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Experimental Research on Relation of Loess Strength Characteristics to Stress-strain

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Abstract: Based on the improved consolidometer and triaxial apparatus, this paper conducted a consolidation and compression test and a triaxial consolidation drainage test of the undisturbed loess Q3 to get experimental data on loess strength characteristics and stress-strain. An analysis of experimental data found that, when vertical pressure is added under different lateral confining pressures, there exist correlations between loess shear strength and loess stress-strain, which shows some changes rules. Then, loess microstructure and deformation mechanisms are analyzed to establish the function relation of strength characteristic indexes to water content and compression modulus respectively. Collectively, this paper has provided a complement to basic research on loess and developed the engineering mechanics theories in loess engineering construction.

Keywords: *Loess, Structure, Strength Characteristics, Stress-strain and Function*

1. Introduction

In China's development of central and western regions, the midstream area of the Yellow River is a priority area for the construction of transportation infrastructure and energy engineering, where the earth's surface is almost completely covered by loess that is well developed and continuously distributed with a wide area, complete stratums and great thickness. Correct understanding of the physico-mechanical and engineering properties of loess is of profound significance to rationally develop and employ it. For this reason, loess has been a key object of study in such fields as geology and engineering, with fruitful results yielded. Even so, special soil structure and engineering properties of loess have led to some deviations of test data and calculation results from engineering practice. As a result, loess areas are still plagued by frequent geological disasters and engineering accidents which has restricted the development of engineering construction in loess areas.

An important factor influencing loess strength characteristics lies in its special structure. Zhu-Jiang Shen, an academician Chinese Academy of Sciences, has proposed that research on soil structure is a core issue of soil mechanics in 21st century. Natural soil masses are all structural. As a typical structural soil, loess has something in common with other soil masses in deterioration ways featuring sudden change, discontinuity and irreversibility. But the unique structural features make loess unique in the conditions, mechanisms and processes of deterioration. For a long time, there has been much research on the relation of loess structure to mechanical properties of soil mass, including relative tests analyzing the influencing factors for the mechanical features of loess [1, 2], statistical research on the analysis of correlation and variability of loess physico-mechanical properties [3], research on the relation of loess strength to microstructure [4,5], research on evaluation methods of collapsible loess structure [6,7,8], research on the relation of loess structure to collapsibility in engineering geological problems [9,10,11], research on the influences of loess structure on slope stability [12,13], relation of loess structure to its bearing capacity and deformation [14,15], etc. Currently, Hu Na [16], Tian Kanliang[17], Chen Kaisheng[18], Wang Yongzhong[19] and Xie Dingyi[20] have successively performed compression tests with lateral confinement, compression tests without lateral confinement and triaxial tests of expensive soil, salinized soil, frozen soil and loess. Besides, they have been proposedquantitative parameters that can reflect the structure of various kinds of soil, making research on soil structure reaching a new level.

In this paper, we conducted a triaxial test and a consolidation compression test of Q_3 loess of Jinnan Region. When analyzing and arranging test data, we found that there exists a correlation between loess strength characteristics and stress-strain. Based on further research on the mechanical properties of loess, this paper is aimed at exploring the law special loess structure affecting its strength characteristics and stress-strain and making a practical study of the structure and mechanic mechanisms of undisturbed loess, so as to provide a basis for the rational development and construction of loess areas.

2. Determination of test scheme

2.1. Sample selection

At present, research on loess primarily concentrates on northwestern China, but regional differences cannot be ignored due to the wide distribution of loess. Western China mainly sees eolian loess in the Loess Plateau in Gansu Province and Shaanxi Province and eastern China mainly sees hydrogenic loess in the North China Plain, while there is a combination of eolian and hydrogenic loess in Jinnan Region, Shanxi Province. This paper researches loess in Jinnan Region, where loess, mainly Quaternary Pleistocene loess, is well developed with widely distributed accumulations and continuous earth surface, covering four of seven China's engineering geology zones of collapsible loess, namely Zone Ⅱ, Ⅲ, Ⅳ$_1$, Ⅳ$_2$. The maximum loess thickness is 80~150m, while the thickness of collapsible loess reaches 20~30m, with collapsible grade and category ranging from Level Ⅰ (None-self-weight) to Level Ⅳ (Self-weight).

