Mechanical Properties and Microcosmic Analysis of Undisturbed Loess in Xining Area with Different Moisture Content

Jingyu Cui, Yu Liu, Banglong Xie, Wuyu Zhang*

School of Civil Engineering, Qinghai University, Xining 810016, Qinghai

*Corresponding author’s e-mail: qdzwy@163.com

Abstract. Aimed at researching intact loess mechanical properties in Qinghai area, this paper analyses these parameters through consolidated and undrained triaxial tests and SEM tests, and tests results are fitted linearly. The results show the maximum deviatoric stress increases with the increase of confining pressure when loess moisture contents are same. SEM images of loess clearly illustrate the close relative between moisture content and the pore distribution. The relationship between water content and shear strength index $c$ and $\phi$ and ratio of pore area is nearly linear. Through using moisture content parameters, loess strength and pore ratio can be deduced by fitting linearly formulation, which has certain reference significance to the local engineering construction.

1. Introduction

Loess is widely distributed in Songliao plain, northwest and north of China, covering an area of about 635,000 km$^2$, accounting for about 6.6% of the total land area[1]. Most of loess is collapsible, and collapsibility is closely related to the mechanical properties of intact loess. Therefore, it is necessary to research the influence of water content on the structure and mechanical properties of loess.

Recent years, many scholars related moisture and every mechanical property and conducted lots of deep research. Through comparing shear strength of saturated and unsaturated loess, Ma obtained the effect of moisture content on the shear strength of loess[2]; Feng conducted the torsional shear tests with different moisture content loess specimens to research the mechanism of moisture content in torsion shear by hollow cylinder torsion shear apparatus[3]; through the study of the humidifying of unsaturated loess shear test, Tai obtained the performance changing of loess humidifying process[4,5]; the relationship between the moisture content and the shear strength of the soil was systematically obtained by Li through the shear tests of the remolded loess specimens under the control of different moisture content and dry density[6-10].

Although many scholars have made extensive and in-depth studies on loess, the nature of loess can not be generalized, and its experimental conclusions are often regional. Therefore, in order to consummate the theory of the influence of moisture content on the shear strength of loess, this paper takes the loess of Xining as the research object to explore the influence of moisture content on the mechanical properties of local intact loess, and explain mechanism from the microscopic perspective.

2. Experiment

2.1. Experiment material
The loess used in this experiment was selected from Qinghai university in Xining, Qinghai province, China. The loess was homogeneous and its basic physical properties were measured through laboratory tests, as shown in table 1.

| Soil depth/m | ω/% | ρ/g·cm⁻³ | dᵢ | e | ωᵢ%/ | ωᵢ/L% | Iᵢ | Iᵢ/L |
|-------------|-----|-----------|-----|---|-------|--------|----|------|
| 4           | 8.81| 1.604     | 2.71| 0.84| 15.78 | 25.98  | 10.91| -0.31 |

2.2. Experiment plan

2.2.1. Triaxial shear test. Obtaining loess mechanical parameters under different conditions through shearing consolidated and undrained intact loess specimens under different moisture contents. Setting three kinds of moisture contents: 10%, 15%, 20% and three confining pressure: 50kPa, 100kPa, 150kPa.

2.2.2. SEM experiment. In the microscopic electron microscope scanning tests, the specimens with typical relative properties in the tests with different moisture contents and confining pressure will be scanned, and the specimens would be scanned are shown in table 2.

| The sample number | ω/% | σ₃/kPa |
|-------------------|-----|--------|
| #1                | 10  | 50     |
| #2                | 10  | 100    |
| #3                | 10  | 150    |
| #4                | 20  | 50     |
| #5                | 20  | 100    |
| #6                | 20  | 150    |

2.3. Experiment method

2.3.1. Triaxial shear test. The intact cylinder loess specimens were made as height of 80 mm, 39.1 mm diameter by cutting plate, and the moisture content of redundant loess which was cut down was measured. Covered cylinder specimens with three valves, natural loess moisture contents supplement to the regulation moisture content as 10%, 15%, 20%. Then placing the sealed samples in the saturator and infiltration for three days in order to make the whole sample moisture content uniformity. After the samples are fully infiltrated, the samples were taken out and conducted the consolidated and undrained triaxial shear test by SLB-1 stress-strain controlled triaxial shear permeation apparatus manufactured by Nanjing soil instrument factory. The axial strain of failure standard is 15%.

