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Analysis on Creep Characteristics and Microscopic Mechanism of Loess Q_2

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Abstract

The mechanical properties of loess are of great significance to engineering practices in the loess area. To explore the creep characteristics of Q_2, reveal the influence of creep on slope stability, and provide theoretical and experimental support for the prediction of landslide, fifteen group samples of Q_2 loess with different moisture contents under triaxial creep tests were conducted. Results show that the isochronal curve at low stress is linear. When the stress is greater than the yield limit, the creep deformation and its rate gradually increase. The isochronal curve gradually bends toward the strain axis, which shows significant nonlinear rheological characteristics, and the nonlinearity becomes more obvious with the increase of stress. Scanning electron microscopy reveals that the creep process is where the area and the number of macropores decrease and the number of small pores increase. The particles form a new aggregate, which forms a relatively stable structure, and the soil becomes dense. With the increase of the soil water content, the pores between particle layers expand, which has a close relationship with the macro test. The conclusions obtained in the study are of reference value to the engineering practice in the loess area.

Keywords: Loess, Creep characteristics, Microstructure, Scanning electron microscopy, Triaxial test

1. Introduction

Loess is widely distributed in northwestern of China. Due to its arid and semi-arid climatic conditions [1], as well as its macroporous structure and sensitivity to water [2], the research on the mechanical properties of loess is of great significance to engineering practices in the loess area [3].

In many cases, the creep strength of soil plays a major role in geotechnical problems [4-5], such as the stabilities of soil tunnels and slopes [6-7]. The slope failure may start from the local high stress area of soil and expand outward to cause landslide when the shear failure stress is reached [8-9]. Deep creep of soil can take a long time, or even a few years. Therefore, the aging deformation characteristic of soil is one of the key research topics in geotechnical engineering, the rheological effect of soil must be considered in slope stability or landslide [10].

Current studies mainly focus on a more micro level and get more distant from macroscopic issues on loess [11], so it is more difficulty to establish the relationship between microstructure and mechanical properties of loess. Thus, it is a very difficult but crucial work to build the relations between the microstructure and the macroscopic mechanical properties of soil.

2. State of art

The rheological properties of the soil are studied first from the beginning of the experiment. Many scholars have conducted lots of research works, For example, based on direct shear creep test results, Yuan, et al. investigated the creep deformation of Guangzhou Luogang soft soil. They found that the soft soil of the region had obvious timeliness and creep deformation characteristics under different stress levels [12]. Yang et al. selected samples at different times in the process of creep under the microstructure test and took the changed parameters of particles and pores to study the variation characteristics of microstructure in the process of creep of the samples [13]. However, due to the complexity and quantitative testing technology of microstructure of clay soil limit, some physical and chemical properties were difficult to determine, only the micro structure from theory aspects was made the qualitative analysis, which was very difficult to be used in the engineering practice.

The ultimate goal of the study is to reveal the properties of the soil and establish a macroscopic mechanical model for the soil [14-15]. Understanding of this issue has been established since the beginning of the structural study [16-17]. However, it is of great difficulty as there is hardly one theory or mathematical tool to analyze this issue at both macro and micro levels [18]. Since current studies focus on a more micro level and get more distant from macroscopic issues [19], it is more difficulty to establish the relationship between microstructure and mechanical properties [20].

In this study, fifteen group samples of Q_2 loess under triaxial creep tests and eight group samples of scanning electron microscopy were proposed to observe the rheological properties and dynamic change of microstructure of loess with different water contents, which can provide a reference for engineering practice.

The rest of this study is organized as follows. Section 3 gives the relevant statement of loess samples and a brief introduction to prepare these samples. Section 4 presents the

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results and discussion. The conclusions are summarized in Section 5.

3. Methodology

3.1 Samples preparation

To reveal the influence of creep on slope stability and to provide theoretical and experimental basis for the prediction of landslide hazards in the loess area, the triaxial creep tests of loess with different water contents were carried out.

The test samples were taken from the typical loess area, Yan'an in Shaanxi Province. The basic physical indices of soil samples are shown in Table 1. Given that the loess had a strong discreteness, to facilitate the comparison and analysis of test results, the uniaxial creep test was carried out by single-specimen multi-level loading. The test results were processed according to the Boltzmann superposition principle [21]. The undisturbed loess samples with different water contents were prepared by the water film transfer method in the laboratory. Each sample size is φ39.1× 80 mm.

