Study on the effect of resistivity and meso-structure evaluation of alkali solution strengthening loess: A case study

Wenle Hu1,2,a, Hua Liu1,2,b* and Tiehang Wang1,2,c

1 School of Civil Engineering, Xi’an University of Architecture and Technology, Xi’an, Shaanxi Province, 710055, China
2 Shaanxi Key Laboratory of Geotechnical and Underground Space Engineering, Xi’an, Shaanxi Province, 710055, China
aemail: wenlehu@xauat.edu.cn, bemail: liuhua029@xauat.edu.cn, cemail: 1273620386@qq.com
*Corresponding author’s e-mail: liuhua029@xauat.edu.cn

Abstract. For evaluating the structure and strength of loess effectively, a series of laboratory tests were performed to investigate and compare the pore meso-structural characteristics, the shear strength and the resistivity of natural loess and loess treated with alkali solutions under 4 different concentrations. Scanning electron microscope(SEM) method, direct shear tests, electrical resistivity tests, and X-ray diffraction analysis were used to detect the changing process in strength parameters, micro-structure, and mineral composition. The evolution result of shear strength index and stress-strain characteristics of loess were analyzed. Combined the SEM micro-structure analysis and X-ray diffraction technology, the microscopic mechanism of alkali solutions and loess interaction was revealed. The results of tests show that the curves of shear stress- displacement featured as strain-hardening, and the increasing of shear strength indexes with the increasing of alkali solutions concentration. Then the relationship between the shear strength index and resistivity was established. The SEM images of LTA specimens were used to quantify the structural parameters by Image Processing Techniques. The changes of multiple structural indicators of LTA such as directionality, abundance, circularity, fractal dimension, and the orientation probability entropy were revealed. The potential mechanism of LTA was revealed by the XRD and EDS tests from the perspectives of mineral composition and chemical element composition. The results of this study show that alkali-loess interaction was the main influence factor for the changes in the shear strength and meso-structure s. The results provide a valuable implication for the construction in the loess deposits.

1. Introduction
Loess is a unique geological deposit that is formed in special circumstances. Extensive loess deposits are found in north and northwest China [1-3]. Since loess soil is characterized by porosity, joint development and metastable structure [4-9], there are many geological hazards happening such as subgrade settlement, cracking, tilting and collapses of buildings when roads, railways and buildings are constructed on loess sites [10-11]. The uniqueness of loess sites is that its bone structure is a unique spatial structure system supported by cemented aggregates and detrital particles [3,12-13], Researches from Chattaraj and Sengupta [14] as well as Pei et al. [15] also verify that the main cause of disasters on loess sites is its poor porous structure. Therefore, research on the structure of loess soil
is of great significance for understanding its macro-mechanical properties, improving its engineering properties, and for practical engineering applications in loess areas with regional characteristics [16].

In the early 19th century, Terzaghi [17] was the first one to study the honeycomb structure of cohesive soil and pointed out that its microstructure is important in geotechnical engineering evaluation. After that, Brewer [18], Leroueil et al. [19], Delage and Lefebvre [20] and many other scholars have studied the arrangement, cementation and structural mechanical properties of cohesive soil particles. Michell [21] defined the combined effect of soil particle arrangement and cementation as soil structure. Thyagaraj and Salini [22], Thyagaraj and Das [23] discussed the porosity and collapsibility of loess soils in their studies on the influence of pore water salinization on osmotic suction and matrix suction. These researches have laid the foundation for the study of soil structure, but they are limited to the investigation of inherent structure of soils. In China, the research of loess structure started relatively late. In 1979, Gao Guorui [3] studied the microstructure of Chinese loess and proposed opinions on classification of microstructure of loess soil. Xu Shimin et al. [24] made quantitative analysis on the porous microstructure of Chinese loess based on Matlab and IPP. But there are few studies on the improvement of the structural properties of loess by chemical means [16].

In general, there are physical methods (dynamic compaction etc.), chemical methods (chemical reagents etc.) and composite methods for dealing with poor geological sites. Chemical methods usually include adding cement, curing agent and other strong cohesive materials. Regarding foundation treatment in loess areas, Li Yunzhang [25] carried out engineering practice of alkali-treated collapsible loess foundation as early as 1982, and his recent researches [26-27] also mostly focused on its engineering mechanics. However, there are few studies on the improvement of the structural properties of loess through alkaline treatment.

