AMSE JOURNALS-AMSE IIETA publication-2017-Series: Modelling B; Vol. 86; N°1; pp141-154
Submitted Jan. 2017; Revised March 15, 2017, Accepted April 15, 2017

Pressure-Dependent Behaviour of Gas Permeability of Undisturbed Loess

Xiangwei Fang, Jie Li, Chunhai Li*

*Department of Civil Engineering, Logistical Engineering University,
Chongqing, 401311, China
Email: fangxiangwei1975@163.com

Abstract

Gas permeability k_a is critical in environmental protection and restoration projects. This paper is aimed to show the pressure-dependent bahaviour of gas permeability of undisturbed loess. Gas permeability tests of loess were carried out in two test series at different saturation along respective drying path. Samples of series 1 are moisture-adjusted and those of series 2 are tested with their natural water content. The pressure-dependent behaviour (Klinkenberg effect) of gas permeability of loess was studied. Incorporating both Klinkenberg effect and influence of saturation, a modified equation was presented. In two test series, values of the Klinkenberg factor b remained the same and k_∞ could be taken as equal, but k'_∞ varied differently with saturation along the drying path. These results suggest that, gas permeability is more sensitive to inflow gas pressure rather than saturation over the saturation period studied, and wetting does not have significant influence on soil structure of loess.

Keywords

Gas permeability, loess, pressure-dependent behavior, Klinkenberg effect

1. Introduction

Even nowadays, in some developing regions, municipal solid wastes are dumped in an uncontrolled manner or buried deep in the ground, posing a threat to the surrounding environment as solid wastes produce, among other things, inflammable and asphyxiating gas during its decomposition process. Therefore, more investigations on gas flow through soil, especially deep soil layers, are critical. In loess plateau region of China, cities are on their expressway of development, the way to deposit the solid wastes might be burying deep, or piled up as tailing pond dam in mining area, and deposited above the riverbed, all these ways could easily lead to geological disasters [1-3]. Loess is difficult to deal with in engineering practice, for geotechnical problems such as landslide, debris flow and subsidence, while subsidence is the major practical problem encountered in loess region, mainly due to its open structure and metastable particle packings [4-5]. Loess in China, according to geological ages, can be classified as Recently deposited loess, Malan loess, Lishi loess and Wucheng loess, corresponding to Holocence test series, Upper Pleistocene test series, Middle Pleistocene test series and Early Pleistocene test series respectively [6-7]. The four stratigraphic units show differences in structure at the grain scale, the denser structure and greater proportion of the fines in Lishi loess and Wucheng loess give them more differences than the others in terms of their properties [8]. An distinctive characteristic of the fabric of undisturbed loess is the presence of cementation which determines, to a large extent, the properties of undisturbed loess [9].

Gas permeability of undisturbed soil depends on grain size distribution, soil pore structure, the effect of soil-air content (air-filled porosity), and the effect of hydrate during gas transition process[10-12]. Models describing gas diffusivity and gas permeability of undisturbed sandy and loamy soils have been proposed a lot, some show good prediction accuracy [13]. Most of the researches on gas permeability of loess are about recently deposited loess or Malan loess, Lishi loess, however, hasn't received much attention, and related investigations are rarely reported [14-16].

This paper aims to present the gas flow behavior through undisturbed Lishi loess. Experiments are carried out to obtain gas permeability k_a of Lishi loess with different degrees of saturation at different inflow gas pressures. The data obtained from gas permeability measurements are analyzed by modifying the method proposed by Yushu Wu, Karsten Pruess, and Peter Persoff [17]. Pressure-dependent behaviour (Klinkenberg effect) of gas permeability of Lishi loess is presented, and comparison are also made between gas permeability of moisture-adjusted and non-moisture-adjusted samples.

2. Materials and methods

2.1 Test system

Test system adopted in this research was developed by Yao Zhihua [16]. The testing system consists of three parts: pressure regulator, triaxial cell, and flowmeter, shown as Figure 1. Confining and inflow pressures, which are generated by air compressor, are applied through pressure regulator. The soil sample to be tested is placed in the testing cell, the applied inflow gas runs through the sample, then goes into the flowmeter. The flowmeter (SF-02DEM electronic soap-membrane flowmeter) used in the test system is developed and modified by Wang Long, Fang Xiangwei et al. It consists of two parts: the test tube and the main machine. These two parts are linked by infrared sensor, by which the time a piece of soap-membrane runs in the test tube is obtained. One end of the tube is connected with the outflow end of traxial cell, the other end is open to the atmosphere. Volumetric flow rate is measured by flowing soap-membrane produced at the bottom of the tube flowmeter. This flowmeter is easy to operate and volumetric flow rate can be read directly on the screen of main machine.