Selecting loess for test use: ① There is a need to select sample from Jinnan Region of Shanxi Province and sample position is required to cover Zone Ⅱ, Ⅲ, Ⅳ$_1$, Ⅳ$_2$ of engineering geology zones; ② Selected sample is required to be undisturbed loess with the same great soil group and soil layer; ③ Prepare sample and test the physical and mechanical properties of undisturbed soil sample.

In this paper, the selected soil samples are Q_3 loess-like silt, the color of which ranges from light-yellow to yellowish-brown. Moreover, the soil is not only relatively uniform and porous with vertical joints, but develops with macropores, covering a slight to medium soil compaction.

Table 1: *Physical and mechanical property indexes of loess in southern Shanxi*

Engineering geology zones	Natural water content (%)	Average dry density (g/cm^3)	Void ratio	Plastic limit (%)
Zone II	7.57～11.33	1.42	0.84～0.93	16.88～17.31
Zone III	10.1～11.28	1.42	0.86～0.93	17.03～17.22
Zone IV$_1$	10.99～11.41	1.42	0.86～0.94	16.31～18.55
Zone IV$_2$	9.59～11.41	1.42	0.91～0.98	16.31～18.56

2.2. Test scheme

2.2.1. Test scheme selection

The strength-deformation characteristics of loess reflect a combination of stabilizability and variability of loess structure. The triaxial and compression tests are two commonly used test methods. A triaxial consolidation drainage test means that strain-stress changes of soil mass can indicate soil strength characteristics in case of lateral confining pressure changes, while a consolidation compression test shows the relation of vertical stress to soil deformation under lateral confinement. Both tests can present data indirectly reflecting the structural features of loess and loess structural decay. This research follows the conventional test methods, namely the laterally confined consolidation compression test and triaxial consolidation test.

2.2.2. Sample selection principles

The plastic limits of selected soil samples in four engineering geology zones in Jinna Region are all between 16.31% and 17.31%. Therefore, the selected samples have a water content of 11%, 15%, 19% and 23%.

Water-film transfer method or air-dry is used to prepare the water content of soil samples. That is to say, when moisture content of the samples is below the required, there is a need to moisten by adding water once or by several times to the samples with a burette based on calculated extra water amount. When the water content meets the requirement, we wrap up the samples with plastic films and place them in a moisture-retention jar for over 48 hours to keep moisture even. When the samples need to be dehumidified, air-dry is used to meet the required moisture content. Similarly, there is a need to wrap up the samples with plastic films and place them in a moisture-retention jar for over 48 hours to ensure full diffusion of moisture. In the process of air-dry, volume shrinkage of the samples is not allowed.

2.2.3. Test methods

A triaxial test was conducted to measure the relation of strength characteristics and stress-strain, namely to calculate the C and φ value of soil mass, while a laterally confined compression test was performed to calculate loess strength parameters and consolidation coefficients.

Test apparatus includes a level-type consolidometer and a triaxial apparatus which are produced by an Apparatus Engineering Co., Ltd. in Jiangsu Province. Improvements were made in the two kinds of apparatus. The level-type consolidometer was improved in the overall level pressure system (porous stones included), namely platform scale and level pressure equipment. When performing a laterally confined consolidation compression test, we exerted vertical pressure on four undisturbed samples with different water content. The pressure ratings are 25kPa, 50 kPa, 100 kPa, 200 kPa and 400 kPa, under which we measured the relation of deformation of soil samples to the exerted pressure until samples became stable.

The test used large-scale true triaxial apparatus independently developed by the Geotechnical

Engineering Institute of Xi'an University of Technology. There were partial modifications of the apparatus. Then, we performed a triaxial consolidation drainage test, with confining pressure being 50 kpa, 100 kpa, 200 kpa and 400 kparespectively. When the samples were installed in the triaxial cell, we opened the drain valve for consolidation. Upon consolidation, we started motor to shear the samples and shut down the motor until the reading of the axial deformation dial gage reached 12mm.