Table 1. Physical indexes of loess samples

Water content (%)	Natural density (g/cm^3)	Liquid limit (%)	Plastic limit (%)	Liquidity index	Plasticity index	Coefficient of compressibility (MPa^{-1})
12.9	1.91	27.6	17.4	-0.44	10.2	0.12

3.2 Multi-level loading test

In the multi-level loading creep test, the loading increment was determined as follows:

First, the failure stress of the soil was calculated according to the following equation,

$$\sigma_{1f} = \sigma_3 \tan^2(45^\circ + \frac{\varphi}{2}) + 2c \cdot \tan(45^\circ + \frac{\varphi}{2}) \quad (1)$$

where, σ_{1f} is the failure stress of the soil, σ_3 is minor principal stress, c is cohesion, and φ is angle of internal friction.

Second, the loading increment was calculated according to the proposed level 8-10 loading, and thus the stable loading criteria was that the deformation did not exceed 0.005 mm in 24 hours.

The loading time for each level was not less than 1000 min, and the creep rate was less than 0.005 mm per hour.

3.3 Preparation of loess with different water contents

Air drying method: soil samples are left in air for natural evaporation to the actual water content.

Water film migration method: the desired amount of water was slowly and evenly dripped into the soil sample, and then the sample was put into a saturated vessel for 2-3 days for curing. This allowed water to spread freely and evenly, so that the soil sample could reache the required water content.

The mass of water that needs to be added or reduced:

$$m_\omega = \frac{(\omega - \omega_0) \times 0.01}{1 + 0.01\omega_0} \times m_0 \quad (2)$$

where , m_ω is the mass of water that needs to add or reduce, m_0 is original mass of water, ω_0 is the actual water content, ω is the required water content.

Five different water contents were provided, which increased from the plastic limit starting. All together 15 groups of test samples were prepared, which the control water contents were 9.7%, 16.3%, 20.1%, 24.2% and saturation, and the confining pressures were 100, 200, and 300 kPa, respectively.

To obtain a more extensive statistical law, eight groups of loess samples were studied through scanning electron microscopy (SEM) during and after the tests. From the aspect of particle morphology, such as particle arrangement, pore characteristics and contact relationship, the microscopic characteristics of loess under different water contents and loads were analyzed. Then the microscopic mechanism for the macroscopic mechanical deformation of loess was revealed, which could provide scientific support for engineering practices.

4. Results and discussion

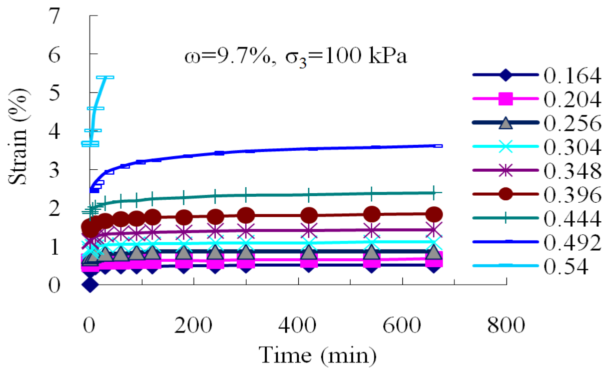
4.1 Creep characteristics of loess Q_2

As can be seen from Fig. 1, loess at Yan'an Fangta landslide zone has the following creep characteristics:

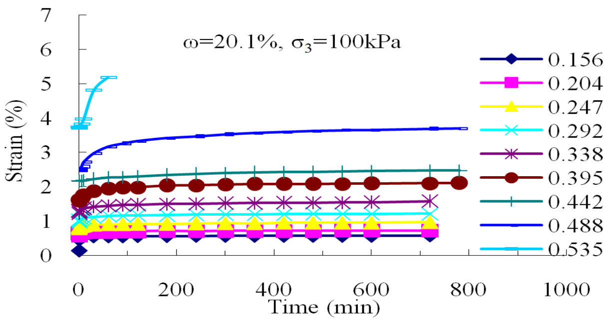
When stress was applied, the loess sample had an instantaneous deformation. As time went on, the deformation increased. In addition, the higher the stress was, the greater the instantaneous deformation and creep deformation were.