Due to its loose and porous salt crystal cement structure, loess soil has attracted the attention of engineers and scientific researchers. Alkaline treatment is a chemical treatment, the processing mechanism of which is based on the chemical reaction between alkali solution and the mineral components and cemented aggregates in the soil. Alkali solution is not colloid material. Although relevant regulations applicable to the treatment of loess soil have been published [28], there are many factors that affect alkaline treatment, such as alkali solution temperature, alkali solution concentration, soil density, soil moisture content, treatment methods and mineral composition of the soil[27]. These regulations do not fully meet the specific requirements of loess affected by regional characteristics. There is no research on the meso-structure analysis and micro-mineral characterization of alkaline treatment in the existing researches, which is also closely related to practical engineering applications.

Based on this, alkaline treatment is performed on collapsible undisturbed loess soil taken from Yaozhou District of Tongchuan City, the plateau region of northwest China, in which process loess soil samples with the same moisture content are treated with alkali solutions of 0.1 mol/L, 0.5 mol/L, 1.0 mol/L and 2.0 mol/L. Then, direct shear test and triaxial compression test are conducted on the samples. Based on meso-structure analysis and micro-mineral characteristic as well as reaction mechanism of alkali solution and loess soil, this paper reveals the structural evolution rules and mechanical behavior of loess under alkaline treatment and expects to provide a valuable reference for the research on alkaline treatment in regional loess sites and its engineering practice.

2. Overview of the tests

2.1. Basic nature of the tests

The undisturbed loess sample used in this test is taken from the foundation pit of a power station site in Yaozhou District, Tongchuan City, Shaanxi Province. The sampling depth is 2–3m. The undisturbed soil sample is cut into blocks of about 30cm×30cm×20cm, the size is marked at the top of the sample. Soil samples are carefully stored in a polyethylene fresh-keeping bag, in order to avoid disturbance as much as possible during transportation and storage. The cumulative analysis curve of particle distribution and basic physical indexes of the test soil samples are shown in Figure 1 and Table 1.
Fig.1 Location of sample spot: Tongchuan City, Shaanxi Province, China.

Table 1. Formatting sections, subsections and subsubsections.

| Proportion | Liquid limit \( w_L / \% \) | Plastic limit \( w_P / \% \) | Optimum moisture content \( w_{opt} / \% \) | Plasticity index \( I_p \) |
|---|---|---|---|---|
| Gs | 2.72 | 35.43 | 21.42 | 16.8 | 14.01 |

2.2. *Infiltration device preparations*

Distilled water is used to prepare the alkali solution of 4 concentrations, i.e., 0.1 mol/L, 0.5 mol/L, 1.0 mol/L and 2.0 mol/L. At the same time, the wetted (distilled water) sample group was set as the standard control group. Alkaline infiltration is carried out by using the specially designed device shown in Figure 2. During the sample preparation process, a rotary switch is used to adjust the air pressure until the air pressure in the cylinder is stable. After that, before the subsequent test, the prepared contaminated samples are placed in humidifier for another 24 hours. In the process of preparing the contaminated samples and the control samples, the moisture content of the samples is adjusted to 25% according to the experimental design value. All samples are sealed respectively and stored for 48 hours.

Fig.2 Undisturbed soil sample improving device

2.3. *Direct shear test and resistivity test*

60 samples are required in direct shear test and triaxial compression test respectively. Three sets of parallel tests are set respectively in direct shear test and triaxial test, including 48 improvement samples and 12 humidification samples. The test process is strictly in accordance with Standard for Geotechnical Test Method [29] (GB/T 50123-2019).
Direct shear test is carried out with a strain-controlled direct shear tester (as shown in Figure 3 (a)). In the preparation process of the test, a ring cutter with a diameter of 61.8 mm and a height of 20.0 mm is used to make direct shear specimens. The vertical pressure applied during the test is 100kPa, 200kPa, 300kPa and 400kPa, the shear rate is controlled at 0.8mm/min, the maximum shear displacement is 8mm, and the shear stress corresponding to the shear displacement of 4 mm is the shear strength value when there is no peak.