3. Test results and analysis

3.1. Change trend for the loess strength characteristics

3.1.1. Change trends for stress-strain curves under a triaxial test

There are 24 loess samples with the same water content (6 for each engineering geology zones respectively) conducted the triaxial consolidation drainage test to calculate data of loess stress-strain under different confining stresses. Because physical and mechanical property indexes of loess samples have variable coefficients less than 0.015, the selected samples can be deemed to be uniform based on similarity principle of statistics.

Fig.1 ~ Fig.4 are stress-strain curves for loess with different water content

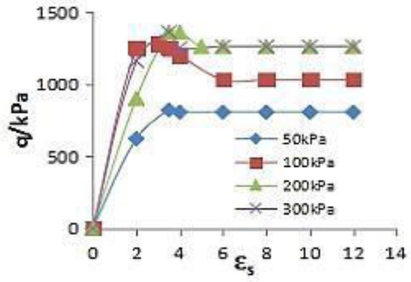

Fig.1: *Loess (W=11%) stress-strain curves*

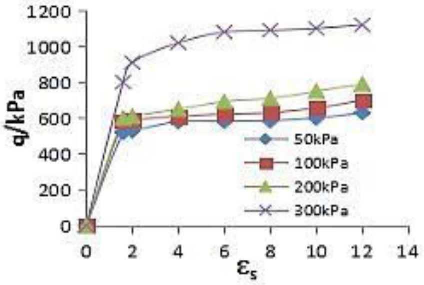

Fig.2: *Loess (W=15%) stress-strain curves*

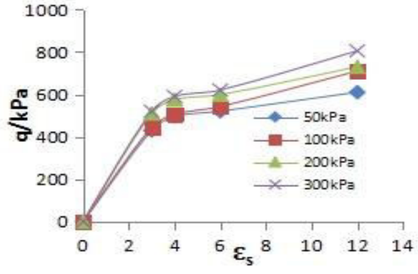

Fig.3: *Loess (W=19%) stress-strain curves*

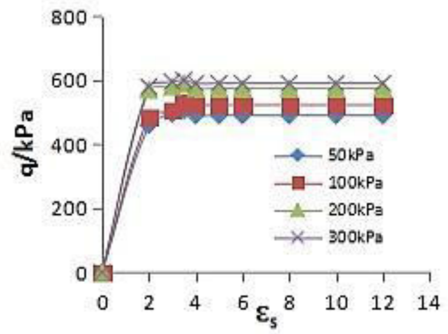

Fig.4: *Loess (W=23%) stress-strain curves*

Fig.5 ~ Fig.8 show the change rules for stress-strain of undisturbed loess with different water content under the same confining pressure.