Fig.1. Test system of gas permeability

2.2 Sampling procedure

The considered soil in this research was from Pucheng, a town near Xi'an (capital city of Shanxi Province) where landscape is flat and the soil is homogeneous. Undisturbed soil were taken from 10m below the ground surface, where a clear "red belt", a paleosol layer, marks the demarcation of Malan loess and Lishi Loess [18]. The soil blocks were obtained in a fresh construction pit, each block about 30 cubic centimeter, then lifted in a basket to the ground and wrapped up by one piece of plastic film first and then one piece of kraft paper over the plastic film, tap was applied over the kraft paper to make soil the soil block was fully wrapped. Wrapped soil blocks were put in a wooden box and transported to the laboratory; foam blocks and pieces of newspapers were used to fill the gaps and voids to ensure the least disturbance to the soil blocks during the transportation. The water content of loess is 22.5%, dry density is 1.333 g/cm3, void ratio is 1.038, liquid limit is 17.2%, plasticity limit is 11.4%. Table 1 gives the particle size fraction of Lishi loess.

Samples used in the tests were prepared of the same size as standard triaxial samples: 80mm in height and 39.1mm in diameter. Two test series of samples (test series1 and test series2) were prepared, samples of test series 1 (sample 1-1, 1-2 and 1-3), the same natural water content as samples in test series 2, were carefully moisture-adjusted to saturation of 75%. When adjusting the water content of samples of test series 1, first place samples in the humidor, then use spray to humidify samples slowly and gently, and let the samples stand in the humidor for 48 hours. Repeat the humidifying process for 4~5 times until the samples reach to the saturation of 75%, so that these samples could be humidified uniformly. Samples of test series 1 went through the wetting cycle before tests following the drying path, and samples of test series 2 (sample 2-1, 2-2, 2-3) would be tested along a drying path from initial saturation.

Table 1. The particle size fraction of the soil

>0.1 （mm）	**0.1~0.05 （mm）**	**0.05~0.02 (mm)**	**0.02~0.01 (mm)**	**0.01~0.005 (mm)**	**0.005~0.002 (mm)**	**0.002~0.001 (mm)**	**<0.001 (mm)**
0%	0%	18.88%	35.52%	24.79%	14.06%	4.52%	2.22%

2.3 Measurement Procedure for gas permeability

Gas permeability was measured in the test system by flowing air through the standard triaxial sample with different saturation at different gas pressures. Three inflow gas pressures, 110kpa, 130kpa and 150kpa are applied on soil samples.

Gas permeability of test series 1 (sample 1-1, 1-2 and 1-3) were measured with their saturation changing from 2% to 75%, while that of test series 2 (sample 2-1, 2-2 and 2-3) were measured with their saturation changing from 2% to 55%. Drying paths for the two test series of experiments are shown in Table 2. The drying of these samples were carried out by air-drying (for very low saturation, samples were dried in air-conditioned room), then weighted, this procedure was repeated until the samples reached the saturation set for measurement of gas permeability. All these samples were weighted before and after each test.

Table 2. Drying paths for the experiments

Test seies1(moisture-adjusted)	**Test seies2(natural saturation)**
sample1-1, 1-2, 1-3	sample2-1, 2-2, 2-3
75.0%	55.0%
67.0%	50.5%
57.0%	40.5%
50.0%	34.0%
39.0%	26.0%
23.0%	11.5%
4.5%	6.0%
2.0%	2.0%

Gas permeability k_a was calculated using a non-Klinkenberg gas flow solution of compressible gas [19]:

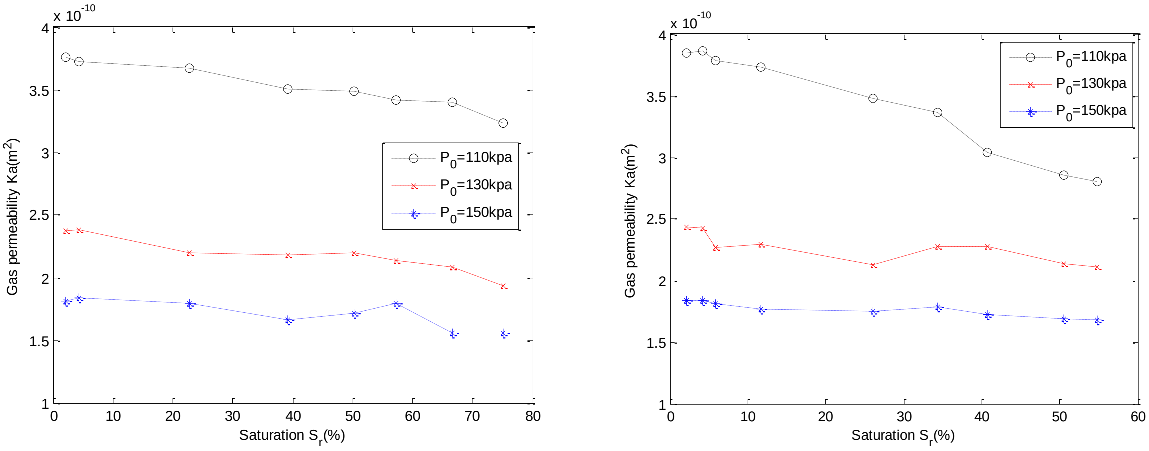
$$k_a = \frac{2\mu L q_L^V P_L}{P_0^2 - P_L^2}$$

(1)

Where μ is the dynamic viscosity of air, μ=1.82×10^{-5}Pa.s for t=20°C; P_0 is the gas pressure at the inflow end (Pa); P_L is the gas pressure at the outflow end (Pa); L is the height of the sample (m); q_L^V is the volumetric flow rate measured at the outflow end (m^3/(s.m^2)). In the tests followed, inflow gas pressure P_0 is varied, while outflow pressure P_L is kept as a constant value. From data obtained in each test conducted, was derived for each sample with a certain saturation and specified inflow gas pressure, they were then averaged to get an average value of k_a, for test series 1 and test series 2 respectively, as a function of saturation and inflow gas pressure.

3. Results

Average gas permeability of test series1 (sample1-1, 1-2 and 1-3) of varied saturation and at different inflow gas pressures are presented in Figure 2(a), and those of test series 2 (sample2-1, 2-2 and 2-3) are presented in Figure 2 (b). Both figures show a slight decrease in gas permeability with saturation at different inflow pressures, and gas permeability almost remains constant for higher saturation.



(a) Test series 1 (b)Test series 2

Fig.2. Average value of gas permeability of the two test series of samples

It is important to note that gas permeability is significantly affected by inflow gas pressure: the gas permeability drops as inflow gas pressure increases, suggesting that gas permeability of undisturbed Lishi loess is pressure-dependent.

Though, for each inflow gas pressure, decline in gas permeability as saturation rises over the interval studied is slight, the higher the inflow gas pressure, the slighter the change of gas permeability with saturation. In test series 1, difference between the value of gas permeability corresponding to the lowest saturation and the highest saturation is 5.3233×10^{-11} (m^2), 4.4467×10^{-11} (m^2) and 2.4990×10^{-11} (m^2), respective to inflow gas pressure of 110kpa, 130kpa and 150kpa.

As for gas permeability of a certain saturation, its rate of change with inflow pressure tends to decline as inflow pressure increases. For instance, in test series 2 when saturation of the soil sample is 54.8%, value of gas permeability drops 6.94534×10^{-11} (m^2) as inflow pressure increases from 110kpa to 130kpa, while it drops 4.25392×10^{-11} (m^2) when inflow pressure increases from 130kpa to 150kpa, in both cases the pressure increment is 20kpa.

Seen from the above, it is clearly shown that gas permeability of undisturbed Lishi loess is more sensitive to inflow gas pressure rather than saturation over the period concerned in this research.

4. Discussion

In these experiments, saturation considered for test series1 lies in the range of 2% to 75%, and that of test series 2 ranges from 2% to 55%. All these results are consistent with earlier findings suggesting that gas permeability remains constant for saturation lower than 60%, a slight decrease would take place for saturation between 60% and 85% [20-21]. Such phenomenon could be interpreted as follows, when soil water content is low, pore water is tightly adsorbed around soil particles, leading to interconnected gas channels inside the soil, as saturation increases to a certain degree, adsorbed films on particle surfaces grow thick enough and the gas channels get blocked.