A self-designed and assembled resistivity test device is used in the test, the principle of the device is shown in Figure 3 (b). In this test, the average resistivity of four parallel samples is taken as the average resistivity in different processing state.

2.4. XRD test, SEM test and EDS test
Prepare 12 standard direct shear samples (2 samples for each concentration (0.1, 0.5, 1.0, 2.0 mol/L) and two humidification samples) by using the device shown in Figure 2, wherein 6 are used for XRD test and 6 are used for SEM and EDS test.

XRD test: Before identifying the mineral phase composition, the soil sample is dried in an oven at 105°C for 24 hours and then ground, and then the dried sample is crushed and placed in a ziplock bag for the next step (Figure 3 (c)).

The SEM and EDS test are carried out according to literature [30]. JSM-7610F Schottky field emission scanning electron microscope (Figure 3(d)) from Japan Electron Optics Laboratory Co., Ltd. is used in the test.

Fig. 3 Macro, micro and micro test equipment

3. Analysis of shear strength test result

3.1. Influence of alkali solution concentration on plasticity of loess soils
The boundary moisture content of soil directly or indirectly affects its engineering properties. Measure the liquid limit and plastic limit of the alkali-treated loess with a combined liquid-plastic limit tester. The liquid limit of the alkali-treated sample is between 35% and 40%, the plastic limit is between 21% and 24%, the liquid limit change range is within 5%, and the plastic limit change range is within 3%. Compose a plasticity diagram, as shown in Figure 4. It can be found that the plasticity index increases as the concentration of alkali solution increases. Theoretically, when NaOH solution is added to the soil, the concentration of cations in the soil increases, the thickness of the counterion layer adsorbed on the surface of the soil particles becomes thinner, the content of bound water decreases correspondingly, and the plasticity index decreases. But it contradicts the test result. On the other hand, alkali solution breaks the agglomerate structure of the loess, the cemented material is precipitated, the content of fine particles increases, its specific surface area and potential bound water content increase, and the plasticity index increases. The comprehensive effects of the above two factors can explain why the plasticity of loess increases to a small extent.
3.2. Influence of alkali solution concentration on direct shear test result

3.2.1. Shear stress-strain relationship. Compose a shear stress-strain curve according to the direct shear test result of alkali-treated loess, as shown in Figure 5. The changing patterns of the shear stress-strain curves of loess samples treated with different concentrations of alkaline solutions are consistent and the alkali-treated soils show strain hardening behavior.

3.2.2. Analysis of direct shear test results. Direct shear strength and its index change obtained from the direct shear test are shown in Figure 6 and Table 2. The shear strengths of humidification samples are 36.48-95.95 kPa as the vertical stress increases from 100 kPa to 400 kPa. The shear strengths of alkali-treated samples are larger than that of humidification samples, and the difference is more obvious as alkaline concentration increases. When the highest concentration of alkaline solution is used, the shear strength of the treated sample is 49.88-123.3 kPa, increasing by 28.50%-36.73% compared with humidification samples. Table 2 shows that the cohesiveness and internal friction angle increase with the increase of alkaline concentration. It can be found from equations (1)-(7) that soil particles are clumped together through colloids that are generated from the chemical reaction between the hydroxyl
in the alkali solution and the metallic oxide in the soil, as a result, the soil cohesiveness increases. The internal friction angle also showed an "abnormal" small increase with the increase of alkaline concentration, resulting from alkaline-soil reaction, in which process the aluminosilicate on the surface of soil particles gradually transforms from solid state to liquid state, the friction on the surface of soil particles decreases and the internal friction angle decreases. In this process, the surface of adjacent soil particles forms a non-water-stable fusion cementation, which forms a water-stable complex after the completion of equation (8), making the cohesiveness of the cemented material stronger. Cementation effect increases the bite force of mutual embedding and interlocking of particles, thereby increasing the internal friction angle. Therefore, it shows that in this case, compared with the effect of the liquid phase trend caused by the expansion and softening of the soil particle surface, the interlocking structure state effect between the particles is dominant.