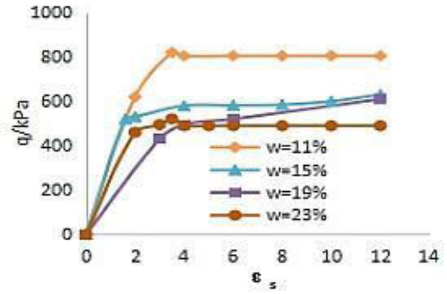

Fig.5: *Loess stress-strain (σ_3=50kpa) curves*

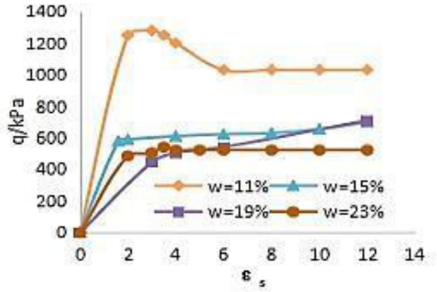

Fig.6: *Loess stress-strain (σ_3=100kpa) curves*

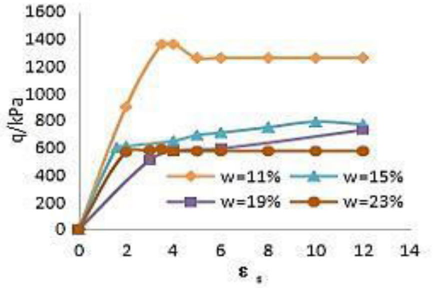

Fig.7: *Loess stress-strain (σ_3=200kpa) curves*

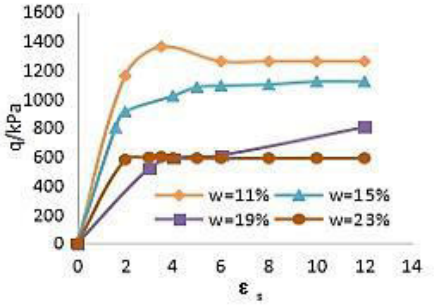

Fig.8: *Loess stress-strain (σ_3=300kpa) curves*

As can be seen from Fig.1 ~ Fig.4, when water content is high, stress-strain curves are hardening; when water content is low, stress-strain curves are softening.

Fig.5 ~ Fig 8 indicate that, under the same confining pressure and stress conditions, the lower the water content, the less is the strain value. Besides, in case of the same confining pressure and deformation, the lower water content of the loess, the larger stress value needs to be added. When the undisturbed loess is destroyed or deformed, the stress needed decreases with the increase of water content, which demonstrates that loess stress is sensitive to water in case of high moisture and it is less sensitive in case of low moisture.

This is because, under confining pressure, soil mass has compaction effects which tend to be obvious with the increase of confining pressure. More closely arranged interior particles of soil indicate greater strength.

3.1.2. Change trend for loess strength characteristics

Based on stress and strain value shown in Fig.1 ~ Fig.8, an envelope figure is drawn for shear stress and strain of loess with different water content. Slopes and intercepts of envelopes are mathematical statistics value of scatters of 24 loess samples, showing the shear envelope of undisturbed loess. The y-axis intercept is c value measuring the strength characteristic cohesion and the included angle between envelops and the x-axis is internal friction angle. Fig.9 and Table 2 show the change trend for strength characteristic indexes of loess with different water content.

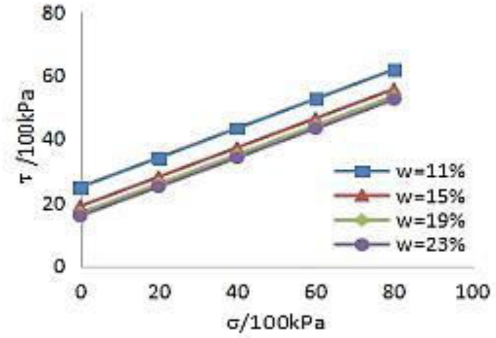

Fig.9: *Envelopes for shear strength of loess with different water content*

Table 2: *Strength characteristics change of loess with different water content*

Shear strength	11%	15%	17%	19%	23%	38.5%
Cohesion(kpa)	25	19.0	17.4	17	16	13
Change		-1.5	-0.8	-0.2	-0.25	-0.19
Internal friction angle	24.78	24.7	24.66	24.62	24.54	21.6
Change		-0.02	-0.02	-0.02	-0.02	-0.19

As shown in Fig.9, with the increase of water content, shear strength of the same soil mass changes as follows: when soil water content increase, soil cohesion is on the decrease at a slowing-down rate, but internal friction angles show small changes. As can be seen from Table 2, when water content is lower than the plastic limit, strength index cohesion c declines significantly with the increase of water content; otherwise, cohesion tends to be leveling off, with a definite change of -0.2. But the friction angle is on a linear decrease as water content increases.

The changes of 24 groups of shear strength c and φ value are drawn to fitted curves, as shown in Fig.10 and Fig. 11.