The pressure-dependent behaviour, namely Klinkenberg effect, of gas flow through undisturbed Lishi loess is obvious and could not be ignored. This effect, named after Klinkenberg [22], says that effective gas permeability at a finite pressure is defined as

$$k_a = k_\infty (1 + \frac{b}{p})$$

(2)

where k_∞ is the absolute, gas-phase permeability under very large gas-phase pressure at which condition the Klinkenberg effects are negligible; and b is the Klinkenberg factor, dependent on the pore structure of the porous media and temperature for a given gas [22].

k_∞ can be derived from k_a, which can be obtained by traditional method to determine gas permeability in laboratory for a one-dimensional steady-state, linear flow problem,

$$k_a = k_\infty (1 + \frac{b}{(P_0 + P_L)/2})$$

(3)

By equating gas permeability of (2) and (3), Klinkenberg constants, k_∞ and b, can be determined. In equation (3), $1/((P_0+P_L)/2)$ is taken as the variable, this variable is proposed and used so that k_∞ can be acquired directly from traditional method to measure k_a, and such method is verified to be effective [17]. Over the saturation period studied, the equation is better to be revised as follows:

$$k_a = k'_\infty (1 + b(\frac{1}{(P_0 + P_L)/2} - c))$$

(4)

Where k'_∞ is modified absolute gas permeability that is defined as follows:

$$k'_\infty = \omega k_\infty$$

(5)

ω is an influential factor of saturation; c is the starting point of the studied interval $\frac{1}{(P_0 + P_L)/2}$, in this case, c is $\frac{1}{(P_0 + P_L)/2}$ when P_0=150kpa, i.e. $c=0.8\times10^{-6}$.

This modification, incorporating the influence of saturation and taking P_0=150kpa as the starting point of the inflow gas pressure range considered, may seem questionable, however, because equation (1) could only be used on condition that Darcy's law is valid. Experiments carried out by Chen Zhenghan [14] and Yao Zhihua [16] on gas permeability of loess both verifies that within pressure period studied in this research, Darcy's law applies. However, it is not clear whether Darcy's law applies when inflow gas pressure is as high as 200kpa, so it would be reasonable to revise the equation as given by equation (4).

Figure 3 and 4 displays the gas permeability as a function of $1/((P_0+P_L)/2)$ at each saturation in test series1 and 2. Coefficients k'_∞ and Klinkenberg constant b of equation (4) are derived by linear fitting. Table 3 lists the value of k'_∞ and b corresponding to each saturation tested of two test series of experiments.