When the stress was higher than a certain critical value, the loess creep deformation developed at a constant rate. Under the action of a high stress, there would be an accelerated creep stage, which developed from generation to failure in a very short time.

For loess under the same confining pressure, as the water content increased, the loess developed faster into the destructive creep stage. Meanwhile, its instantaneous deformation increased, and failure occurred at a very low stress, especially when the loess was saturated. This shows that water is the main cause for reduction of the long-term strength of the loess and thus landslide.



(a)



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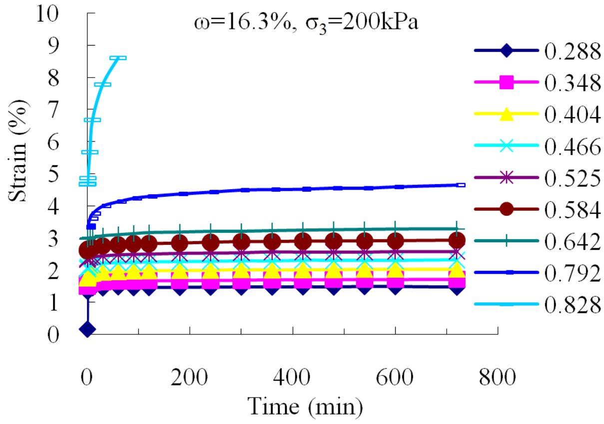

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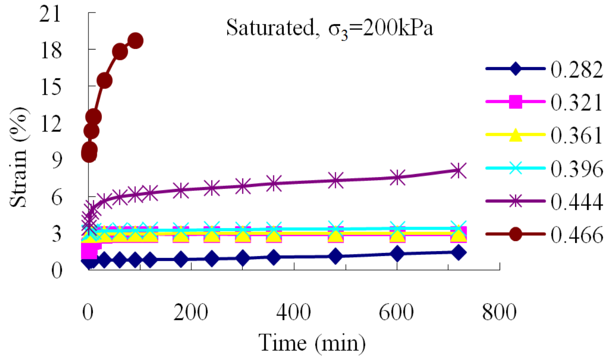

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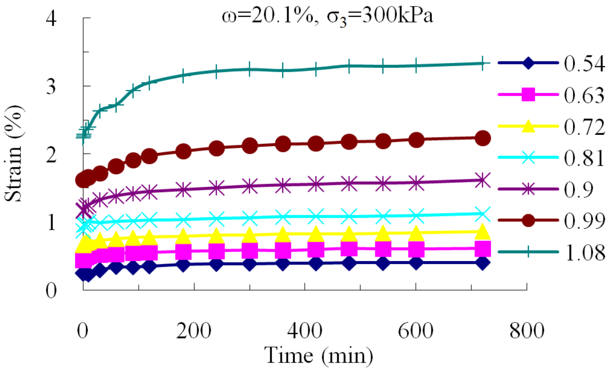

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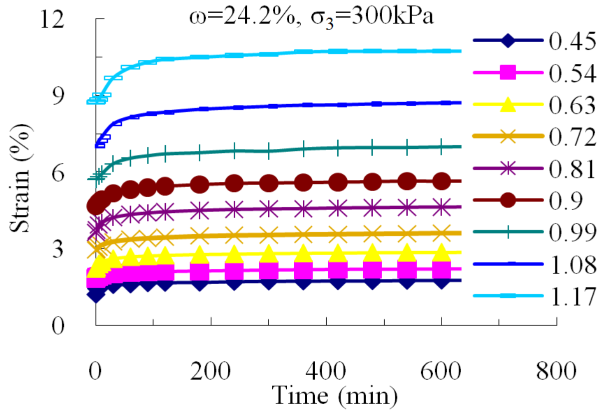


(f)

Fig. 1. Stain-time curves under different confining pressures and water contents

For the same water content, the larger the confining pressure was, the larger the instantaneous deformation was. The steeper the slope of the curve got, and the longer it took from the generation of deformation to failure. This is why the natural loess slope can maintain its long-term stability in one state.