$$\text{Al}_2\text{O}_3 + 2\text{NaOH} \rightarrow 2\text{NaAlO}_2 + \text{H}_2\text{O} \quad (1)$$

$$2\text{NaAlO}_2 + \text{H}_2\text{O} \rightarrow 2\text{Na}^+ + 2\text{AlO}_2^- + \text{H}_2\text{O} \quad (2)$$

$$\text{SiO}_2 + 2\text{NaOH} \rightarrow \text{Na}_2\text{SiO}_3 + \text{H}_2\text{O} \quad (3)$$

$$\text{Na}_2\text{SiO}_3 + \text{H}_2\text{O} \rightarrow 2\text{Na}^+ + \text{SiO}_3^{2-} + \text{H}_2\text{O} \quad (4)$$

$$\text{MgCO}_3 + \text{OH}^- \rightarrow \text{Mg(OH)}_2 + \text{CO}_3^{2-} + \text{H}_2\text{O} \quad (5)$$

$$\text{SiO}_3^{2-} + \text{CO}_2 + 3\text{H}_2\text{O} = \text{H}_2\text{SiO}_3 \left(\text{colloid}\right) + \text{CO}_3^{2-}, \quad (6)$$

$$2\text{AlO}_2^- + \text{CO}_2 + \text{H}_2\text{O} = 2\text{Al(OH)}_3 \left(\text{colloid}\right) + \text{CO}_3^{2-}, \quad (7)$$

$$\text{CO}_3^{2-} + 2\text{H}_2\text{O} = 2\text{OH}^- + \text{H}_2\text{CO}_3. \quad (8)$$

Table 2 Direct shear strength indexes of loess treated with different alkali solutions.

| Conditions | Cohesion (kPa) | Internal friction angle (°) |
|------------|---------------|-----------------------------|
| Wetted loess | 18.2 | 11.2 |
| LTA 0.1 | 19.2 | 11.4 |
| LTA 0.5 | 20.6 | 11.6 |
| LTA 1.0 | 23.2 | 12.5 |
| LTA 2.0 | 26.9 | 13.2 |

Fig.6 Direct shear strength of loess treated with different alkali solutions.
3.3. Influence of alkaline concentration on result of direct shear test
The relationship between shear strength and resistivity of loess samples under different alkaline concentrations is shown in Figure 7. The Figure shows that resistivity and shear strength are approximately linearly related, and the lower the resistivity value is, the lower the shear strength is.

Fig.7 The stress-strain relationships of loess treated with different alkali solutions.

3.4. Mathematical model fitting
Take shear strain $\varepsilon$ as the x-coordinate and shear stress as the y-coordinate. The shear stress-strain curve shows strain hardening behavior. Equation (9) can well describe the stress-strain relationship. In the process of fitting trial calculation, the value of $\alpha$ fluctuates around 0.50 overall. Therefore, all stress-strain curves are re-calculated by fixing the value of $\alpha$ to 0.50, and the effect is ideal, as shown in Figure 5.

$$\tau = \beta \varepsilon^\alpha$$  \hspace{1cm} (9)

Sort out the fitting parameter $\beta$ of each sample, and carry out correlation analysis with alkaline concentration. Compare the function equations obtained under different vertical pressures, obtain the equation with the vertical pressure, and substitute the function equation into the equation (9) to get equation (10), which describes the relationship between shear stress and vertical pressure, and between alkaline concentration and horizontal strain.

$$\tau_{p,n,\varepsilon} = (30.1798 \times n + 0.7616 \times p + 67.011) \times \varepsilon^{0.5}$$  \hspace{1cm} (10)

Where, $\tau_{p,n,\varepsilon}$ is predicted shear stress, $p$ is vertical pressure, $n$ is alkaline concentration, $\varepsilon$ is horizontal strain.