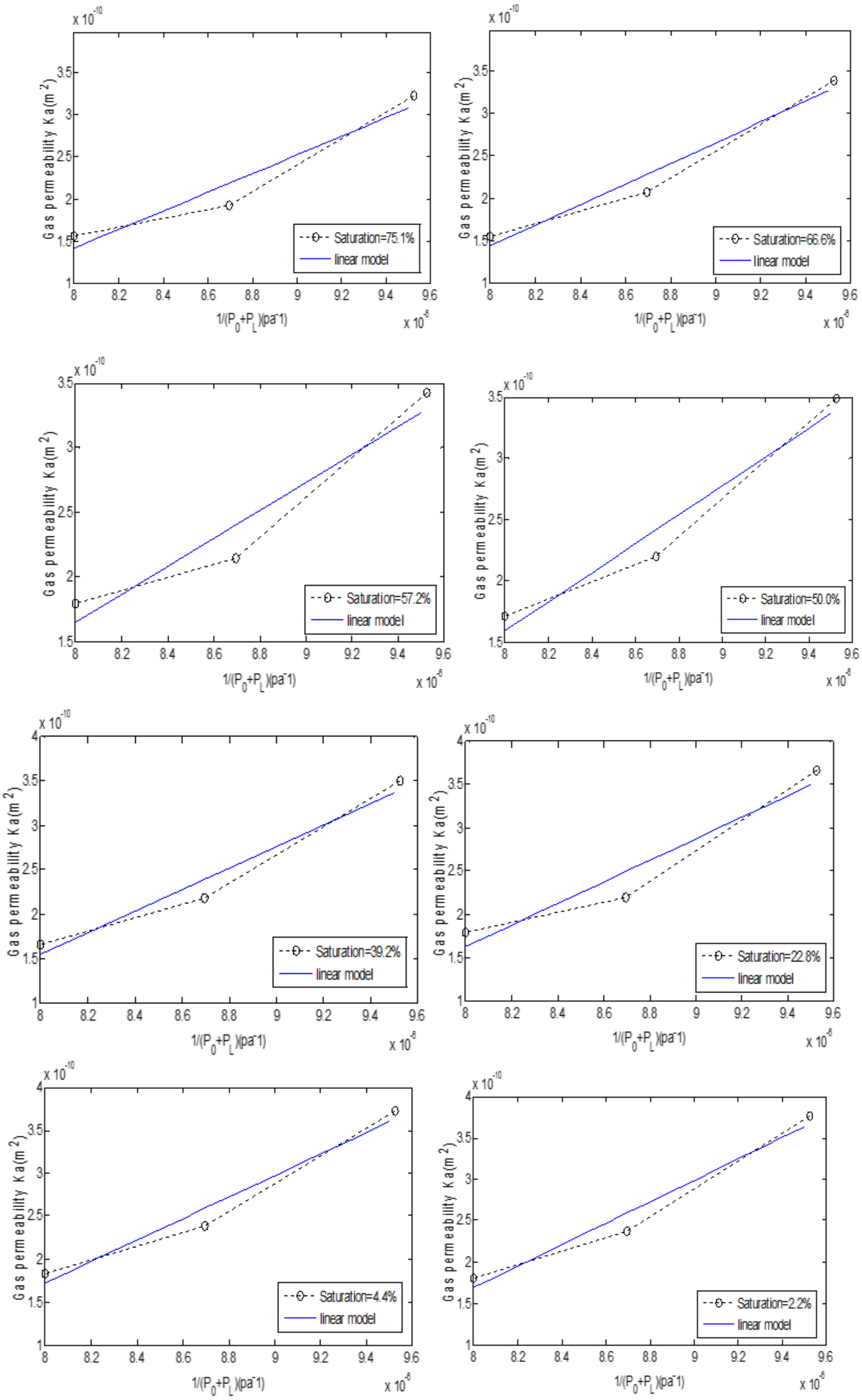


Fig.3. Gas permeability as a function of $1/(P_0+P_L)$ at different saturation of test series 1