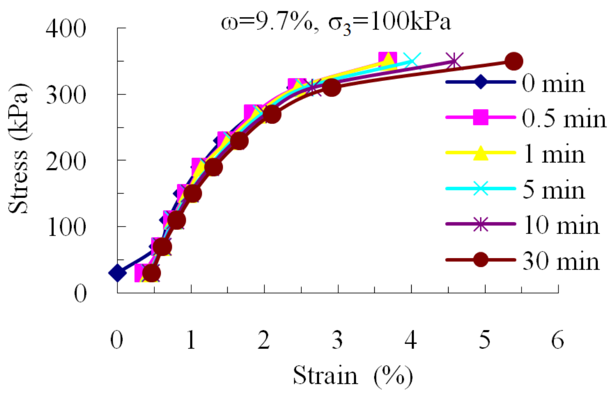
Through macroscopic observation of creep failure of loess Q_2 with different water contents (Fig. 2), it can be found that loess is compressed and slightly expanded. When it was at a low water content, brittle failure was likely to occur, which was a pure shear failure. As water content increased, the loess samples demonstrated the plastic failure. Their vertical displacement deformation was obvious, which indicated water content had a significant impact on soil deformation and failure.


(a) ω=24.4% (b) ω=9.7%

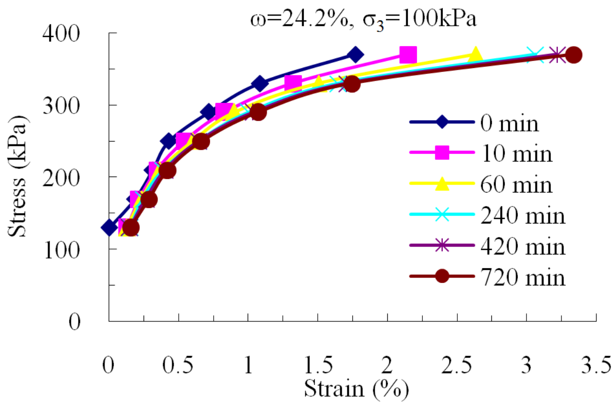
Fig. 2. Creep failure of loess Q_2 with different water contents

4.2 Isochronal stress-strain characteristics of loess Q_2

To analyze the creep characteristics of loess and the relationship between stress and strain during creep, an isochronal stress-strain curve was obtained from the creep curves (Fig. 3). It can be seen that the isochronal stress-strain curves of the loess with different water contents are fold lines. With the increasing of water content, the curves show no obvious turning point. In general, these curves have the following characteristics.



(a)



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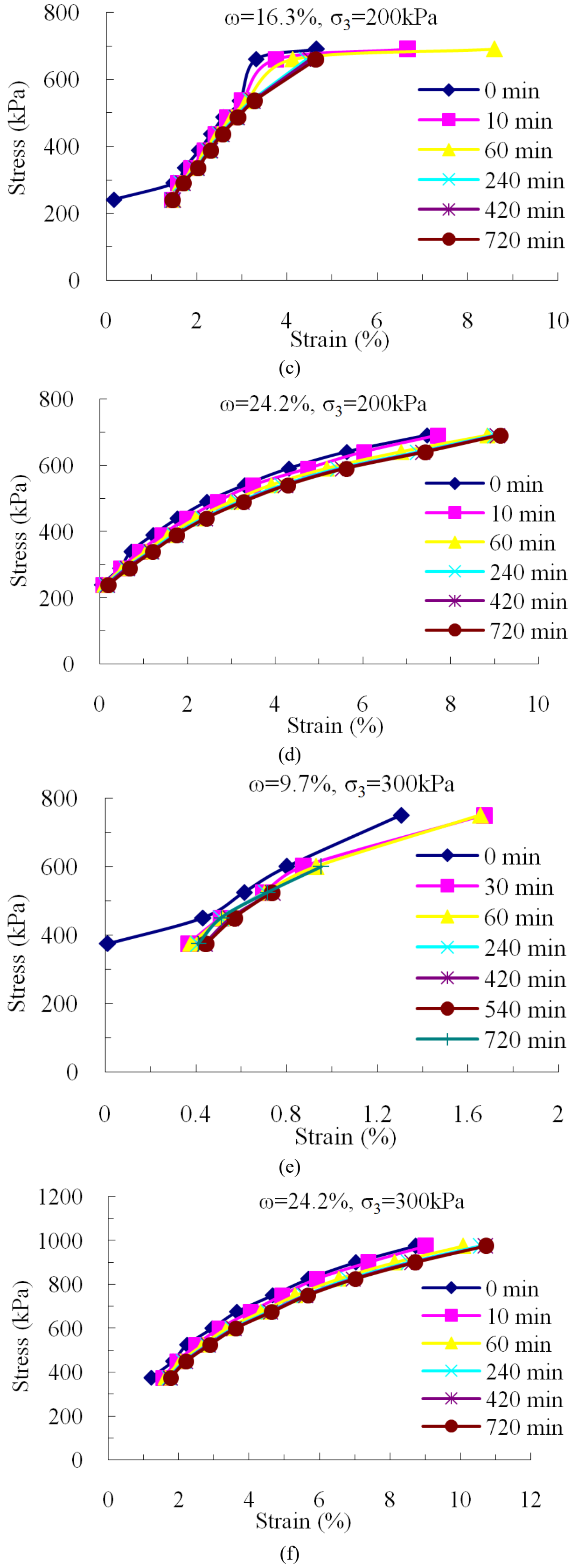