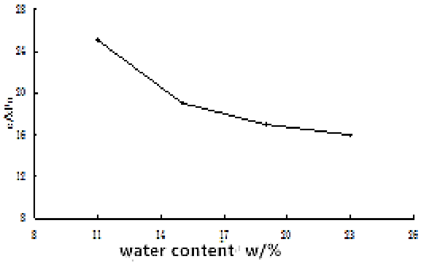

Fig.10: *Fitted curve for the relation of strength index c water content w*

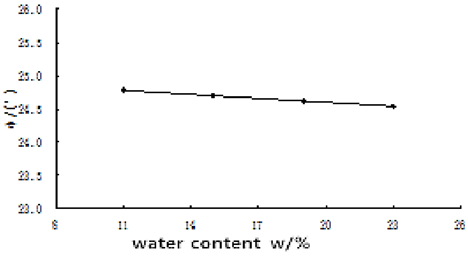

Fig.11: *Fitted curve for the relation of strength index φ to water content w*

As shown in Fig.10, when water content is lower than the plastic limit, cohesion decreases with the rising water content and the fitted curve changes can be approximately expressed as an exponential curve; on the contrary, cohesion presents a linear decrease and the fitted curve changes can be written as a linear function. As shown in Fig.11, cohesion and internal friction angle at a certain point can be calculated as:

$$c=-18.8\ln 100w+70.12 \qquad w<wp \qquad (1)$$

$$c=c_{wp}-A(w-wp) \qquad w\geq wp$$
$$\varphi=\varphi_{wp}-B(\varphi-\varphi_{wp}) \qquad (2)$$

Where, c is the cohesive value;

W is the soil water content (%);

c_{wp} is cohesion of soil plastic limits;

A is the coefficient of soil property (Q3 loess-like silt of Jinnan Region stands at 20);
φ represents the value of internal friction angle at a certain water content;
Φwp is the internal friction angle value of soil plastic limits, and B is the coefficient of soil property (Q3 loess-like silt of Jinnan Region stands at 0.02)

3.2. Change trend for soil stress-strain under fixed confining pressure

Without lateral expansions, the loess-like silt with different water content was conducted the consolidation compression test in a consolidometer. Table 3 shows the test results.

***Table 3:** Change trend for soil stress-strain compression modulus in case of different water content (Unit: Mpa)*

Parameter	0~50kPa	Change	50~100kPa	Change	100~200kPa	Change	200~400kPa	Change
11%	1.36		1.41		1.68		2.44	
15%	0.95	-10	1.00	-10	1.42	-7	2.33	-2.75
19%	0.77	-4.5	0.85	-4	1.22	-5	2.24	-2.25
23%	0.69	-2	0.78	-2	1.05	-3.4	2.19	-1.25

Under various levels of pressure, compression modulus curves of loess with different water content were drawn (see Fig.12).

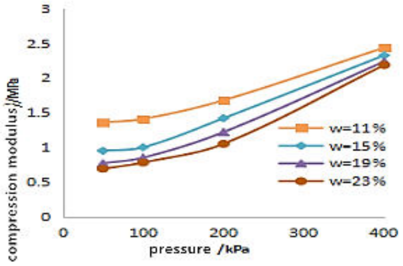

***Fig.12:** Compression modulus curves of loess with different water under various levels of pressure*

As can be seen in Table 3 and Fig.12, in case of the same water content, loess compression modulus, as a strength characteristic index, increases along with pressure and the change tends to decrease; in case of the same pressure range, compression modulus falls with the increased water content. Within the same variation range of pressure, a smaller compressive deformation of loess means a greater compression modulus.

3.3. Mechanism analysis of the relation of loess structure and strength characteristics to stress and strain

Q_3 loess-like silt of Jinnan Region has significant structural constitutive structure, microstructure of which is a typical granules - contact - aerial structure or granules - contact - aerial /mosaic structure [22]. All loess samples have a macrostructure that is a skeleton unit of clastic particles, with only a small amount of cement. From shallow to deep strata, connection between skeleton particles shifts from point to surface, but there are unstable aerial pores in pores formed due to the arrangement of skeleton particles. The granule structure featuring a combination of point contact and aerial pores remain to be very unstable. Soil deformation has a correlation with both the number and size of aerial pores.

The following describes the influence mechanism of loess water content on soil structure. At the contact points of particles appears a small amount of cement, composition of which is mainly chemical substances that are common lyotropic ions in sedimentary rocks on crustal surface, including potassium ions, sodium ions, calcium ions and some free iron ions. Those ions may ionize and dissolute when reacting with water for their relatively active chemical properties. As soil water content goes up, there are more dissolved ions and less cement attached to particles. With the thickening water films between granules, there exist double-film electrostatic interactions. As a result, under applied stress, loess with high water content is subject to great strain, low strength and easily destructive structure.