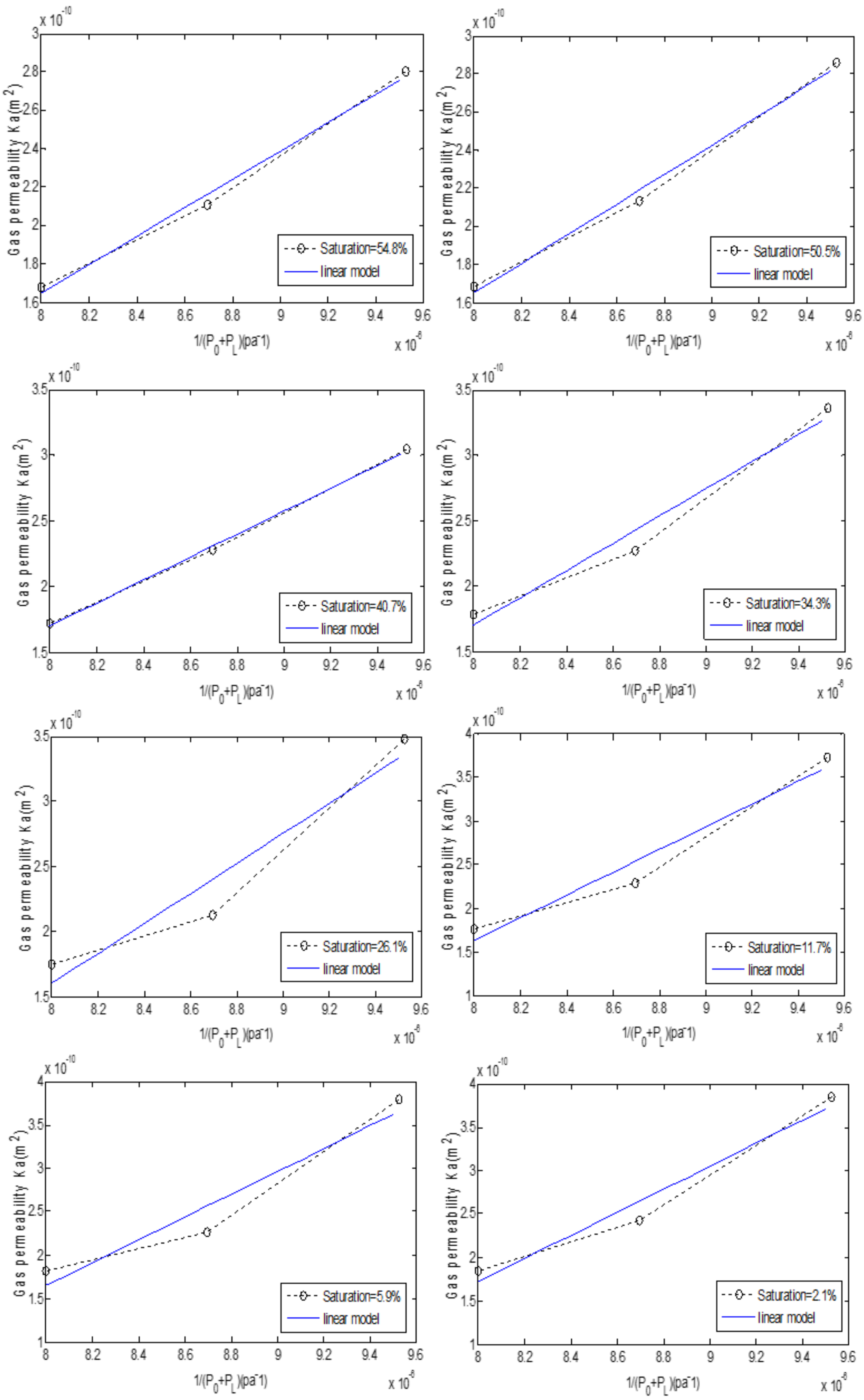


Fig.4. Gas permeability as a function of $1/(P_0+P_L)$ at different saturation of test series 2

Table 3. Values of k'_{∞} and b of test series 1 and 2 at different saturation

test series 1			test series 2		
Saturation	k'_∞ **(m²)**	b **(pa)**	**Saturation**	k'_∞ **(m²)**	**b(pa)**
75.1%	8.80×10^{-4}	0.125	54.8%	5.92×10^{-4}	0.125
66.6%	9.60×10^{-4}	0.125	50.5%	6.16×10^{-4}	0.125
57.2%	8.80×10^{-4}	0.125	40.6%	6.96×10^{-4}	0.125
50.2%	9.60×10^{-4}	0.125	34.3%	8.00×10^{-4}	0.125
39.2%	9.60×10^{-4}	0.125	26.1%	9.60×10^{-4}	0.125
22.8%	1.04×10^{-3}	0.125	11.7%	1.04×10^{-3}	0.125
4.4%	9.60×10^{-4}	0.125	5.9%	1.04×10^{-3}	0.125
2.1%	1.04×10^{-3}	0.125	2.1%	1.04×10^{-3}	0.125

As is shown in Table 3, in both test series of tests, values of k'_∞ are affected by saturation while b remains the same value of 0.125 (pa), and when saturation of samples drops to 2.1%, the two k'_∞ are equal to 1.04×10^{-3} (m²).

Physically, k_∞ is the absolute, gas-phase permeability under very large gas-phase pressure at which condition the Klinkenberg effects are negligible, so k_∞ can be taken approximately as 1.04×10^{-3} (m²) as the corresponding saturation of k'_∞ now is low enough. The value of b, which is dependent on the pore structure of the media, remains the same in both test series 1 and 2, implying that wetting (represented by test series 1) and drying (represented by test series 1and 2) has no significant effect on structure of Lishi loess. Hysteretic effect of hydraulic conductivity is, to some extent, attributed to changes in pore size along wetting or drying path [23]. But such hysteretic effect in gas permeability as of function of saturation is not clearly observed, as shown in Figure 5, especially when inflow gas pressure is higher. All these findings might indicate that wetting does not have significant influence on soil structure of undisturbed Lishi loess.