Fig. 3. Stress-strain curves under different water contents and confining pressures

The isochronal curves under different confining pressures gradually shift to the strain axis with time, which indicates the strain increases and the deformation modulus decreases over time.

Under low stress, the curve can be approximated as a straight line, which shows linear viscoelastic properties. With the gradual increasing of stress, the curve no longer changed in a linear manner, but gradually moved to the strain axis, which showed obvious nonlinear viscoplastic properties.

The isochronal stress-strain curve was linear at low stress at the moment of loading, and was almost a bunch of curves at other moments, which showed the trend of normalization. The curve indicates the loess has consistent creep deformation characteristics.

When the shear stress was less than a certain stress value, the stress-strain curve approximated to a straight line and showed approximate linear rheological properties. When the stress was greater than the yield limit, the creep deformation and deformation rate gradually increased, and the isochronal curve gradually bent toward the strain axis, showing significant nonlinear rheological characteristics. Its nonlinearity became more and more evident with time and the increasing of stress.

4.3 Mechanism of Microscopic Deformation

Through scanning electron microscopy, the microscopic deformation and creep process of loess under different loadings and water contents were analyzed. The macroscopic rheological mechanism was explained from the microscopic point of view, and the connection between microscopic deformation and macroscopic mechanical properties was established.

4.3.1 Deformation analysis under different loadings

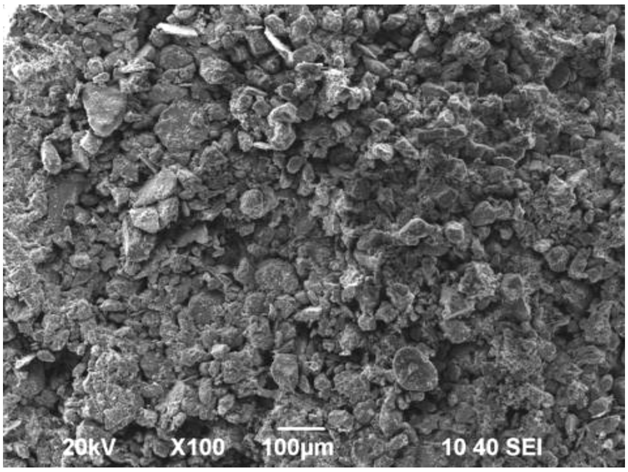
Fig. 4 shows the microscopic deformation of loess Q_2 with the same water content and under the same confining pressure at a magnification of 100x. It can be seen that in the undisturbed loess, macropores are developed, the particles are distributed randomly, and microcrystalline calcium carbonate cements are commonly seen in the pores, usually in granular shape. The basic units are mainly debris, inlaid with framework particles and pores that are cemented together. After level 1 loading was applied, the space between particles became smaller, and mineral particles were stretched and changed into more regular and oriented one; displacement of the particles was very small. In the post-failure stage, the particles were compact and distributed directionally, with scratch on their surface.

