Collapse Behavior and Microstructural Change of Loess under Different Wetting-Drying Cycles

Kang-ze Yuan¹, Wan-kui Ni¹* and Xiang-fei Lü¹,²*

¹Department of Geological Engineering, College of Geological Engineering and Geomatics, Chang'an University, No.126 Yanta Road, Xi'an, Shaanxi 710054, P.R. China
²School of Environmental Science and Engineering, Chang’an University, No. 126 Yanta Road, Xi’an, Shaanxi 710054, P. R. China

*Corresponding author. E–mail addresses: niwankui@chd.edu.cn; Sophie_Lv@126.com

Abstract. Densely compacted loess on which many man-made infrastructures are built are often exposed to strong weathering processes such as repeated wetting-drying (WD) cycles. In this paper, explore the relationship between collapsibility and wetting-drying cycles. all the samples were characterized by the XRD, surface micrographs, MIP and Collapsibility analysis. The results illustrated that the dominant inter-aggregate pore size and its peak intensity decrease as the specimens were increasing from 1 WD Cycle to 4WD Cycles, while intra-aggregate pores remained almost unchanged. Therefore, we finally get the wetting-drying cycles with a small number of times, the collapsibility coefficient will decrease. And the size of the particles and pore play an important role in collapsibility.

Keywords: Collapsibility, Microstructure of Loess, Wetting-Drying Cycles

1 Introduction

As the most important collapsible soil, loess is of great important in Northwestern China since it is one of the most productive soil covering 630,000 km² and 30 % of arable land in the surface of mainland China, especially in the type region Shanxi, Shaanxi, Gansu and Ningxia [1]. Loess is the yellow silt deposits carried by wind during the Quaternary period in the geological age. Like other geotechnical materials, its macro mechanical properties are mainly composed of the mineral components and the microstructure inside the loess [2,3]. In the Loess Plateau, loess is the most important filling material and foundation. It is widely used as an attractive material for compacted fill in compacted embankments, artificial slopes and backfills[4,6]. Especially, the changes in microstructure of loess under different drying and wetting cycles reflect physical and mechanical verities of loess[7,8]. Due to rainfall and evaporation, the surface loess continuously undergoes wetting-drying cycles, which affects the microstructure of the loess and also affects the macro-mechanical properties [9].

In the light of these considerations, we want to carry out different wetting-drying cycles on loess particles. In particular, the XRD, surface micrographs, MIP and Collapsibility analysis were used to characterized the microstructure and collapsibility of loess particles. The aim of this work is to report some findings explaining how the surface microstructure of the loess particles and collapsibility can be influenced by the different wetting-drying cycles.
2 Experimental

2.1 Sampling
Undisturbed loess samples were collected from loess Plateau in Shaanxi Luo Chuan loess national geopark(35°42'46.09''N, 109°26'0.10''E), China, though exploring the well in 7.0 m as original samples. In order to minimize changes to their properties, all the samples were retrieved by hand, sealed in plastic film inside a cylindrical iron bucket, and transported to the laboratory. The tested loess samples were light brown silty soil with slight plasticity. The main physical properties of the loess were determined following the ASTM 2006[10] standard test methods as listed in Table 1:

| Sample         | In-situ density (g/cm³) | Natural moisture content (%) | Specific gravity | Plastic limit (ωp/%) | Liquid limit (ωl/%) | Plasticity index (Ip) | Void ratio |
|----------------|-------------------------|-----------------------------|------------------|----------------------|---------------------|----------------------|------------|
| Original Loess | 1.3                     | 20.5                        | 2.72             | 19.5                 | 28.8                | 9.3                  | 1.24       |

![Fig. 1 Major occurrence of Loess Plateau in China and sampling location at excavation site (latitude 35°42'46.09'', longitude 109°26'0.10'').](image)

The sampled loess sample was crushed in the laboratory, the loess was first crushed, then air-dried, and sieved with a 2 mm sieve. The “double oedometer” method is used to evaluate its initial collapsibility coefficient, which is defined according to the following equation:

$$\delta_s = \frac{h_p - h_o'}{h_o}$$  \hspace{1cm} (1)

where $h_o$ is the initial height, $h_p$ is the stable sample height under a given load before wetting, and $h_p'$ is the stable height under the same load after wetting.

2.2 Wetting and Drying cycle Tests
The loess sample was air-dried to a moisture content of 12% during a wet-dry cycle, and then dried in an air oven at 105 ° C. for 8 hours, then saturated in a mold for 10 days under vacuum, and finally the sample was dried to moisture content of 12%. In this study, loess specimens were subjected to 1, 2, 3, and 4 WD cycles. XRD, MIP, digital microscope, and collapse tests were performed on the loess samples while completing one or more WD cycles.