As Figure 8 shows, sort out the fitting parameter of each sample, and carry out correlation analysis with alkaline concentration. Compare the function equations obtained under different vertical pressures, obtain the equation with the vertical pressure, and substitute function equation into equation (9) to get equation (10), which describes the relationship between shear stress and vertical pressure, and between alkaline concentration and horizontal strain.

$$\tau_{p,\rho,\varepsilon} = (-1.9284 \times \rho + 1.051 \times p + 137.467) \times \varepsilon^{0.5}$$  \hspace{1cm} (11)

Where, $\tau_{p,\rho,\varepsilon}$ is predicted shear stress, $p$ is vertical pressure, $\rho$ is resistivity, $\varepsilon$ is horizontal strain.

3.5. Evaluation of resistivity of alkali-treated undisturbed loess soil
Based on the above discussion, the functional relationship between the engineering mechanics index and alkaline concentration and the functional relationship between electrical parameters and alkaline concentration are different. According to the standard for soil engineering property evaluation put forward in Code for Investigation of Geotechnical Engineering (GB50021-2001) [31] and
considering the particularity of engineering mechanical properties and electrical parameter changes of alkali-treated loess, the evaluation grade of the engineering properties of alkaline treated loess is shown in Table 3.

![Parameter fitting curve of hardening model.](image)

**Table 3** Evaluation of resistivity of alkaline treated soil considering different parameters of soil.

| Types          | Processing degree | Alkali concentration /mol•L⁻¹ | Index change /% | Soil resistivity/Ω•m |
|----------------|-------------------|-------------------------------|-----------------|---------------------|
| Cohesion       | Micro-processing  | ≤0.1                          | ≤5↑             | ≥60                 |
|                | Low processing    | 0.1~0.5                       | 5~15↑           | 60~55               |
|                | Medium processing | 0.5~1.0                       | 15~30↑          | 55~45               |
|                | High processing   | 1.0~2.0                       | 30~45↑          | 45~30               |
|                | Extremely high    | ≥2.0                          | ≥45↑            | ≤30                 |
| Internal friction angle | Micro-processing  | ≤0.1                          | ≤2↑             | ≥60                 |
|                | Low processing    | 0.1~0.5                       | 2~5↑            | 60~55               |
|                | Medium processing | 0.5~1.0                       | 5~10↑           | 55~45               |
|                | High processing   | 1.0~2.0                       | 10~20↑          | 45~30               |
|                | Extremely high    | ≥2.0                          | ≥20↑            | ≤30                 |

4. **Analysis of meso and micro test results**

4.1. **Scanning Electron Microscope (SEM)**

Figure 9 shows the SEM images of undisturbed loess samples, humidification loess samples and alkaline-treated loess samples. It can be found that the cementation (bounding between the particles) of undisturbed loess is well developed, the inter-particle agglomeration is also obvious, and typical inter-particle connection occurs between points and edges and between edges. In humidification loess samples, water molecules enter the pores under the suction of the matrix, weakening the cementation effect among particles. Alkali solution strengthens the cementation effect between particles. It can be clearly seen from the ×1000 image that white material is generated between the particles. This is due to the action of alkaline and loess, in which process sodium aluminosilicates are formed by the action of alkaline and loess, and the calcium hydroxide around the soil particles promotes the transformation of sodium aluminosilicates from non-water state to hydraulic calcium aluminosilicates, which improves its strength and water stability [25].
4.2. Quantitative analysis

Soil porosity and particles are important indicators to reflect the structure of soil. Matlab and IPP are used to process the scanned image structure of loess [24], as shown in Figure 1. Number of pores, area, circumference, long axis length, short axis length, direction angles are extracted from the result. Based on the researches of Lei Xiangyi et al. [32], Liu Songyu et al. [33], and Shi Bin [34], quantitative analysis is further performed to analyze the changes of multiple structural indicators of the loess before and after alkaline treatment, including directional frequency, unit circularity, fractal dimension and orientation probability entropy.