4.3.2 Deformations under different water contents

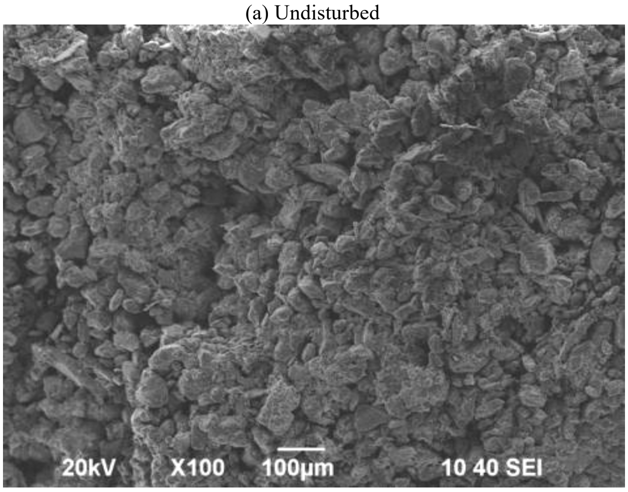
Fig. 5 illustrates the SEM images of Q_2 loess with different water contents under the same confining pressure, with the magnification of 100x. It can be seen from these images that when the water content is low, the soil particles have very clear outlines. As the water content increased, the particle boundary became less clear. The loess particles did not exist in the form of single particles, but cement together into aggregated ones. Some relatively large pores still existed in the loess. The inter-particle pores were gradually reduced, and the loess particles were gradually compacted and occupied by the pore water.

4.3.3 Loading influence on rheology

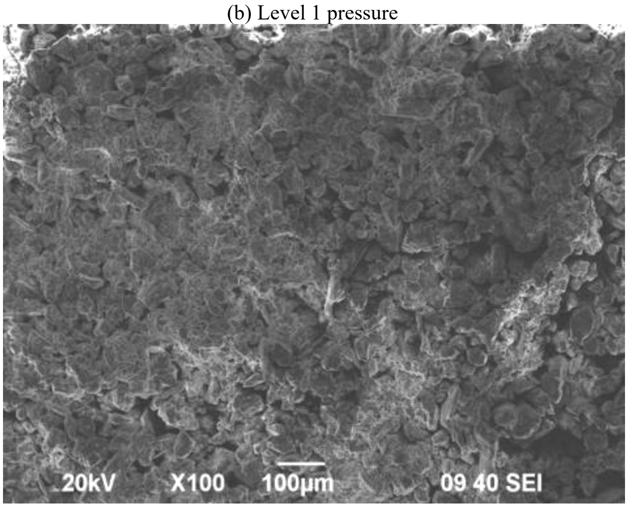
Due to the existence of large pores in the loess particles, the soil skeleton was destroyed after a certain effective stress being applied and the loess particles moved. During the moving process, some small loess particles filled into the large pores, which caused the loess porosity to decrease rapidly, which resulted in transient plastic and instantaneous elastic deformations.



(a) Undisturbed



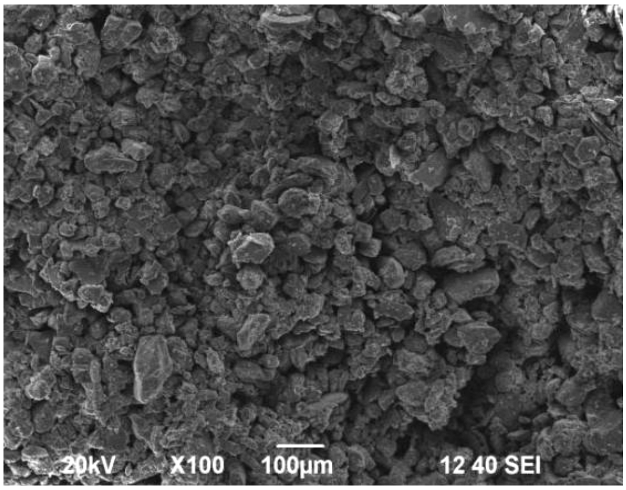
(b) Level 1 pressure



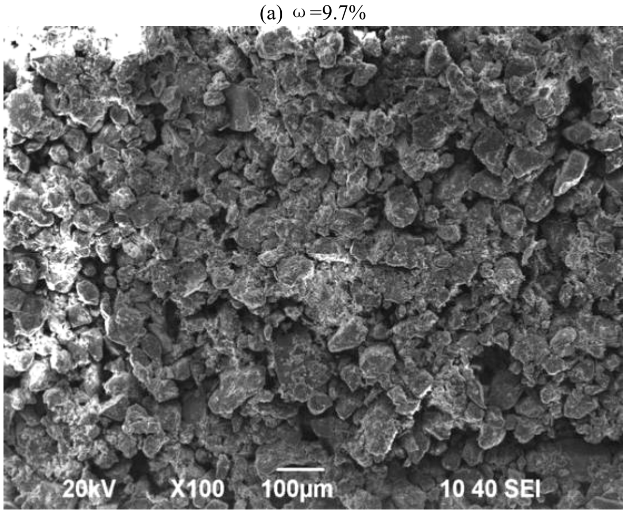
(c) Failure

Fig. 4. Micro deformation of loess Q_2 at the confining pressure of 100 kPa (magnified 100 times)