According to the above analysis, under vertical stress and the lateral confining pressure, there is displacement of soil particles, exhausted air and lost moisture in aerial pores as well as increased soil compaction. As the applied load stress increases, there is a gradually greater strain and compression modulus. Soil has compaction effects under confining pressure. With the upward confining pressure, compaction effects tend to be increasingly significant and internal soil particles are arranged more closely, indicating a greater strength.

3.4. Correlation between stress-strain and loess strength characteristics

We study the consolidation and compression modulus of undisturbed loess (200kPa-400kPa) to draw a curve showing the relation of cohesion c, a stress-strain shear strength index, to compression modulus.

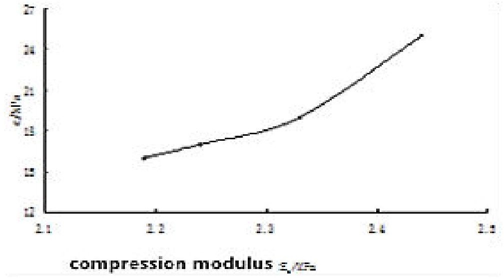

***Fig.15:** Relation curve of strength index c to compression modulus*

As shown in Fig.15, strength characteristic index c increase along with greater compression modulus, the value of which represents the compaction of soil particles arrangement. A greater compression modulus means a less consolidation and compression, smaller porosity and greater structural strength. Meanwhile, soil stress-strain shear strength becomes greater, but has negative correlation with water content. Such change trend can be compared with the rest groups of samples concerning the correlation between water content, loess structural strength and stress-strain index c.

Likewise, we study the consolidation and compression modulus of undisturbed loess (200kPa-400kPa) to draw a curve showing the relation of strength characteristic index φ to consolidation and compression modulus.

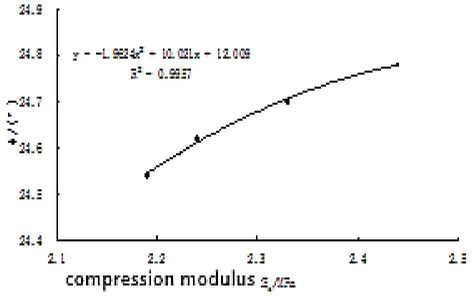

Fig.16: *Relation curve of strength index φ to compression modulus*

Fig.16 indicates that, with the growth of consolidation compression modulus, soil internal friction angle highlights a rising trend. Fitting the relation curve of strength index φ to compression modulus can be written as:

$$\phi = -1.9624(E_s)^2 + 10.021E_s + 12.009 \qquad (3)$$

When, $E_s \to 0$, shear strength characteristic index φ has the minimum value, which is consistent with the practical situation. The derivation of Eq. (3) can be calculated. When $E_s = 2.55$, φ has the maximum value of 24.8°. This demonstrates that internal friction angle cannot increase infinitely along with greater compression modulus and there exists a critical value.

3.5. Conclusions

In this paper, a lateral-confinement compression test and a triaxial consolidation drainage test were conducted to analyze the change trend for the relation of Q_3 loess structural strength characteristics to stress and strain. Furthermore, the special loess microstructure is analyzed to interpret the inherent mechanism of strength changes and growing trend for stress and strain. The paper has provided basis for selecting constitutive models, using appropriate mechanical parameters and rationally developing and employing soil in engineering construction in loess areas. Nonetheless, presented research is only limited to Q_3 loess-like silt of Jinnan Region, Shanxi Province, and on this basis, the following describes what remained to be further researched.

(1) This paper studies Q_3 loess-like silt in Jinnan Region, where there is still loess-like silty clay that differs greatly with silt in particle composition, aerial structure of skeleton and cement. It is suggested to carry out further research;

(2) There is a need to explore the loess structural strength in other areas of Shanxi Province and study factors influencing structural strength;

(3) It is suggested to research and explore the structural properties of Q_2 and Q_4 loess in Shanxi Province;

(4) Loess parameters and properties are studied to provide data support for the research on loess both in China and the world at large, improve engineering construction quality and reduce damages.

Acknowledgements

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