4.2.1. Unit directional frequency. Directional frequency reflects the directional characteristics of soil pores and particle arrangement. It can be seen from Figure 11(a) that the maximum values of pore directional frequency occur in many directions in the undisturbed soil samples and humidification soil samples, indicating the orientation of the samples is poor. With the addition of alkali solution and the increase of its concentration, maximum values concentrate in the range of 60°~120°, indicating the orientation of pores is poor. This may be related to the improvement method of alkaline infiltration. It can be seen from Figure 11(b) that the particle direction frequency distribution of the undisturbed soil sample and the humidified soil sample are relatively uniform. With the addition of alkali solution and the increase of concentration, the particle orientation is more concentrated within a certain angle range, and the orientation of particles is improved to varying degrees.
4.2.2. Characteristics of unit structure. Pores and particle distribution in humidification samples and alkali-treated samples show different features. In order to understand the reasons for the differences in its meso structure, statistical calculations and analysis are carried out on unit abundance, unit circularity, fractal dimension, and orientation probability entropy. The following describes the physical and mathematical meanings of the four structural indicators above: (where the area of the unit is defined as \( s \); the perimeter is \( l \); the length of the long axis is \( \beta \); the length of the short axis is \( \alpha \))

1. **Unit abundance \( \lambda \)** is the ratio of the short axis to the long axis of the unit (pore/particle) (as shown in equation (12)), which reflects the structural change of soils. The abundance value is in the range of \([0, 1]\). The closer its value is to 1, the closer the unit is to an isometric state; the closer its value is to 0, the smaller the abundance is, indicating the unit is closer to elongated shape.

2. **Unit circularity \( \chi \)** describes the change trend of the unit surface (as shown in equation (13)). The closer the \( \chi \) value of the particle is to 1, the closer the particle is to round shape.

3. **Fractal dimension \( D \)** describes the relationship between the perimeter and the area of the unit (as shown in equation (14)), and its value reflects the complexity of the soil structure.

4. **Directional probability entropy \( H \)** is used as a structural parameter describing the arrangement of particles (as shown in equation (15)), which is used to describe the ordering of soil structure. It is calculated as following: divide 0-180° into \( n \) locations, \( m_i \) is the number of particles of the long axis in the \( i^{th} \) area, \( M \) represents the total number of particles, the range of \( H \) value is \((0, 1)\). The larger the \( H \) value of the particle is, the less ordered the particle arrangement is, in other word, the arrangement of the particles is more chaotic.
\[ \lambda = \frac{\beta}{\alpha} \quad (12) \]

\[ \chi = \frac{l^2}{4\pi \times s} \quad (13) \]

\[ \ln l = (D/2) \times \ln s + C \quad (14) \]

\[ H = -\sum_{i=1}^{n} \frac{m_i}{M} \times \frac{\ln \left( \frac{m_i}{M} \right)}{\ln n} \quad (15) \]

The meso-structural indexes of alkali-treated loess calculated according to the above method is shown in Table 4. Generally speaking, with the increase of alkaline concentration, pore abundance decreases first and then increases, pore circularity increases gradually, pore fractal dimension increases first and then decreases, and the pore orientation probability entropy decreases gradually; particle abundance decreases gradually, circularity increases gradually, fractal dimension increases first and then decreases, and particle orientation probability entropy increases first and then decreases. The reasons for the changes are mainly: first, ion displacement reaction is completed the moment when solution infiltrates into the soil, and hydroxides of alkali metals are generated around the soil particles (as shown in equation (5), (6), (8)); second, in the process of alkali-loess reaction, free silica and alumina react with fine particles in the soil, leading to generation of sodium silicate, and part of the SiO2 dissolves; third, under the action of sodium hydroxide solution, the softening of the surface layer of soil particles promotes the cementation of the particles, and the complexation of calcium hydroxide improves the water stability of the solid-liquid transformation.

| Processing conditions | Natural loess | Wetted loess | LTA 0.1 M | LTA 0.5 M | LTA 1.0 M | LTA 2.0 M |
|-----------------------|--------------|-------------|-----------|-----------|-----------|-----------|
| Pore abundance        | 0.6178       | 0.6216      | 0.6268    | 0.6061    | 0.5991    | 0.6233    |
| Particle abundance    | 0.6115       | 0.6225      | 0.6216    | 0.6155    | 0.6095    | 0.6079    |
| Pore circularity      | 2.3700       | 2.3800      | 1.5978    | 2.4100    | 2.3540    | 2.5985    |
| Particle circularity  | 2.8964       | 2.2606      | 2.1240    | 2.3730    | 2.3371    | 0.4149    |
| Pore fractal dimension| 1.1500       | 1.1700      | 1.2456    | 1.3530    | 1.2818    | 1.2420    |
| Particle fractal dimension | 1.2177 | 1.2603 | 1.3098 | 1.2644 | 1.2697 | 1.2468 |
| Pore orientation probability entropy | 0.97724 | 0.9853 | 0.9659 | 0.9817 | 0.9764 | 0.9755 |
| Particle orientation probability entropy | 0.9797 | 0.9755 | 0.9695 | 0.9837 | 0.9844 | 0.9690 |
4.3. Analysis of minerals and element test result