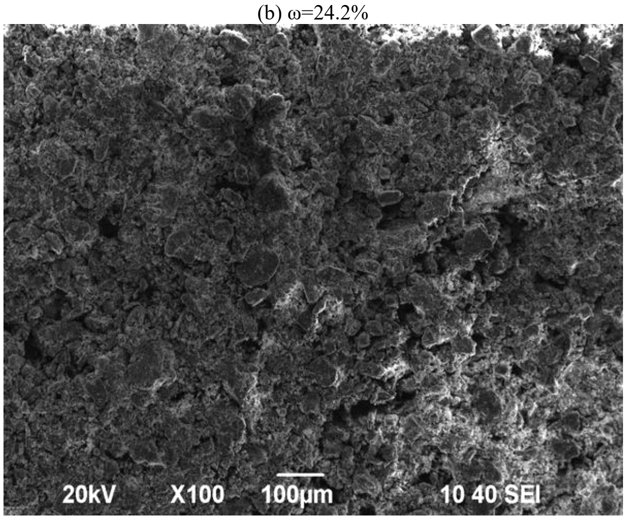
As the creep deviatoric stress increased, the inter-particle inlaying effect and friction will produced a great viscous resistance, due to the creep rate changing unevenly. With the increasing of shear stress duration, the structural unit began to present a micro-oriented arrangement. When stress was low, the creep decayed rapidly and tended to stabilize. With the increasing of loading time and stress, the strong connection between structure elements was destroyed by different degrees, and the viscous resistance decreased. With the increasing of stress and the decrease of viscous resistance, the area and the number of macropores decreased on the microscopic level, while the number of small pores increased. Then the soil became denser and laterally confined.



(a) ω =9.7%



(b) ω=24.2%



(c) Saturated

Fig. 5 Comparison of microscopic deformation of Q_2 with different water contents at confining pressure of 100 kPa

As a result, the soil sample showed hardening effect. If the load was increased and being applied for long time, the soil would become denser and the particles tend to be tightly spaced. In the end, no failure stage occurred and the creep curve showed decay stability.

5. Conclusions

In this study, Macroscopic triaxial rheological tests and microscopic scanning electron microscopy were performed on loess Q_2, Yan'an in Shaanxi Province. Based on the analysis of the test results, the following conclusions are drawn:

(1) Through macroscopic observation of creep failure of loess Q_2 with different water contents, it is found that Loess is compressed and slightly expanded. When it is at a low water content, brittle failure is likely to occur, which is a pure shear failure. As water content increases, the loess samples demonstrate plastic failure, insteading of shear failure. The vertical displacement deformation is obvious, which indicates water content has a significant impact on soil deformation and failure.

(2) The isochronal stress-strain curve is linear at low stress at the moment of loading, and which is almost a bunch of curves at other moments, that shows the trend of normalization. The curve indicates loess has consistent creep deformation characteristics.

(3) When the shear stress is less than a certain stress value, the stress-strain curve approximates to a straight line and shows linear rheological properties. When the stress is greater than the yield limit, the stress-strain curve shows an obvious turn, the creep deformation rate gradually increases. The isochronal curve gradually bends toward the strain axis, which shows significant nonlinear rheological characteristics. Its nonlinearity becomes more and more obvious over time and with the increase of stress.

(4) The micropores reveal the creep mechanism of loess. It is a process where the area and amount of macropores in the loess decrease. Small particles will regather into a new aggregate, they embed in each other and form a relatively stable structure. Connection between the particles becomes tight and the soil becomes dense. As the water content increases, free water gradually flows into the pores of the particles, which results the continuous expansion of the pores and loose bonding between these particles.

The analysis of the rheological mechanism is helpful to the understanding and in-depth study of the rheological model. However, the soil itself is a heterogeneous system, its creep property is a more complex problem, understanding of its internal characteristics and the mechanism are not clear, which need to be further in-depth researched to promote and improve the rheological analysis theory and method of soil.

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