2.3.2. Microscopic scan experiment. Six specimens were cut into a long strip of sample size as 2cm×2cm×1cm and sculpted a scratch along the long side of the middle line location, then drying specimens for 8 hours at 105 ℃ in the oven. After the time was up, the samples were taken out, broken apart along the long side scratch and then sprayed gold to the specimens to increase the conductivity. Finally, the samples were sent to JSM-6610LV electron microscope for microscopic scanning.

3. Results and discussion.

3.1. The deviator stress-strain relationship of intact loess with different moisture content and confining pressure
When the moisture content is 10%, 15% and 20%, the deviation-stress strain curves of the samples under the confining pressures of 50kPa, 100kPa and 150kPa are shown in figure 4.
According to the figure 1, the deviative-stress-strain curve of intact loess presents strain hardening type under all kinds of conditions. With the same water content, the maximum deviatoric stress increased with the increasing of confining pressure. And with the same confining pressure, the maximum deviatoric stress decreased with the increasing of water content. When the confining pressure is big, the specimen was constrained by lateral constraints, which limited the lateral deformation of the loess sample and drove the deform toward the axial direction. Therefore, the ability to resist the axial load is improved. When the water content increased, the spatial distance between soil particles becomes more indirect, the mechanical bite force between them became weak, and the bond strength decreased, so the loess strength and the maximum deviatoric stress also decreased.

3.2. Shear strength index of intact loess under different moisture content

According to Moore-coulomb theory, get common tangent of Molar stress circle through the test data of loess under three confining pressure, obtained the loess shear strength index $c$ and $\phi$ and soil moisture content had a great effect on $c$ and $\phi$, shown in figure 2, cohesion of intact loess decreased obviously.
with the increasing of moisture content. Through fitting linearly of three cohesion of loess under different moisture contents, fitting equation was obtained:

\[ c = 46.375 - 1.722 \omega, \quad R^2 = 0.958 \]  

(1)

Internal friction angle increased slightly with the increasing of moisture content and it’s not obvious, shown in figure 3. Through fitting linearly of three internal friction angle of loess under different moisture contents, fitting equation was obtained:

\[ \varphi = 30.040 - 0.189 \omega, \quad R^2 = 0.908 \]  

(2)

According to the upper equations, the strength index of intact loess has an extremely close linear relation with moisture content, so loess strength index can be deduced by natural moisture content of intact loess.

3.3. Relationship between moisture content and maximum deviatoric stress

It can be seen from figure 4 that both water content and confining pressure are factors which affecting the maximum deviatoric stress. When the moisture content is 10%, the maximum deviatoric stress under the confining pressure of 50kPa decreased about 48.6% when confining pressure is 150kPa, and when the moisture content is 15% and 20%, this data decreases by 51.6% and 56.7% respectively. When confining pressure is 50kPa, the maximum deviatoric stress of the specimen with 20% moisture content is reduced by 35.8% compared with that with 10% moisture content. When confining pressure is 100kPa and 150kPa, this parameter is 29.1% and 23.7% respectively. From the test data, the effect of confining pressure on the maximum deviatoric stress is more obvious.

3.4. Relationship between quantitative analysis of microscopic image and moisture content

All images taken by microscopic scanning were quantitatively analyzed by using the particle and crack image recognition and analysis system (PCAS). In the process of analysis, the original microscopic images were firstly binarized (see figure 5), then vectorized (see figure 6). Finally, the parameter of pore area ratio \( P \) was obtained. The \( P \) value represents the ratio of the pore area to the total area in the image, ranging from 0 to 1. The closer the \( P \) value to 1, the larger the pore area is. The quantitative results of this microscopic scanning are shown in table 3.
Table 3. Quantitative results of microscopic tests

| The sample number | \( \omega /\% \) | \( \sigma_3 \)/kPa | \( P \) |
|------------------|-----------------|-----------------|---|
| #1               | 10              | 50              | 0.4927 |
| #2               | 10              | 100             | 0.4714 |
| #3               | 10              | 150             | 0.4510 |
| #4               | 20              | 50              | 0.4625 |
| #5               | 20              | 100             | 0.4366 |
| #6               | 20              | 150             | 0.4178 |