4.3.1. XRD phase test result. XRD graphs of humidification samples and alkali-treated samples are almost consistent, so no further comparison is conducted. Figure 12 (a) shows there are many diffraction peaks in undisturbed loess, mainly including primary minerals such as quartz, calcite, potash feldspar, chlorite, and clay minerals such as montmorillonite, indicating complicated mineral composition [35]. Figure 12 (b) shows that in the process of alkaline treatment, the interaction between alkali solution and loess consumes part of the metal oxides such as silicon dioxide and calcium oxide, and forms complexes such as calcium aluminosilicate, leading to the improvement of cementation.

Fig.12 Mineral composition analysis of loess treated with different concentration alkali liquor.

4.3.2. EDS test results. EDS spectrum of the alkali-treated loess sample shows that the types and percentages of main metal elements except for carbon, oxygen, sulfur and other non-metal elements are shown in Figure 13. It shows that the contents of Na and Ca increase when alkali solution is added to loess soil. Compared with undisturbed loess soil, the percentages of Si and Al are not consistent, but generally show a decreasing trend except for that in samples treated with 1.0 mol/L and 1.5 mol/L alkali solution, which verifies why the contents of these elements increase slightly in alkali-treated loess samples.

Fig.13 Comparison of metal elements in Loess treated with alkali solution of different concentrations.

4.4. Analysis of minerals and element test result
As shown in Figure 14, particles are clumped together from the mode of evenly distributed state and point contacting to interlocking state. The main reason is the interaction between alkali solution and loess, which changes the shear strength and mesostructured of loess, promoting surface activation of soil particles and resulting in particle agglutination. Then the mechanical strength of soil is improved.
5. Conclusions

This paper studied the evolution of the structure and strength of alkaline-treated loess by means of direct shear test, triaxial test, SEM, XRD and other test methods, so as to clarify the engineering application mechanism of alkaline-treated loess sites. The results reveal that:

1) The plasticity index of the loess soil increases as alkaline concentration increases. Direct shear test result shows that the shear strength of the samples increase as alkaline concentration increases. The shear stress-strain curve of the alkaline-treated loess shows strain hardening behavior.

2) Both cohesiveness and internal friction angle increase with the increase of alkaline concentration, because alkaline solution promotes surface activation of soil particles and soil grits, hydraulic complex is formed and then cohesiveness of the soil is improved. Activated colloid promotes the bite force between particles by means of embedding and interlocking interaction, and then the internal friction angle increases. Regarding the alkaline-treated loess, there is a linear positive relationship between shear strength and alkaline concentration, a linear negative relationship between resistivity and alkaline concentration, and a negative relationship between shear strength and resistivity. The changing patterns of cohesiveness with alkaline concentration and resistivity are the same with shear strength. Therefore, this paper establishes a shear stress-horizontal strain equation under the same alkaline concentration and resistivity.

3) Quantitative analysis of the meso-image shows that with the increase of alkaline concentration, pore abundance increases first and then decreases, pore circularity increases gradually, pore fractal dimension increases first and then decreases, and pore orientation probability entropy decreases gradually. Particle abundance decreases gradually, particle circularity increases gradually, particle fractal dimension increases first and then decreases, and particle orientation probability entropy increases first and then decreases.

4) In the micro perspective, test result shows that during the process of alkaline treatment, the interaction between alkaline and loess consumes part of the metal oxides such as silicon dioxide and calcium oxide, calcium aluminosilicate and other complexes are generated, improving cementation effect. After alkaline treatment, the contents of sodium and calcium in metal elements increase.

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