3 Results and Discussion

3.1 XRD analysis
Fig. 2 showed the XRD pattern of Loess samples under the different WD cycles. It exhibits prominent peaks at 20.9°, 26.7°, 36.6°, 39.5°, 42.5°, 50.2°, 60.0° and 68.4°, which are similar to the reported values for quartz (SiO₂) [11]. The diffraction pattern also illustrated speaks at 9.0°, 17.9° and 55.0°, which are
characteristic peaks of Muscovite \((K_{0.77}Al_{1.93}(Al_{0.5}Si_{3.5})O_{10}(OH_{2}))\) \(^{[12]}\). For the Albite \((Na(AlSi_{3}O_{8}))\), the peaks at 28.0°, 31.1° and 45.6° can show its trait \(^{[13]}\). As well as the peaks at 25.2° and 29.5° are matching the feature of calcite \((CaCO_{3})\) \(^{[14]}\). XRD patterns are nearly identical, indicating that different WD cycles do not cause detectable change in mineralogical composition.

Among all these peaks, Quartz accounts for two peaks (2θ=20.9°, 26.7°), corresponding to the crystal face are (100) and (011), indicating its crystal plane structure are sheet and cube structure, respectively. Muscovite holds one peak (2θ=9°), which crystal face is (110), suggesting its crystal plane structure is sheet structure. This structure is consistent with that we know muscovite. Albite also have one peak (2θ=28.0°) and the crystal face is (040), expression its crystal plane structure is sheet structure. The last peak (2θ=29.5°) is belong to calcite, its crystal face is (21-2), performance its crystal plane structure is cube structure. In summary, structure of surface mineral in loess is dominated by sheet and cube. It revealed that the formation of loess particles is formed by the accumulation of layers.

3.2 The Surface Micrographs of loess particles by Digital Microscopy

The digital microscope were used to evaluate the features of loess particles after different drying-wetting cycles. Fig. 3 exhibits the micrographs of loess with different WD cycles. The particle size under different WD cycles is shown in Table 2. As the WD cycle increases, the size of the particles becomes smaller and smaller. After the WD cycle, the macropores on the surface gradually decreased, the soil particles were denser and smaller, and no microcracks were observed.

**Fig. 2** XRD patterns of different loess samples (Q = quartz, M = Muscovite, A = Albite, Ca = CaCO\(_3\)).

3.2 The Surface Micrographs of loess particles by Digital Microscopy

The digital microscope were used to evaluate the features of loess particles after different drying-wetting cycles. Fig. 3 exhibits the micrographs of loess with different WD cycles. The particle size under different WD cycles is shown in Table 2. As the WD cycle increases, the size of the particles becomes smaller and smaller. After the WD cycle, the macropores on the surface gradually decreased, the soil particles were denser and smaller, and no microcracks were observed.

**Fig. 3** Photographs of surface taken with the Keyence microscope using (A) 1 WD cycle, (B) 2 WD cycles, (C) 3 WD cycles and (D) 4 WD cycles
Table 2 The particle size under different WD cycles

| WD Cycle Times | size range of loess particle |
|----------------|----------------------------|
| 1              | 21.9–50.2 µm               |
| 2              | 19.4–51.5 µm               |
| 3              | 24.0–47.1 µm               |
| 4              | 20.2–45.0 µm               |

3.3 MIP analysis
Fig. 4 shows the pore size distributions of the loess sample under different WD cycles and specimens with different WD Cycles under a vertical pressure of 800 kPa. By comparing the pore size distributions curves obtained from WD cycles, Figure 3A shows that all four samples have two peaks on the pore density curve, which defines the first macropore family of inter-aggregate pores with dominant diameters of approximately 13953 nm, 11336 nm, 13953 nm and 11336 nm in specimens with dry densities of 1 WD Cycle, 2 WD Cycles, 3 WD Cycles and 4 WD Cycles respectively. The second family of micropores in the aggregate pores has the same major diameter at 32.4 nm. The figure also shows that as the sample increases from 1 WD cycle to 4WD cycle, the inter-aggregate pore size and its peak intensity decrease, It decreased rapidly when the WD Cycles increased third to fourth. At the same time, the corresponding porosity of the pores in the aggregate remains almost unchanged when the WD Cycles increased from 1 WD Cycle to 4WD Cycles. Figure 3B provides the pore size distribution of samples with different WD cycles at a vertical pressure of 800 kPa. As the WD cycle increased, the dominant inter-aggregate pore population remained almost unchanged, while the peak intensity of the sample decreased. In contrast, the dominant intra-aggregate pore population and its peak intensity remained almost unchanged after loading.

![Fig. 4](image)

Fig. 4 the pore size distributions of the loess sample(A)under different WD cycles; (B)specimens with different WD Cycles under a vertical pressure of 800 kPa.

3.4. Collapsibility
Fig. 4 showed the collapsibility coefficient of Loess samples under the different WD cycles. As the WD cycle increases, the size of the collapsibility coefficient becomes smaller and smaller, this is because the size of the particles becomes smaller and smaller. And surface macropores are gradually reduced, closer distance between loess particles.