It can be clearly seen from the above figure that the moisture content and confining pressure have a significant impact on the porosity of the intact loess. With the same moisture content, the proportion of pore area decreases with the increasing of confining pressure, while with the same confining pressure, the proportion of pore area decreases with the increasing of moisture content. Linear fitting was performed on logarithmic data points (see figure 7 and 8), and the following fitting equation was obtained:

\[
\begin{align*}
\text{When } \omega = 10\% , & \quad P = 0.513 - 4.17 \times 10^{-4} \sigma_3, \quad R^2 = 0.998 \\
\text{When } \omega = 20\% , & \quad P = 0.484 - 4.47 \times 10^{-4} \sigma_3, \quad R^2 = 0.983
\end{align*}
\]

Figure 7. Relationship between pore area ratio and confining pressure at a moisture content of 10%  
Figure 8. Relationship between pore area ratio and confining pressure at a moisture content of 20%

4. Conclusion

(1) For intact loess with different water contents in Xining, under low confining pressure, its deviator-stress strain curve presents strain hardening type, cohesion decreasing with the increasing of water content, internal friction angle increasing slightly with the increasing of water content, and the holitic shear strength decreasing.

(2) Based on the analysis of the data, it can be deduced that the moisture content has obvious regularity on shear strength index \( \phi \) and \( c \), loess from the same area has similar properties. the fitting equation concluded through experimental data between moisture content, \( c \) and \( \phi \) values, can be used to predict the of shear strength of regional loess.

(3) Water content is closely related to the pore structure of loess. The higher the moisture content of loess, the smaller the porosity area. However, the resulting loess compactness does not represent the improvement of loess strength.

Acknowledgements

This study was supported by the National Natural Science Foundation of China (Grants No.51768060), the Fundamental Research Program and the Cooperation Program of Qinghai Province (Grants No. 2017-ZJ-792 and No.2017-HZ-804), and the Technological Innovation Service Platform of Qinghai
Province (Grants No. 2018-ZJ-T01). The Civil Engineering Innovation Fund of Qinghai University (TC2019-02). The authors would like to thank all the supports.

References

[1] Xie, D. Y., Xing, Y. C. (2016) Soil Mechanics for Loess Soils. Higher Education Press. Beijing

[2] Ma, J. Y., Chen, Y. B., Zhu, F. et al. (2018) Comparison of shear strength between saturated and unsaturated loess. J. Scientific and Technological Innovation, 10: 96–98

[3] Feng, Y. Z., Zhang, W. Y., Ma, Y. X., et al. (2018) Experimental study on stress–water content–strain relationship of remolded loess under directional shear stress path. J. Journal of Qinghai University, 01: 47–53

[4] Tai, J. (2016) Experimental study on the shear characteristics of an unsaturated loess. J. Soil Eng. and Foundation, 30(03): 391–394

[5] Ou, X. P., Li, Li, T., Chen, M. L. (2016) Research on the collapsible loess’s humidifying mechanical properties based on the triaxial tests. J. Journal of wuhan university of technology, 38(06): 49–54

[6] Li, B. P., Wang, Z., Hu, B. (2017) Triaxial test study on shear strength of remolded loess in guanzhong area. J. Yangtze River, 48(S2): 227–230

[7] Yang, P., Wu, M. H., Xu, D. X. (2015) Laboratory test on effect of moisture content on deformation characteristics of remolded loess. J. Journal of Engineering geology, 23(06): 1066–1071

[8] Wang, M., Zhang, W. Y., Chang, L. J., et al. (2016) Effects of moisture content and dry density on strength of remolded loess in Qinghai. J. Journal of Qinghai University, 34(02): 5–11

[9] Zhang, K., Li, M. Z., Yang, B. B. (2016) Research on effect of water content and dry density on shear strength of remolded loess. J. Journal of Anhui University of Science and Technology(Natural Science), 36(03): 74–79

[10] Liang, Y., Du, X. (2016) The Influence of Water Content on the Mechanical Properties of Undisturbed Loess’Cohesion and Angle of Internal Friction under the Lateral Unloading Condition. J. Science Technology and Engineering, 16(18): 234–237