved expansive soil, the pores between the soil are significantly reduced, and the compactness of the soil is improved. Form a denser and more stable cement stone-soil particle skeleton, improve the mechanical strength of cement-improved expansive soil. The interface area between slurry and soil particles in cement-improved expansive soil becomes a weak link due to a large amount of CH. MK has a large number of broken chemical bonds, and the surface energy is large. Its active silica and active alumina form hydrated calcium silicate C-S-H and hydrated calcium aluminate C-A-H through the excitation of CH. The density of C-S-H and C-A-H produced by the secondary reaction is slightly lower than that of the primary reaction. The low-density C-S-H and C-A-H replace CH, and the decrease of CH can improve the durability of the soil in the acidic environment. The gel material produced by the volcanic ash effect further fills the capillary pores and improves its strength and impermeability[15].

Compared with the cement-modified expansive soil with 4% MK content, the cement-modified expansive soil with 8% MK content has a slight improvement in the pore structure of the soil, but there are more small particles in the overall structure, more small aggregates in the soil, more small pores, and no obvious increase in cementing materials. The reason may be that the MK activity is not fully activated, resulting in excessive cement water demand and increased small pores. In order to better stimulate the activity, the fineness of MK is low, and the excess MK enters the pores of the expansive soil as small particles, without more gel material. Cementing affects the internal structure of the improved expansive soil. It may cause the mechanical strength of the improved expansive soil to remain unchanged or slowly

ISSN 2663-1563 Vol. 6, Issue 4: 62-69, DOI: 10.25236/AJAGE.2024.060410

decrease, which is consistent with the previous mechanical test results.




(a)Plain soil 500X (b)Plain soil 5000X

(c)7%C+0%MK soil sample 500X (d)7%C+0%MK soil sample 5000X

(e)7%C+4%MK soil sample 500X (f)7%C+4%MK soil sample 5000X

(g)7%C+8%MK soil sample 500X (h)7%C+8%MK soil sample 5000X

*Figure 6: SEM microstructure diagram*

## 4. Conclusion

Through mechanical tests and microscopic tests, the mechanical properties and microscopic mechanism of cement-metakaolin composite improved expansive soil were studied, and the following conclusions were drawn.

(1) Cement-metakaolin as an admixture reduces the free expansion rate of expansive soil and effectively improves the expansion and shrinkage characteristics of expansive soil.

(2) The incorporation of metakaolin can effectively improve the mechanical properties of cement-

ISSN 2663-1563 Vol. 6, Issue 4: 62-69, DOI: 10.25236/AJAGE.2024.060410

improved expansive soil. After the incorporation of metakaolin, the unconfined compressive strength and shear strength of cement-improved expansive soil are significantly improved, and the cohesion and internal friction angle are effectively improved. When the content of metakaolin is 4%, the unconfined compressive strength and shear strength reach the highest.

(3) It can be seen from SEM that the incorporation of metakaolin does not change the type of cement hydration products, but the content of gel material increases, which better optimizes the pore structure and improves the soil structure.

## Acknowledgments

This study was supported by the National Nature Science Foundation of China (U1204511) and the Key Research Projects of Henan Higher Education Institutions (19A560027)

## References

*[1] Khadka D S, Jayawickrama W P, Senadheera S, et al. Stabilization of highly expansive soils containing sulfate using metakaolin and fly ash based geopolymer modified with lime and gypsum[J]. Transportation Geotechnics, 2020, 23: 100327.*
*[2] Leng T, Tang C S, Xu D, et al. Research progress on engineering geological characteristics of expansive soil[J]. Journal of Engineering Geology, 2018, 26(1): 112-128.*
*[3] Wang M W, Wang D M, Sheng C C, et al. Experimental study on impact performance of lime-basalt fiber improved expansive soil[J]. Journal of Hefei University of Technology (Natural Science), 2018, 41(11): 1515-1518.*
*[4] Wasim M T, Jahanzaib I, Khalid F, et al. Strength Mechanism of a Swelling Soil Improved with Jute Fibers: A Laboratory Treatment[J]. Geotechnical and Geological Engineering, 2023, 41(7): 4367-4380.*
*[5] He J, Huang X, Yan F Y, et al. Research Progress of Biomimetic Geotechnical Technology[J]. Chinese Journal of Geotechnical Engineering, 2023, 45(6): 1200-1211.*
*[6] Xiao J Z, Liu Y S, Wang D, et al. Experimental study on engineering characteristics of expansive soil improved by microbial technology [J]. Chinese Journal of Geotechnical Engineering, 2023, 45(S1): 97-101.*
*[7] Weng C P, Ren H X. Dynamic backbone curve model of expansive soil improved by biological enzyme[J]. Journal of Central South University (Science and Technology), 2021, 52(4): 1109-1117.*
*[8] Zhou H L, Liang Y J, Li B, et al. Summary of research status of metakaolin cement soil[J]. Bulletin of the Chinese Ceramic Society, 2020, 39(9): 2858-2863.*
*[9] Rinu S, J. A P, Miladin R. Sustainability Benefits Assessment of Metakaolin-Based Geopolymer Treatment of High Plasticity Clay[J]. Sustainability, 2020, 12(24): 10495.*
*[10] Xia Y J, He W. Effect of metakaolin on dynamic properties and microscopic characteristics of cemented soil[J]. Yangtze River, 2022, 53(6): 212-216.*
*[11] Poon C, Kou S, Lam L. Compressive strength, chloride diffusivity and pore structure of high performance metakaolin and silica fume concrete[J]. Construction and Building Materials, 2005, 20(10): 858-865.*
*[12] Li Z, Ding Z. Property improvement of Portland cement by incorporating with metakaolin and slag[J]. Cement and Concrete Research, 2003, 33(4): 579-584.*
*[13] Qian X Q, Zhan S L, Li Z J. Study on physical and mechanical properties of highly performance concrete mixed with metakaolin[J]. Journal of Building Materials, 2001, (1): 75-78.*
*[14] Deng Y F, Wu Z L, Liu S Y, et al. The influence of geopolymer on the strength of cement solidified soil and its mechanism analysis[J]. Chinese Journal of Geotechnical Engineering, 2016, 38(3): 446-453.*
*[15] Chu C F, Li X C, Deng Y F, et al. Effect of metakaolin on mechanical properties of cement modified marine soft soil[J]. Chinese Journal of Geotechnical Engineering, 2013, 35(S1): 170-174.*
*[16] Jia J C. Study on expansion mechanism and mesoscopic expansion model of expansive soil[D]. Dalian University of Technology, 2010.*
*[17] Kong X M, Lu Z C, Zhang C Y. Research progress of cement hydration mechanism and the effect of polymer admixture on cement hydration[J]. Journal of the Chinese Ceramic Society, 2017, 45(2): 274-281.*
*[18] Wang Q, Li S Y, Wang J, et al. Effect of graphene oxide on cement hydration process and its main hydration products [J]. Journal of the Chinese Ceramic Society, 2018, 46(2): 163-172.*