The change of the collapsibility coefficient can be divided into several stages according to the increase of the WD cycle. For example, for sample 1 WD cycle, when the vertical pressure is in the range of 0 to 200 kPa, the collapsibility coefficient increases very quickly, and then slowly increases until it reaches a maximum value at 600 kPa vertical pressure. Thereafter, when the vertical pressure exceeds 600 kPa, it remains stable or decreases. And when the vertical pressure is large enough, the collapsibility coefficient of the samples under different WD cycles tends to be uniform. The tended of other samples is similar 1 WD cycle.
Fig. 5. Under different wetting-drying cycles, the collapse coefficient of compacted loess samples is a function of load.

4. Conclusion
Based on original loess from Luo Chuan and the XRD, surface micrographs, MIP and Collapsibility of all samples were tested after different drying-wetting cycles. The main conclusions are illustrated as follows:

1. The formation of loess particles is formed by the accumulation of layers. And main peaks of the crystal planes in the XRD patterns of the four loess samples were basically the same, different WD Cycles cause detectable change in mineralogical composition hardly.

2. Loess particles are more compactly arranged under the action of wetting-drying cycles, resulting in a decrease in void ratio.

3. The dominant inter-aggregate pore size and its peak intensity decrease as the specimens were increasing from 1 WD Cycle to 4 WD Cycles, while intra-aggregate pores remained almost unchanged.

4. The collapsibility of remolded loess with different WD Cycles is mainly determined by the decrease in diameter and population of inter-aggregate pores.

In conclusion, as the number of wetting-drying cycles increases, the reduction in diameter and population of inter-aggregate pores. Therefore, the collapsibility coefficient is mainly affected by these two points. Further studies will be devoted to better understand the puzzling mechanisms involved in the drying-wetting cycle of loess samples, based on the size of particles and porosity.

Acknowledgements
This research was financially supported by the Second Tibetan Plateau Scientific Expedition and Research (STEP) program (Grant No. 2019QZKK0906), China Postdoctoral Science Foundation (Program No. 2018M631117), the key research and development program of Shaanxi China (Program No.2017ZDXM-SF-087 and Program 2019ZDLSF05-07), Natural Science Basic Research Plan in Shaanxi Province of China (Program No. 17JK0096), SAFEA: High-End Foreign Experts Project (Program No. GDW20186100251) and the Fundamental Research Funds for the Central Universities (Program No. 300102298102).

References
[1] Deng, J., Wang, L., Zhang, Z., Bing, H., 2010. Microstructure characteristics and forming environment of late Quaternary Period loess in the Loess Plateau of China. Environ Earth Sci 59, 1807–1817.
[2] Li, X., Li, L., 2017. Quantification of the pore structures of Malan loess and the effects on loess permeability and environmental significance, Shaanxi Province, China: an experimental study. Environ Earth Sci 76, 523.
[3] Assadi-Langroudi, A., Ng’ambi, S., Smalley, I., 2018. Loess as a collapsible soil: Some basic particle packing aspects. Quaternary International 469, 20–29.
[4] Yang, Y., Ju, Y.W., 2013. High Fill Embankment of Collapsible Loess Settlement Observation and Research. Advanced Materials Research 838–841, 874–877.

[5] Gao, W., Wang, X., Dai, S., Chen, D., 2016. Study on stability of high embankment slope based on black hole algorithm. Environmental Earth Sciences 75.

[6] Zhao, X., Huang, J., Wu, P., Gao, X., 2014. The dynamic effects of pastures and crop on runoff and sediments reduction at loess slopes under simulated rainfall conditions. CATENA 119, 1–7.

[7] Qiu, J., Wang, X., Lai, J., Zhang, Q., Wang, J., 2018. Response characteristics and preventions for seismic subsidence of loess in Northwest China. Natural Hazards 92, 1909–1935.

[8] Chen, R., Xu, T., Lei, W., Zhao, Y., Qiao, J., 2018. Impact of multiple drying–wetting cycles on shear behaviour of an unsaturated compacted clay. Environmental Earth Sciences 77.

[9] Liu, W., Tang, X., Yang, Q., Li, W., 2015. Influence of drying/wetting cycles on the mechanical cyclic behaviours of silty clay. European Journal of Environmental and Civil Engineering 19, 867–883.

[10] ASTM. 2006. Standard practice for classification of soils for engineering purposes (Unified Soil Classification System). ASTM standard D2487. American Society for Testing and Materials, West Conshohocken, Pa.

[11] Liu, Z., Liu, F., Ma, F., Wang, M., Bai, X., Zheng, Y., Yin, H., Zhang, G., 2016. Collapsibility, composition, and microstructure of loess in China. Canadian Geotechnical Journal 53, 673–686.

[12] Ma, F., Yang, J., Bai, X., 2017. Water sensitivity and microstructure of compacted loess. Transportation Geotechnics 11, 41–56.

[13] Ma, F., Yang, J., Bai, X., 2017. Water sensitivity and microstructure of compacted loess. Transportation Geotechnics 11, 41–56.

[14] Xie, X., Qi, S., Zhao, F., Wang, D., 2018. Creep behavior and the microstructural evolution of loess-like soil from Xi’an area, China. Engineering Geology 236, 43–59.