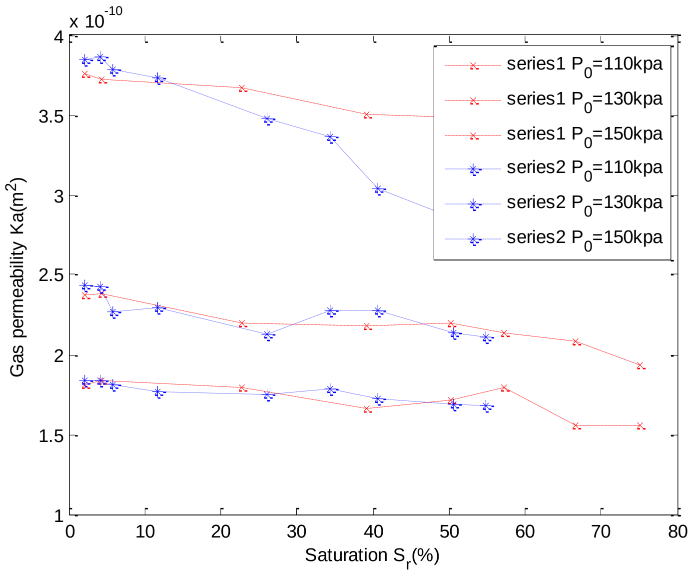


Fig.5. Average values of gas permeability of test series 1 and test series 2

Figure 6 plots coefficient k'_∞ against saturation, it shows that test series 1 and 2 have the same value of k'_∞ when saturation comes near zero, this is condition where k'_∞ can be taken as k_∞. However, as saturation increases, k'_∞ of test series 1 and test series 2 starts to exhibit large difference, coefficient of test series 2, air-dried from natural saturation, tends to drop more rapidly whereas that of test series 1 which has gone along wetting path before drying decreases steadily. Besides, even at nearly the same saturation, the two coefficients of the two test series don't agree with each other in value. This behaviour seems to suggest that factor ω is not merely a simple function of saturation. Confusing as it might be, though structure of the two test series could be assumed as the same, for Klinkenberg constant b and k_∞ are considered equal, and k'_∞ seems to be subject only to saturation, it should, somehow, be noted that spatial variability of distribution of liquid and gas phase may cause variability in value of factor ω, in other words, ω is not a single valued function of saturation.

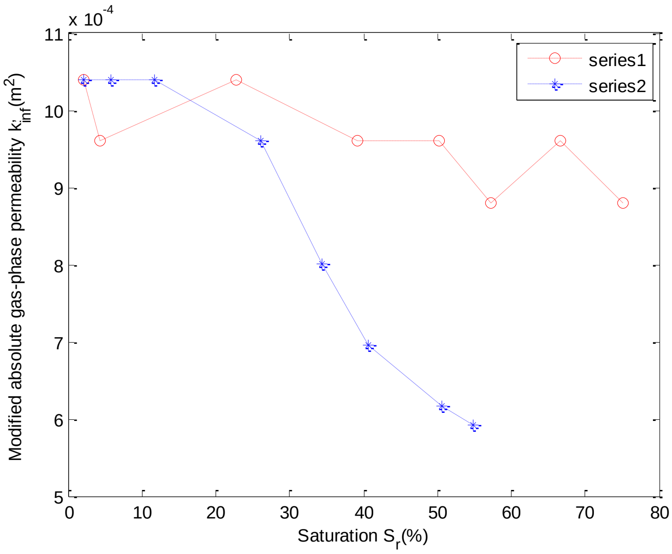


Fig.6. Modified absolute gas-phase permeability k'_∞

5. Conclusions

Gas permeability (k_a) of undisturbed Lishi loess with different saturation at varied inflow pressures were measured. The data obtained revealed that over the saturation period studied (2%-75%), gas permeability of undisturbed Lishi loess is dependent of the inflow gas pressure, and undergoes only a slight decline with the increase of saturation.

A modified equation incorporating both Klinkenberg effect (pressure-dependent behaviour) and influence of saturation was proposed. In both test series of samples, values of the Klinkenberg factor b remained the same, values of k_∞ were equal as well, suggesting that wetting does not have significant influence on soil structure of Lishi loess.

Factors ω (k'_∞) of the two test series, concerning saturation, did not vary with saturation in the same way along the drying path. Thus it could be assumed that ω is not a single-valued function of saturation, and might be closely related to spatial variability of distribution of liquid and gas phase in soil.

Acknowledgments

This work was financially supported by the National Natural Science Foundation of China (No.11272354, No.51479208).

References

1. A.M. Assallay, C.D.F. Rogers, I.J. Samalley, Formation and collapse of metastable particle packing and open structure in loess deposits, 1997, Engineering Geology, vol. 48, no. 1-2, pp. 101-115.
2. H. Chen, Analysis of numerical simulation of wading landslide in Three Gorges Reservoir area based on Outang landslide, 2016, Mathematical Modelling of Engineering Problems, vol. 3, no. 2, pp. 71-74.
3. J. Chen, Y. Zheng, J. Yan, Influence on deposition of the Three Gorges Reservoir caused by the reservoirs built upstream, 2015, International Journal of Heat and Technology, vol. 33, no. 2, pp. 63-68.
4. T.A. Dijikstra, I.J. Smalley, C.D.F. Rogers, Particle packing in loess deposits and the problem of structure collapse and hydroconsolidation, 1995, Engineering Geology, vol. 40, no. 1-2, pp. 49-64.
5. S. Zhang, L. Zhang, Q. Qi, Q. Li, P. Shi, Numerical simulation of the characteristics of debris flow from a tailing pond dam break, 2015, International Journal of Heat and Technology, vol. 33, no. 3, pp. 127-132.
6. Zhang Zonghu, Zhang Zhiyi, Wang Yunsheng, Loess in China, 1989, Geological Publishing House, Beijing, China.
7. Liu Zudian, Mechanics and Engineering of Loess, 1989, Science and Technology Publishing House of Shanxi province, Xi’an, China.

8. Liu houjian, Zhou Tianhong, Engineering properties of Q_2 loess, 2001, Proceedings of National Conference on Loess, Lanzhou, China, pp. 66-72.
9. G.A.M. Kruse, T.A. Dijkstra, F. Schokking, Effects of soil structure on soil behaviour: Illustrated with loess, glacially loaded clay and simulated flaser bedding examples, Engineering Geology, 2007, vol. 91, no. 1, pp. 34-45.
10. S.A. Rodeck, B.A. DeVantier, B.M. Das, Air-permeability measurement for soil at low and high pressure, 1994, Journal of Environmental Engineering, vol. 120, no. 5, pp. 1337-1343.
11. P. Moldrup, T.G. Poulsen, P. Schjl'lnning, T. Olesen, T. Yamaguchi, Gas permeability in undisturbed soils: Measurement and predictive models, 1998, Soil Science, vol. 163, no. 3, pp. 180-189.
12. Y.D. Zhang, D. Wang, J.P. Yang, L. Tian, L. Wu, Research on the hydrate formation in the process of gas phase CO_2 pipeline Transportation, 2016, International Journal of Heat and Technology, vol. 34, no. 2, pp. 339-344.
13. T.G. Poulsen, P. Moldrup, P. Schj&oslash, Gas permeability and diffusivity in undisturbed soil: SVE implications, 1998, Journal of Environmental Engineering, vol. 124, no. 10, pp. 979-986.
14. Chen Zhenghan, Xie Dingyi, Wang Yongsheng, Research on transport of fluid in unsaturated soil and its application in engineering, 1993, Chinese Journal of Geotechnical Engineering, vol. 15, no. 3, pp. 9-20.
15. Wang Yongsheng, Xie Dingyi, Guo Qingguo, Measurement of gas permeability and study on transport of fluid in unsaturated soil, 1993, Northwest Water Power, vol. 1, pp. 43-49.
16. Yao Zhihua, Chen Zhenghan et al, Experimental research on gas permeability of unsaturated Q_3 loess, 2012, Chinese Journal of Rock Mechanics and Engineering, vol. 31, no. 6, pp. 1264-1273.
17. Y.S. Wu, K. Pruess, P. Persoff, Gas flow in Porous media with Klinkenberg effect, 1998, Transport in Porous Media, vol. 32, nol. 1, pp. 117-137.
18. Liu Houjian, On engineering properties of Q_2 loess in Xi'an, 1994, North-west Geology, vol. 15, no. 3, pp. 47-53.
19. A.E. Scheidegger, The physics of flow through porous media, 1958, Soil Science, vol. 86, no. 6, pp. 355.
20. J.F.T. Juca, F.J. Maciel, Gas permeability of a compacted soil used in a landfill cover layer, 2006, International Conference on Unsaturated Soils, Carefree, USA, pp. 1535-1546.
21. D.G. Fredlund, H. Rahardjo, Soil mechanics for unsaturated soils, 1993, John-Wiley and Sons, New York, USA.

22. L.J. Klinkenberg, The permeability of porous media to liquids and gases, 1941, Socar Proceedings, vol. 2, no. 2, pp. 200-213.
23. N. Ling, J. William, Unsaturated soil mechanics, 2004, John-Wiley and Sons, New York, USA.